Physics at LHC
lecture six

Sven-Olaf Moch

Sven-Olaf.Moch@desy.de

DESY, Zeuthen

---

in collaboration with **Klaus Mönig**

– Humboldt-Universität, January 08, 2010, Berlin –

Plan

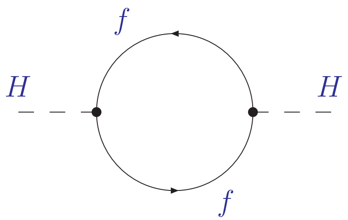
- Large extra dimensions
  - hierachy problem
  - theory
  - phenomenolgy
- Literature
  - *Phenomenology, astrophysics and cosmology of theories with submillimeter dimensions and TeV scale quantum gravity*
    Arkani-Hamed, Dimopoulos, Dvali [hep-ph/9807344]
  - *A Large mass hierarchy from a small extra dimension*
    Randall, Sundrum [hep-ph/9905221]
- Review
  - *TASI 2004 Lectures on the phenomenolgy of Extra Dimensions*
    Kribs [hep-ph/0605325]
  - *Dark Matter and Collider Phenomenology of Universal Extra Dimensions*
    Hooper, Profumo [hep-ph/0701197]

Motivation

History

- Unification of gravity with electromagnetism in 5-dim. space-time Kaluza 1919
- Compactification of fifth dimension (circle of small radius) Klein 1926
  - particles moving through extra dimension appear very massive
  - excited states of ordinary particles known as Kaluza-Klein modes
- String theory cannot be formulated in four dimensional space-time
  - bosonic string in $D = 26$
  - fermionic string ($\mathcal{N} = 1$ supersymmetry) in $D = 10$
- Hierarchy problem
  - Radiative corrections to Higgs mass with quadratic divergences induce large hierachies $\mathcal{O}(M^2_{\rm Planck}/M^2_{\rm electro-weak}) \sim 10^{-32}$

Hierarchy problem



- Higgs mass receives
radiative corrections from fermion loops
  - the size of corrections is proportional to the UV cutoff Λ squared

$$\delta M_H^2 = \frac{\lambda_f^2}{4\pi^2}\left(\Lambda^2 + m_f^2\right) + \ldots$$

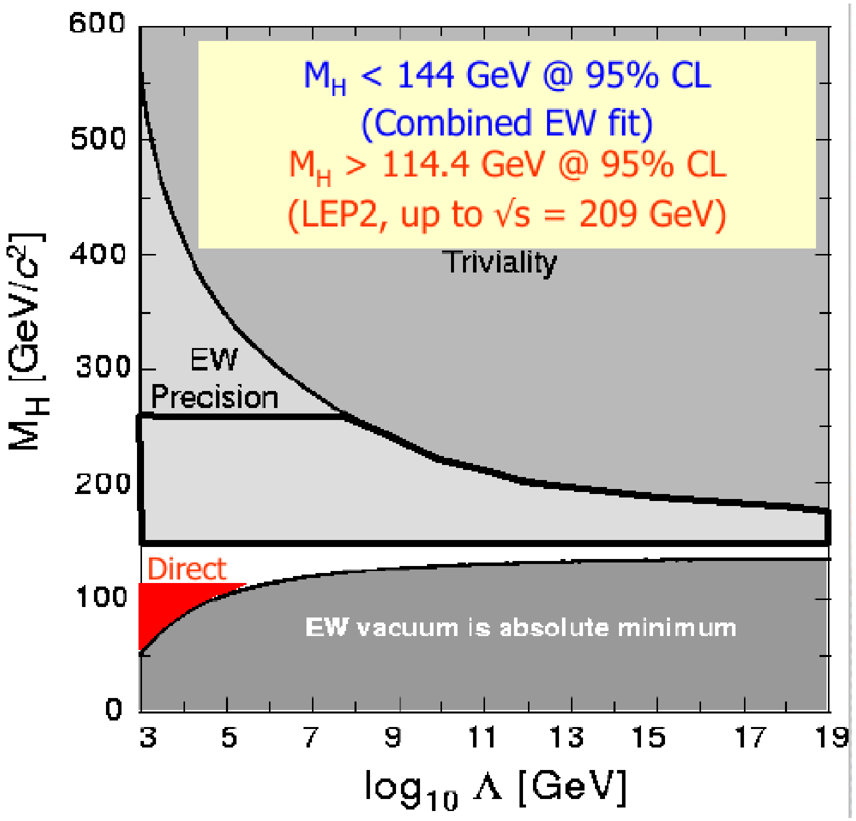
- Cancellation of quadratic divergences to Higgs mass δM_H^2 under renormalization requires fine tuning
  - if UV cutoff $\Lambda \sim \mathcal{O}(M_{\rm Planck})$ then a precision $\mathcal{O}(M^2_{\rm Planck}/M^2_{\rm electro-weak}) \sim 10^{-32}$ is required
- Standard Model as effective theory should have ratio of scales $\sim \mathcal{O}(1)$
  - high degree of fine tuning considered to be unnatural

