W^+W^- production at LHC at NLO in extra dimension models

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TIFR, Mumbai,

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Plan of talk

- Hierarchy Problem
- ADD model
- W^+W^- production in ADD model
- Results

The LHC Search

- Mechanism for spontaneous symmetry breaking - The Higgs Boson
- Physics beyond the Standard Model

New Physics

- Super Symmetry
- Large extra-dimensions
- Something more exotic

Eventual Aim

- Discover the model
- Determine the parameters of the model

Gauge hierarchy problem

- $SU(2) \times U(1)$ broken by scalar Higgs
- W and Z boson masses $\rightarrow \mu_H^2 \sim (100\ GeV)^2$
- Scalar $(mass)^2$ receives additive renormalization
- Bare $mass^2$ is of order $-\Lambda_{Plank}^2$ and cancel to μ_H^2
  - $\rightarrow$ fine-tuning problem
  - $\rightarrow$ hierarchy problem

Solution to Hierarchy Problem

- Supersymmetry
- Extra dimension models
  - ADD
  - RS
- etc.

ADD model

- Introduces extra spatial dimensions
  - World is $D = 4 + d$ dimensional
  - d spatial dimensions are compact
- Brings D-dimensional Planck scale M_S down to EW scale
- Only one fundamental scale, EW scale
- Thereby solves hierarchy problem

N. Arkani-Hamed, S. Dimopoulos and G. Dvali,

Phys. Lett. **B429**, 263 (1998)

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

Phys. Lett. **B436**, 257 (1998)

$$F_{grav} \sim \frac{1}{r^2} \qquad 3 - spatialdimensions \tag{1}$$

$$F_{grav} \sim \frac{1}{r^{d+2}} \qquad d - extraspatialdimensions \tag{2}$$

Deviation from square law !

$$F_{elec} \sim \frac{1}{r^{d+2}} \qquad d - extradimensions \tag{3}$$

Deviation from squar law !
SM fields are localized on D-3 brane

Effect of gravity on SM fields

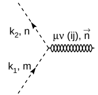
- KK reduction
- For a given KK level
  - one spin-2 state
  - $d-1$ spin-1 states
  - $d(d-1)/2$ spin-0 states
  - all are mass degenerate
- Coupling of KK states to matter
  - through energy momentum tensor

- Interaction: $-\frac{k}{2}\int d^4 x h^{\mu\nu} T_{\mu\nu}$
- where $\kappa = \sqrt{16\pi G_N}$
  G_N : Newton's constant in 4-dim
- $\kappa^2 R^d = 8\pi(4\pi)^{d/2}\Gamma(d/2) M_s^{-(d+2)}$

T. Han, J. D. Lykken and R. J. Zhang,
Phys. Rev. D **59** (1999) 105006

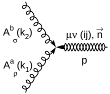
G. F. Giudice, R. Rattazzi and J. D. Wells,

Nucl. Phys. B **544** (1999) 3



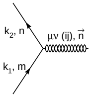
$$\tilde{h}^{\vec{n}}_{\mu\nu}\,\Phi\Phi : \quad -i\,\kappa/2\;\delta_{mn}\,(\,m^2_{\Phi}\,\eta_{\mu\nu} + C_{\mu\nu,\rho\sigma}\,k_1^{\rho}\,k_2^{\sigma}\,)$$

$$\tilde{\phi}^{\vec{n}}_{ij}\,\Phi\Phi : \quad i\,\omega\,\kappa\,\delta_{ij}\,\delta_{mn}\,(\,k_1\cdot k_2 - 2\,m^2_{\Phi}\,)$$



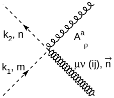
$$\tilde{h}^{\vec{n}}_{\mu\nu}\,AA : \quad -i\,\kappa/2\;\delta^{ab}\,(\,(\,m^2_{A} + k_1\cdot k_2\,)\,C_{\mu\nu,\rho\sigma} + D_{\mu\nu,\rho\sigma}\,(k_1, k_2) + \xi^{-1}\,E_{\mu\nu,\rho\sigma}\,(k_1, k_2)\,)$$

$$\tilde{\phi}^{\vec{n}}_{ij}\,AA : \quad i\,\omega\,\kappa\,\delta_{ij}\,\delta^{ab}\,(\,\eta_{\rho\sigma}\,m^2_{A} + \xi^{-1}\,(k_{1\rho}\,p_{\sigma} + k_{2\sigma}\,p_{\rho})\,)$$