Large extra dimensions

- $M_{\rm Planck}$ in 4 dimensions is not a fundamental scale

Higgs mass and triviality

- Higgs mass cannot be too light or the Higgs potential will not have a Mexican hat shape and will turn negative at large values
  - for Standard model to be valid up to Planck scale $M_H > 135$ GeV
- Triviality
  - If Higgs mass is too large
    the Higgs self-coupling drives mass to infinity above certain scale
- Standard model holds all the way up to Planck scale if
  135 GeV $< M_H < 175$ GeV



Gravity

Gravity in a nut-shell

- Einstein-Hilbert action in 4-dimensions

$$S = -\frac{1}{2} \int d^4x \sqrt{-g}\, M_\star^2\, R$$

  - Ricci tensor $R_{\mu\nu}$ and Ricci scalar $R = g^{\mu\nu} R_{\mu\nu}$
  - mass scale $M_\star$ related to Newton's constant G_N:
    $M_\star = \left(\frac{1}{8\pi G_N}\right)^{1/2}$

- Variational calculus δS leads to Einstein equation
  - Metric tensor $g_{\mu\nu}$
  - Energy-momentum tensor $T_{\mu\nu}$
  - Cosmological constant Λ

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R \;=\; 8\pi G_N T_{\mu\nu} - \Lambda g_{\mu\nu}$$

Kaluza-Klein theory

- Gravity and electromagnetism in 5-dim. space-time with one dim. compactified on circle of circumference L Kaluza 1919; Klein 1926
- Einstein-Hilbert action $S = \int d^5x \sqrt{-g^{(5)}}\, M_\star^3 R^{(5)}$
  - metric $g_{MN}^{(5)}$ on $R_4 \otimes S^1$ expanded $g_{MN} = \eta_{MN} + h_{MN}/(2M_\star^{3/2})$
  - five-dimensional graviton h_{MN} contains five physical components
- Massless fields
  - 4-dimensional $(4-d)$ graviton $h_{\mu\nu}$, massless vector field $A_{\mu 5}$ and massless scalar field ϕ

$$\begin{pmatrix} h_{\mu\nu} & A_{\mu 5} \\ A_{5\nu} & \phi \end{pmatrix}$$

- Action comprises 4-dimensional gravity plus a gauge field
  - coupling strength $g^2 = (M_\star L)^{-1}$ (ϕ with gravitational couplings only)

$$\int d^4x (M_\star^3 L) R^{(4)} - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2} \partial_\mu \phi \partial^\mu \phi$$