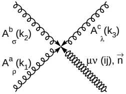
$$\tilde{h}^{\vec{n}}_{\mu\nu}\,\psi\psi : \quad -i\,\kappa/8\;\delta_{mn}\,(\,\gamma_{\mu}\,(k_{1\nu} + k_{2\nu}) + \gamma_{\nu}\,(k_{1\mu} + k_{2\mu}) - 2\,\eta_{\mu\nu}\,(\not{k}_1 + \not{k}_2 - 2\,m_{\psi})\,)$$

$$\tilde{\phi}^{\vec{n}}_{ij}\,\psi\psi : \quad i\,\omega\,\kappa\,\delta_{ij}\,\delta_{mn}\,(\,3/4\,\not{k}_1 + 3/4\,\not{k}_2 - 2\,m_{\psi})$$



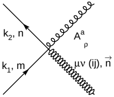
$\tilde{h}^{\vec{n}}_{\mu\nu}\,\Phi\Phi A$: $\quad i\, g\, \kappa/2\; C_{\mu\nu,\,\rho\sigma}\,(\,k_1^{\sigma} + k_2^{\sigma}\,)\; T^a_{nm}$

$\tilde{\phi}^{\vec{n}}_{ij}\,\Phi\Phi A$: $\quad -\,i\,\omega\, g\, \kappa\; \delta_{ij}\,(\,k_{1\rho} + k_{2\rho}\,)\; T^a_{nm}$



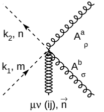
$\tilde{h}^{\vec{n}}_{\mu\nu}\,AAA$: $\quad g\, \kappa/2\; f^{abc}\,(\,C_{\mu\nu,\,\rho\sigma}\,(k_{1\lambda} - k_{2\lambda}) + C_{\mu\nu,\,\rho\lambda}\,(k_{3\sigma} - k_{1\sigma})$
$\qquad + C_{\mu\nu,\,\sigma\lambda}\,(k_{2\rho} - k_{3\rho}) + F_{\mu\nu,\,\rho\sigma\lambda}\,(k_1, k_2, k_3)\,)$

$\tilde{\phi}^{\vec{n}}_{ij}\,AAA$: $\quad 0$



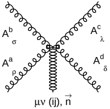
$\tilde{h}^{\vec{n}}_{\mu\nu}\,\psi\psi A$: $\quad i\, g\, \kappa/4\; T^a_{nm}\,(\,C_{\mu\nu,\,\rho\sigma} - \eta_{\mu\nu}\,\eta_{\rho\sigma}\,)\;\gamma^{\sigma}$

$\tilde{\phi}^{\vec{n}}_{ij}\,\psi\psi A$: $\quad -\,i\; 3/2\;\omega\, g\, \kappa\; \delta_{ij}\; T^a_{nm}\,\gamma_{\rho}$



$\tilde{h}^{\vec{n}}_{\mu\nu}\,\Phi\Phi AA$: $-i\,g^2\,\kappa/2\;C_{\mu\nu,\,\rho\sigma}\,\{\,T^a,\,T^b\,\}_{nm}$

$\tilde{\phi}^{\vec{n}}_{ij}\,\Phi\Phi AA$: $i\,\omega\,g^2\,\kappa\,\delta_{ij}\,\eta_{\rho\sigma}\,\{\,T^a,\,T^b\,\}_{nm}$



$\tilde{h}^{\vec{n}}_{\mu\nu}\,AAAA$: $-i\,g^2\,\kappa/2\,(\,f^{eac}\,f^{ebd}\,G_{\mu\nu,\,\rho\sigma\lambda\delta} + f^{eab}\,f^{ecd}\,G_{\mu\nu,\,\rho\lambda\sigma\delta} + f^{ead}\,f^{ebc}\,G_{\mu\nu,\,\rho\sigma\delta\lambda}\,)$