Kaluza-Klein theory

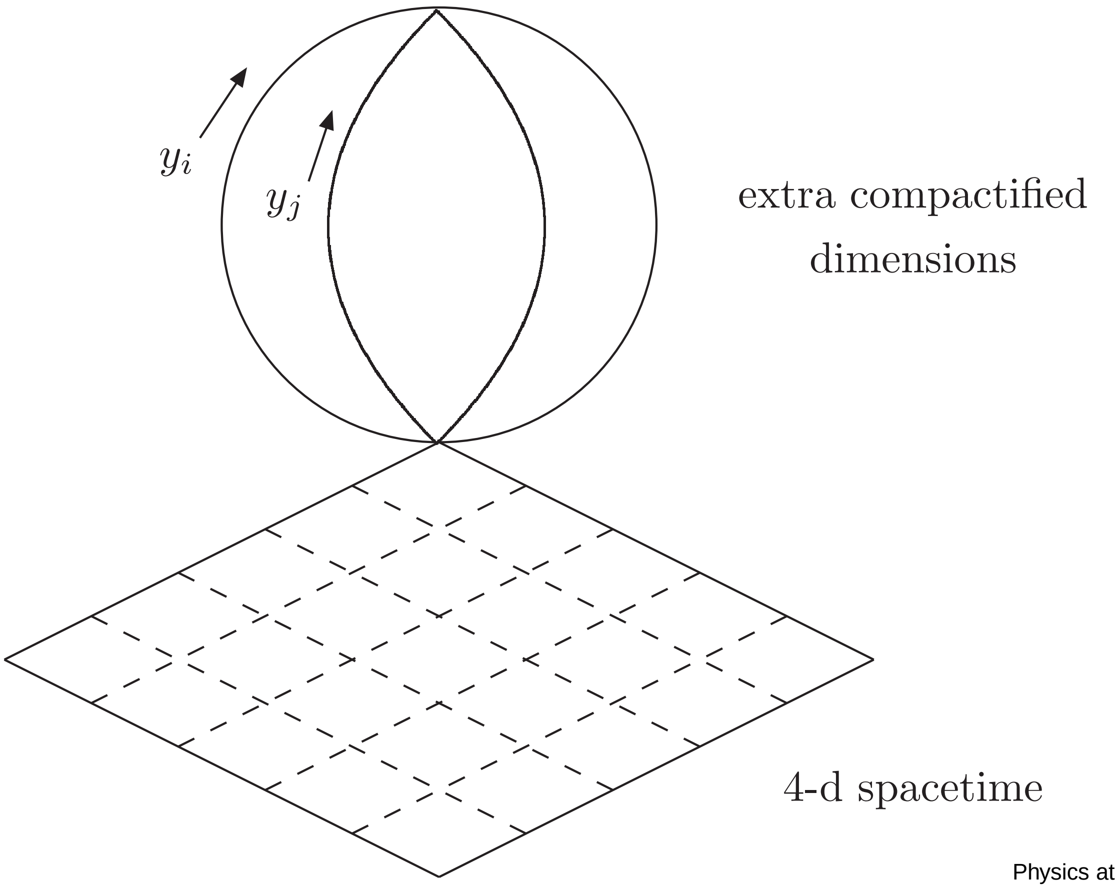
- Original Kaluza-Klein proposal suffers from three problems
  - gravitationally coupled scalar field ϕ postulated
  - gauge field strength of order one only for $L^{-1} \sim M_\star$
  - no chiral fermions exist in 5-dim. space-time
    (“doubling” of massless fermions)

Large extra dimensions

- Large extra dimensions at the millimeter scale (ADD model)
  Arkani-Hamed, Dimopoulos, Dvali ‘98
  - all SM fields confined to 4-dim. brane
  - only gravity propagates in space of extra dimensions (the bulk)
  - fundamental Planck scale as perceived in bulk similar in magnitude to electroweak scale (cf. hierarchy problem)
- Fundamental Planck scale M_{Planck} lowered to electroweak scale by additional small space dim. (RS model) Randall, Sundrum ‘98
  - large degree of spatial curvature
  - exponential “warp factor” in metric of RS model makes M_{Planck} (near the electroweak scale) appear to 4-dim. observer on our brane to be much higher (cf. hierarchy problem)
- Universal Extra Dimensions (UED) Appelquist, Cheng, Dobrescu ‘01
  - all SM fields propagate through all of the dimensions of space (no confinemet to a particular brane)

ADD cartoon

- The world according to ADD
- $R_4 \times M_n$ spacetime with n-dim. compact manifold M_n
  - 3-brane for Standard Model $(3+1)$-dimensional spacetime
  - extra compact spatial dimensions of radius $\sim r$



ADD models

- Action for brane and bulk separated $S = S_{\text{bulk}} + S_{\text{brane}}$
- Bulk
  - $4 + n$-dimensional Einstein-Hilbert action

$$S_{\text{bulk}} = -\frac{1}{2} \int d^{4+n}x \sqrt{-g^{(4+n)}} M_\star^{n+2} R^{(4+n)}$$

  - line element $ds^2 = g_{MN}^{(4+n)} dx^M dx^N$
- Extra dimensions in higher dimensional action "integrated out"
  - expansion of g_{MN} about flat spacetime with fluctuations $h_{\mu\nu}$
- Line element $ds^2 = (\eta_{\mu\nu} + h_{\mu\nu})\, dx^\mu dx^\nu - r^2 d\Omega_{(n)}$
  - metric $d\Omega_{(n)}$ on n-dimensional torus
- Factorization of metric
  - effective replacements of $(4 + n)$-dim. metric and Ricci scalar

$$\sqrt{-g^{(4+n)}} \quad \rightarrow \quad \sqrt{-g^{(4)}}$$

$$R^{(4+n)} \quad \rightarrow \quad R^{(4)}$$

ADD models

- Effective 4-dim. action for bulk

$$
\begin{aligned}
S_{\rm bulk} &= -\frac{1}{2} M_\star^{n+2} \int d^{4+n}x \sqrt{-g^{(4+n)}} R^{(4+n)} \\
&= -\frac{1}{2} M_\star^{n+2} \int d^4x \int d\Omega_{(n)} r^n \sqrt{-g^{(4)}} R^{(4)} \\
&= -\frac{1}{2} M_\star^{n+2} (2\pi r)^n \int d^4x \sqrt{-g^{(4)}} R^{(4)}
\end{aligned}
$$

- Famous result for 4-dim. Planck scale

$$
M_{\rm Pl}^2 = M_\star^{n+2} (2\pi r)^n
$$

  - $M_{\rm Pl}$ depended on number n and radius r of extra dimensions

Deviations from Newtonian Gravity

- Gauss's law in $(4+n)$ dimensions
  - two masses m_1, m_2 feel gravitational potential
  - $r' \ll r$

$$V(r') = -G_N^{(4+n)} \frac{m_1 m_2}{r'^{1+n}}, \qquad (r' \ll r)$$

  - $r' \gg r$ (gravitational flux cannot penetrate in extra dimensions)
  - usual $1/r'$ potential is obtained

$$V(r') = -G_N \frac{m_1 m_2}{r'}, \qquad (r' \gg r)$$

- D-dim. Newton's constant G_N^D related to D-dim. Planck scale
  - $M_\star = \left(\frac{1}{8\pi G_N^D} \right)^{1/(D-2)}$
  - effective 4-dimensional M_{Planck}

$$M_{\text{Pl}}^2 \sim \left(M_{\text{Pl}(4+n)} \right)^{n+2} r^n$$

Limits on numbers of dimension

- Assume equal-sized extra dimensions

$$r = \frac{1}{2\pi}\left(\frac{M_{\rm Pl}^2}{M_\star^{n+2}}\right)^{1/n}$$

- Require $M_\star$ close to weak scale for solving the hierarchy problem
  - for $M_\star = 1$ TeV expect $\mathcal{O}(1)$ deviations from Newtonian gravity

number of extra dimensions	r
$n = 1$	$\sim 10^{12}$ m
$n = 2$	$\sim 10^{-3}$ m
$n = 3$	$\sim 10^{-8}$ m
$\vdots$	
$n = 6$	$\sim 10^{-11}$ m