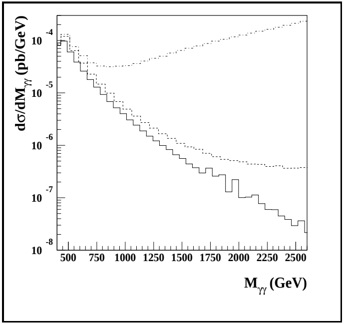
$\tilde{\phi}^{\vec{n}}_{ij}\,AAAA$: 0

- LHC could shed light on the existence of new physics
- There are many important discovery modes such as
  - di-lepton l^+l^-
  - di-photon $\gamma\gamma$
  - di-jets jj
  - di-bosons W^+W^-, ZZ etc.
- In the above processes a KK graviton can appear as a propagator and modify the predictions based on SM
- Enhancement/Reduction over SM prediction gives an indication to existence of New Physics

- Many studies already exist at LO and NLO order in EDMs
- diphoton at LO: Eboli et al

  Phys.Rev.D61:094007,2000.

  $d = 3, \ M_s = 3, \ 6.7 \ TeV$



- Karg, Kramer, Li and Zeppenfeld,
  NLO QCD corrections to graviton production at hadron colliders

  Phys. Rev. D **81**, 094036 (2010)
- Karg *et al.*,
  ZZ+jet and Graviton+jet at NLO QCD: recent applications using GOLEM methods

  arXiv:1001.2537 [hep-ph]
- Kumar, Mathews, Ravindran and Seth,
  Vector boson production in association with KK modes of the ADD model to NLO in QCD at LHC

  arXiv:1004.5519 [hep-ph], J.Phys.G G38 (2011) 055001
- Kumar, Mathews, Ravindran, Seth,
  Graviton plus vector boson production to NLO in QCD at the LHC.

  PRD NPB847 (2011) 54-92

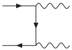
- Cross-section

$$\sigma = \int\int dx_1 dx_2 \; f_{a/P}(x_1,\mu_F^2) f_{b/P}(x_2,\mu_F^2) \; \hat{\sigma}_{a,b}(x_1,x_2,\mu_F^2,\mu_R^2)$$

- pdf's $f_{a/P}$ not predicted by PQCD but evolution determined by the DGLAP eqn.
- μ_F not a parameter of QCD.
- Successive higher order calculations reduce sensitivity to μ_F and μ_R.

Leading order diagrams

- SM



- Gravity

$$D(s) \;=\; \sum_{\vec{n}} \frac{i}{s - m_{\vec{n}}^2 + i\varepsilon}$$

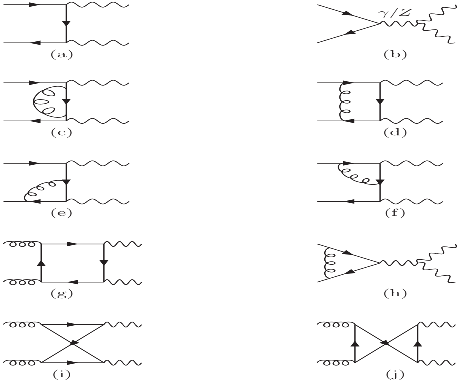
- Gluon initiated Feynman diagrams appear at LO.
- $\implies$ Cannot borrow SM $K-$ factors

- We will show that $d\sigma/dM_{W^+W^-}$ varies by 18.8% as the factorization scale is varied between $Q/2$ and $2Q$
- A next-to-leading order (NLO) calculation in QCD is needed to reduce this theoretical uncertainty.
- We will report at the end a significant reduction in uncertainity

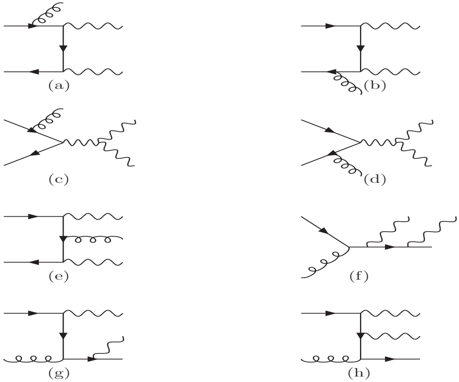
- N. Agarwal, V. Ravindran, V. K. Tiwari and AT,