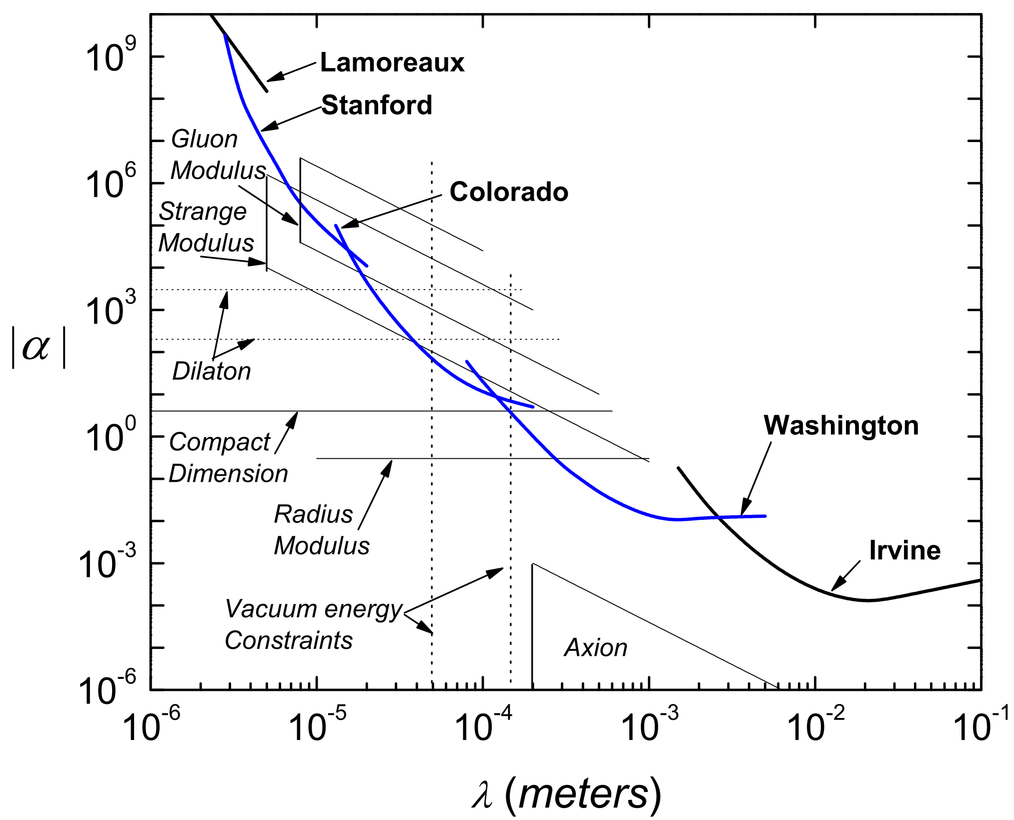
- Upshot
  - gravitational force comparable to gauge forces at weak scale
  - gravity is brought done to weak scale
  - 4-dim. Planck scale is not fundamental scale

Gravity at short distances

- Search for deviations of gravity potential in submillimeter range

$$V = -\frac{G_N m_1 m_2}{r_{12}} \left[1 + \alpha \exp(-r_{12}/\lambda) \right]$$

  - restrictions on ADD model with 2 extra dimensions (best sensitivity: Univ. of Washington experiment Adelberger et al. '01–'08)
  - compilation of expermental limits Long, Price '03



Universal extra dimensions

Motivation

- UED models are remarkably simple
  - flat metric with one or more compact extra dimensions
- UED models allow for stable proton (at times $\tau_p \geq 10^{33}$ yrs) (unlike RS and ADD models)
  - global symmetries in UED limit higher dimensional operators for proton decay
- Dark matter candidate in UED models
  - LKP (lightest Kaluza-Klein particle) is neutral and absolutely stable
- UED models avoid constraints from electroweak precision tests of SM
  - e.g. absence of FCNC, lepton number violating interactions, decays $B \to X_s \gamma$, ...
- UED testable at terascale collider experiments

Orbifolds

- Compactifications of manifolds
  - e.g. $\mathbf{R}_1 \to \mathbf{S}_1$ (identifcation of end-points in $\mathbf{R}_1$)
- Orbifolds are quotient spaces of manifold $\mathbf{M}$ and discrete group $\mathbf{G}$
  - there exist additional fixed points on $\mathbf{M}$ invariant under $\mathbf{G}$
  - example: $\mathbf{R}_1 \to \mathbf{S}_1/\mathbf{Z}_2$
- String theory relies on compactification (e.g. toroidal orbifold constructions $\mathbf{T}_2/\mathbf{Z}_3$)

Orbifolds for UED models

- Complication: fermions in $D > 4$ are non-chiral
- Orbifold compactification for chiral fermions to exist
- Phenomenology in UED models typically restricted to 5-dimensions
  - 5-dim. case with $\mathbf{S}_1/\mathbf{Z}_2$ orbifold removes unwanted fermionic degrees of freedom

The Lagrangian

- Standard Model in $4+D$ space-time dim.
  - all SM fields can propagate in the extra (universal) dimensions
  - compactification at a scale $1/R$

$$
\begin{aligned}
\mathcal{L}(x^\mu) \;=\; \int \mathrm{d}^D y \Big\{ & -\sum_{i=1}^{3} \frac{1}{2\hat{g}_i^2} \mathrm{Tr}\Big[F_i^{AB}(x^\mu,y^a) F_{iAB}(x^\mu,y^a)\Big] + \\
& + |(D_\mu + D_{3+a}) H(x^\mu,y^a)|^2 + \mu^2 H^*(x^\mu,y^a) H(x^\mu,y^a) - \lambda\big[H^*(x^\mu,y^a) H(x^\mu,y^a)\big]^2 + \\
& + i\left(\overline{Q},\overline{u},\overline{d},\overline{L},\overline{e}\right)(x^\mu,y^a)\left(\Gamma^\mu D_\mu + \Gamma^{3+a} D_{3+a}\right)(Q,u,d,L,e)(x^\mu,y^a) + \\
& \Big[\overline{Q}(x^\mu,y^a)\Big(\hat{\lambda}_u\; u(x^\mu,y^a) i\sigma_2 H^*(x^\mu,y^a) + \hat{\lambda}_d\; d(x^\mu,y^a) H(x^\mu,y^a)\Big) + \mathrm{H.c.}\Big] + \\
& \Big[\overline{L}(x^\mu,y^a)\hat{\lambda}_e\; e(x^\mu,y^a) H(x^\mu,y^a) + \mathrm{H.c.}\Big]. \qquad (3)
\end{aligned}
$$

In Eq. (3), the summation over fermion generations has been suppressed, and we indicate with F_i^{AB} the $(4+D)$-dimensional gauge field strengths associated with the $SU(3)_c \times SU(2)_W \times U(1)_Y$ gauge group. $D_\mu = \partial/\partial x^\mu - \mathcal{A}_\mu$ and $D_{3+a} = \partial/\partial y^a - \mathcal{A}_{3+a}$ are the covariant derivatives, with $\mathcal{A}_A = -i\sum_{i=1}^{3} \hat{g}_i \mathcal{A}^r_{Ai} T^r_i$ being the $(4+D)$-dimensional gauge fields, and $\hat{g}_i$ the $(4+D)$-dimensional gauge couplings. The latter, as well as the Yukawa matrices, $\hat{\lambda}_{u,d,e}$, have dimension $(\mathrm{mass})^{-D/2}$. The symbols Q,u,d,L,e describe the $(4+D)$-dimensional fermions, whose zero modes correspond to the SM fermions. Capitalized letters indicate $SU(2)_W$ doublets, while lower case letters indicate $SU(2)_W$ singlets. The $(4+D)$-dimensional gamma matrices, Γ^A, are anticommuting $2^{K+2}\times 2^{K+2}$ matrices, where $D=2K$ if D is even, and $D=2K+1$ for odd D, satisfying the $(4+d)$-dimensional Clifford algebra $\{\Gamma^A,\Gamma^B\} = 2g^{AB}$. In particular, for the case of $D=1$, one can set $\Gamma_\mu = \gamma_\mu$, and $\Gamma_4 = i\gamma_5$.

KK modes

- decomposition of gauge/scalar fields in KK modes for $5D$ model

$$(H,\mathcal{A}_\mu)(x^\mu,y) = \frac{1}{\sqrt{\pi R}}\Big[(H_0,\mathcal{A}_{\mu,0})(x_\mu)+\sqrt{2}\sum_{n=1}^{\infty}(H_n,\mathcal{A}_{\mu,n})(x_\mu)\cos\left(\frac{ny}{R}\right)\Big]$$

$$\mathcal{A}_5 = \sqrt{\frac{2}{\pi R}}\sum_{n=1}^{\infty}\mathcal{A}_{5,n}(x_\mu)\sin\left(\frac{ny}{R}\right)$$

- Two $5D$ fermion fields $\psi_{L,R}$ (left and right handed spinors)
- Construct SM fields from chiral projection of zero modes