  Nucl. Phys. B **830** (2010) 248

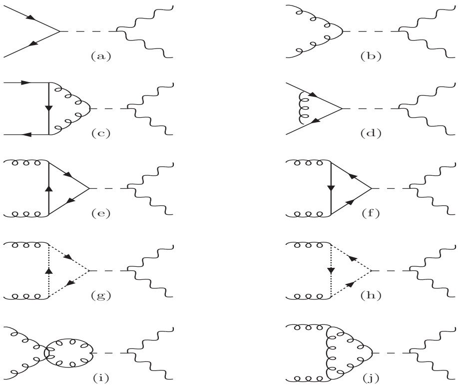
SM virtual



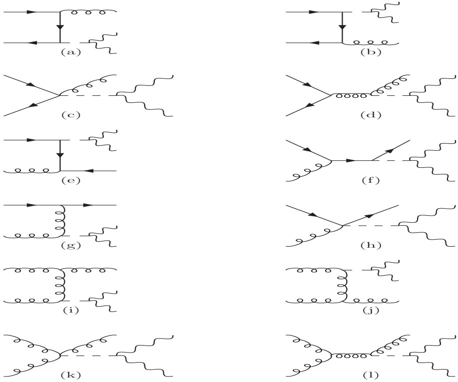
SM real



BSM virtual

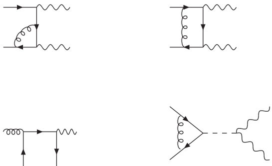


BSM real



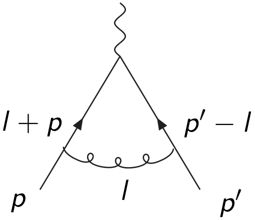
Parts of NLO computation

- Loop diagrams
- Real emission diagrams



- No Ultra-Violet divergences
- Integral over loop momentum gives infrared divergences
- Divergences appear as poles in ϵ in dimensional regularization ($n = 4 + \epsilon$)

- IR singularities in Feynman diagrams
- Example: Form factor

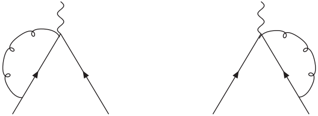


$$\left.\begin{array}{l} p^2 = 0 \\ p'^2 = 0 \end{array}\right\} \text{Onshell}$$

$$\mathcal{I} = \int d^4 l \, \frac{1}{l^2} \frac{1}{(p+l)^2} \frac{1}{(p'-l)^2} \qquad (4)$$

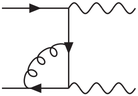
- When **all** the 3 propagators are onshell $\mathcal{I}$ diverges logarithmically
- This happens when $l \to 0$
- This is called **soft** singularity

- Propagators can go onshell in collinear configurations as well
- This gives **collinear** singularities

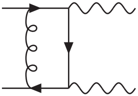


- In the fig. offshell propagator has been contracted to a point

- In the present case (W^+W^-) we have (sample diagrams)



only collinear singular



both soft and collinear singular

- the virtual level cross-section is of the following form

$$\overline{|M^V|^2}_{q\bar{q},sm} = a_s(\mu_R^2) f(\epsilon, \mu_R^2, s) C_F \left[\Upsilon(\epsilon) \ \overline{|M^{(0)}|^2}_{q\bar{q},sm} + \overline{|M^V|^2}^{fin}_{q\bar{q},sm} \right],$$

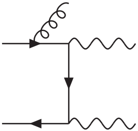
$$\overline{|M^V|^2}_{q\bar{q},gr} = a_s(\mu_R^2) f(\epsilon, \mu_R^2, s) C_F \left[\Upsilon(\epsilon) \overline{|M^{(0)}|^2}_{q\bar{q},gr} + k \overline{|M^{(0)}|^2}_{q\bar{q},gr} \right]$$

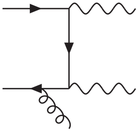
where

$$\Upsilon(\epsilon) = -\frac{16}{\epsilon^2} + \frac{12}{\epsilon}, \qquad f(\epsilon, \mu_R^2, s) = \frac{\Gamma\left(1 + \frac{\epsilon}{2}\right)}{\Gamma(1+\epsilon)} \left(\frac{s}{4\pi\mu_R^2}\right)^{\frac{\epsilon}{2}}$$

- overlap of soft and collinear singularities appear as double poles $\frac{1}{\epsilon^2}$
- Note that although the diagrams are very different in SM and BSM the singularity structure is same

- Real emission also gives soft and collinear singularities upon phase space integration.