$$\psi^{\mathrm{SM}} = P_L\psi_{L,0}+P_R\psi_{R,0}$$

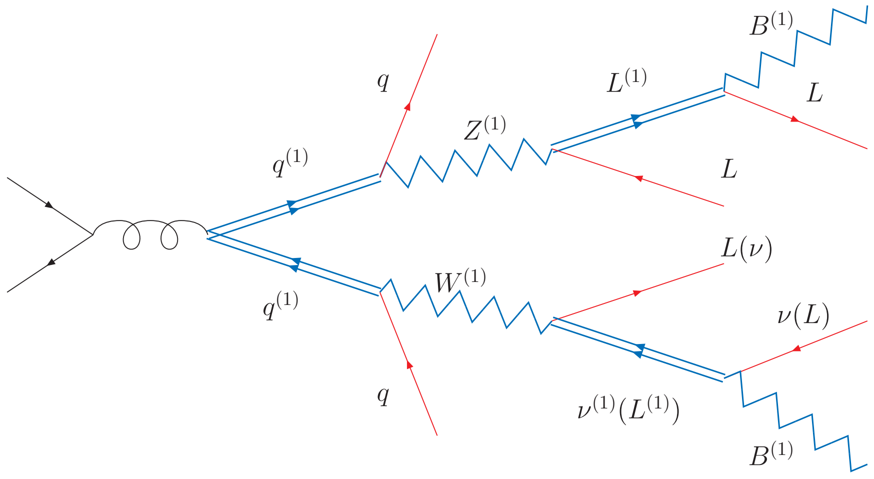
$$\psi(x^\mu,y) = \frac{1}{\sqrt{\pi R}}\Big[\psi^{\mathrm{SM}}(x^\mu) + \sqrt{2}\sum_{n=1}^{\infty}P_L\,\psi_{L,n}(x^\mu)\cos\left(\frac{ny}{R}\right)+P_R\,\psi_{R,n}(x^\mu)\sin\left(\frac{ny}{R}\right)\Big]$$

KK parity

- KK level of particle measures its momentum in extra dimension
- Orbifold compactification breaks translational invariance in extra dimension
  - KK-number is not conserved quantity
- KK parity (subgroup of KK-number conservation)
  - conservation of *evenness* or *oddness* of KK number in interaction
    e.g. 5-dim. case with $\mathbf{S}_1/\mathbf{Z}_2$ leaves KK parity as $\mathbf{Z}_2$ symmetry (odd KK numbers charged)