- The double poles cancel between real and virtual contributions
- The uncanceled collinear singularities are removed by mass factorization
- This introduces the factorization scale, μ_F

Checks:

- Gauge invariance
- Check on the correct implementatin of phase space slicing method.
- SM Matrix elements and total cross-section compared with existing literature.

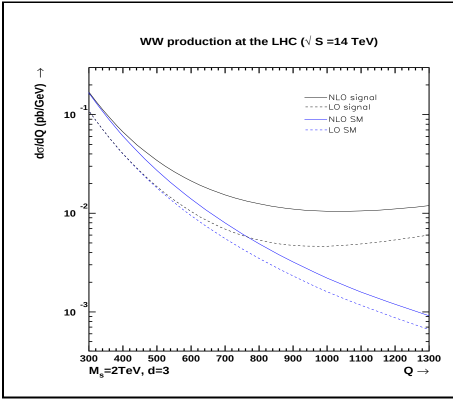
  J.Ohnemus, Order-α_s calculation of hadronic W^+W^- production, PRD 44, 1403 (1991)

  Campbell and Ellis, PRD 60, 113006 (1999)

- The finite pieces, after cancellation/ mass factorization of poles, are calculated using MC integration
- We use CTEQ6L and CTEQ6M pdf's
- A cut on rapidity of 2.5 Z bosons is placed.
- We obtain invariant mass and rapidity distributions.

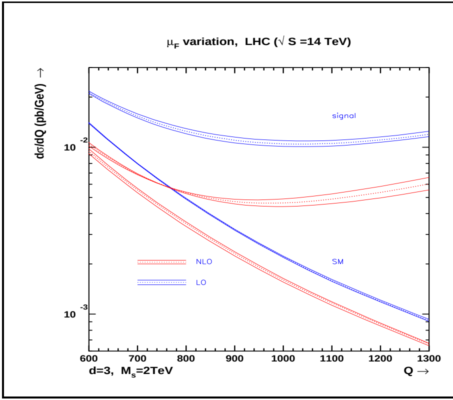
Results: K factor

- Invariant mass distribution: $d = 3$, $M_s = 2\ TeV$. we observe that the K factors (defined as $K = d\sigma^{NLO}/d\sigma^{LO}$) are large.
- For the signal the K factor varies beween 1.55 to 1.98 for Q between 300 and 1300 Gev.

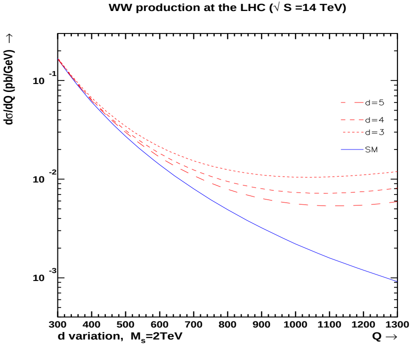


Results: μ_F variation

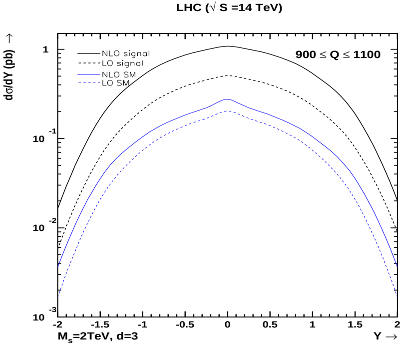
- μ_f dependence significantly reduced.
- At $Q = 1300\ GeV$: $Q/2 < \mu_F < 2Q \rightarrow$ 18.8% at LO for the signal, NLO $\rightarrow$ 7.6%.



Results: variation of no. of extra dimensions



Rapidity distributinon



THANK YOU !

Additional slides

- D : $4 + d$ dimensions
  - compactified, scale R
- M_s : D-dimensional Planck scale
- M_{Pl} : Effective Planck scale in 4-dimensions

$$M_{Pl}^2 = M_s^{d+2} R^d \tag{5}$$

$$M_{Pl} \sim 10^{18} \quad GeV \qquad M_S \sim 1\,TeV \tag{6}$$

$$d = 1 \rightarrow R \sim 10^{12}\,cm \tag{7}$$