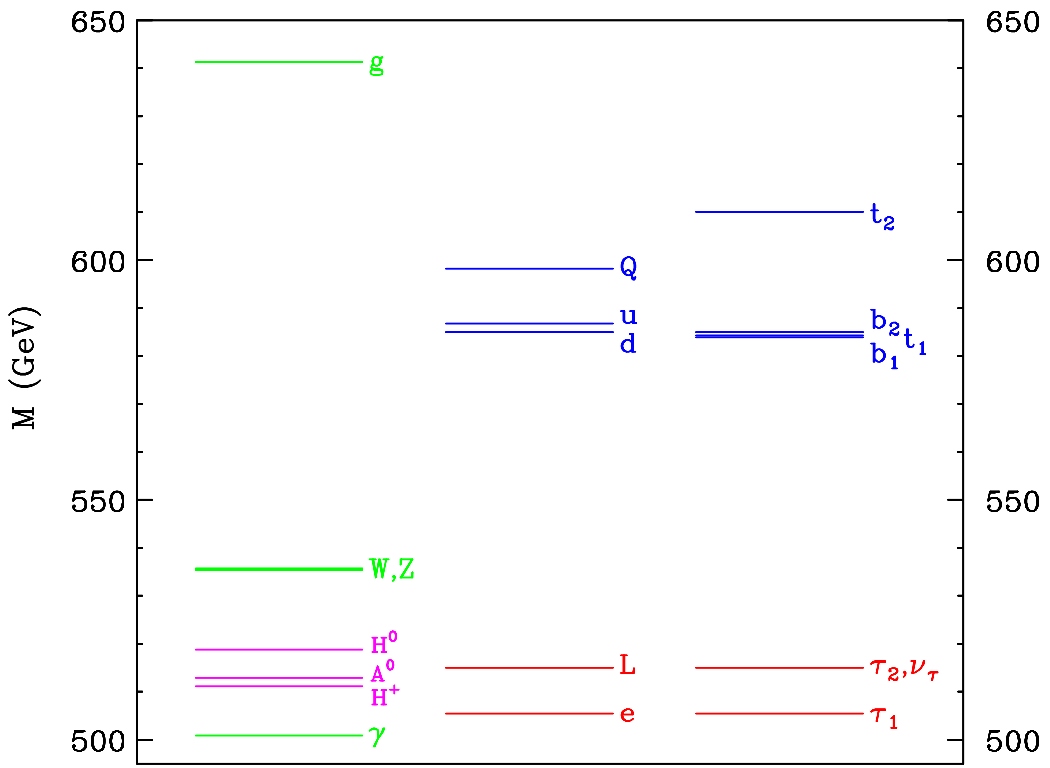
KK parity

- KK level of particle measures its momentum in extra dimension
- Orbifold compactification breaks translational invariance in extra dimension
  - KK-number is not conserved quantity
- KK parity (subgroup of KK-number conservation)
  - conservation of *evenness* or *oddness* of KK number in interaction e.g. 5-dim. case with $\mathbf{S}_1/\mathbf{Z}_2$ leaves KK parity as $\mathbf{Z}_2$ symmetry (odd KK numbers charged)
- Phenomenological consequences
  - pair-production of excited KK-modes in interactions
  - LKP is stable
  - similarity to R-parity in SUSY



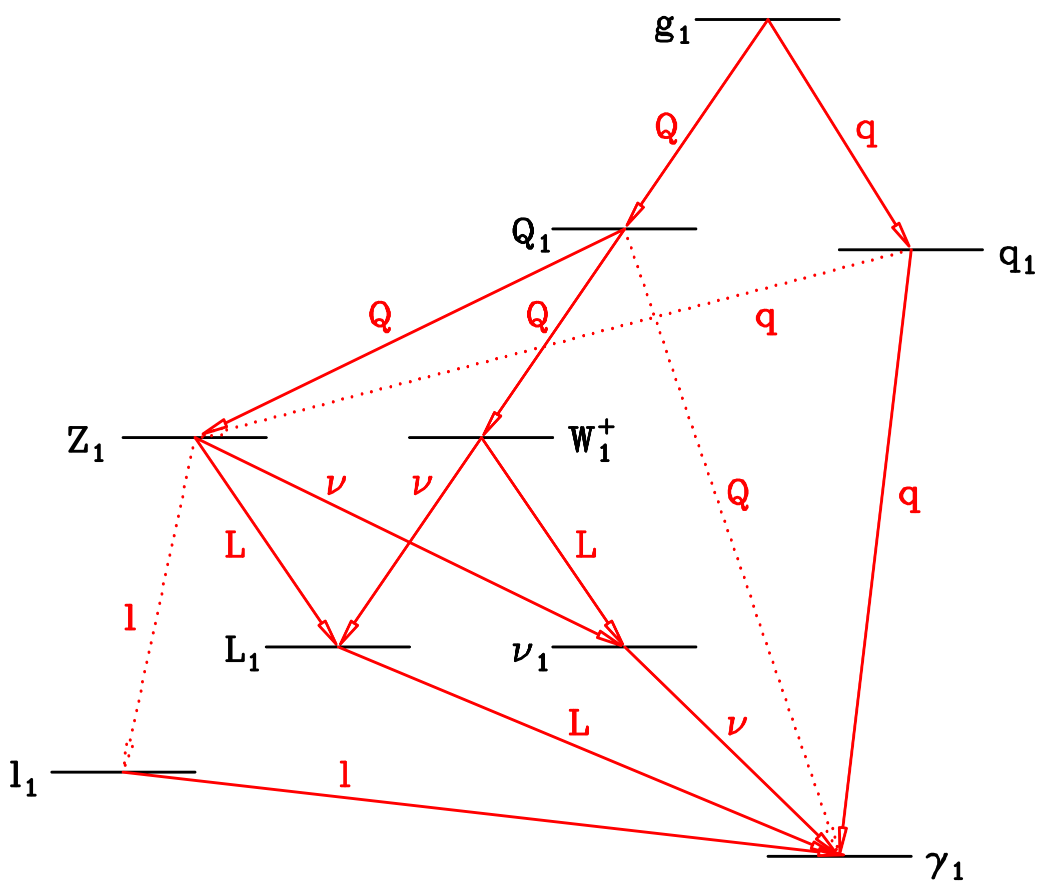
Particle spectrum

- Spectrum of first level Kaluza-Klein states
  - effective mass $m^2_{X(n)} = \frac{n^2}{R^2} + m^2_{X(0)}$
  - compactification radius $R^{-1} = 500\mathrm{GeV}$



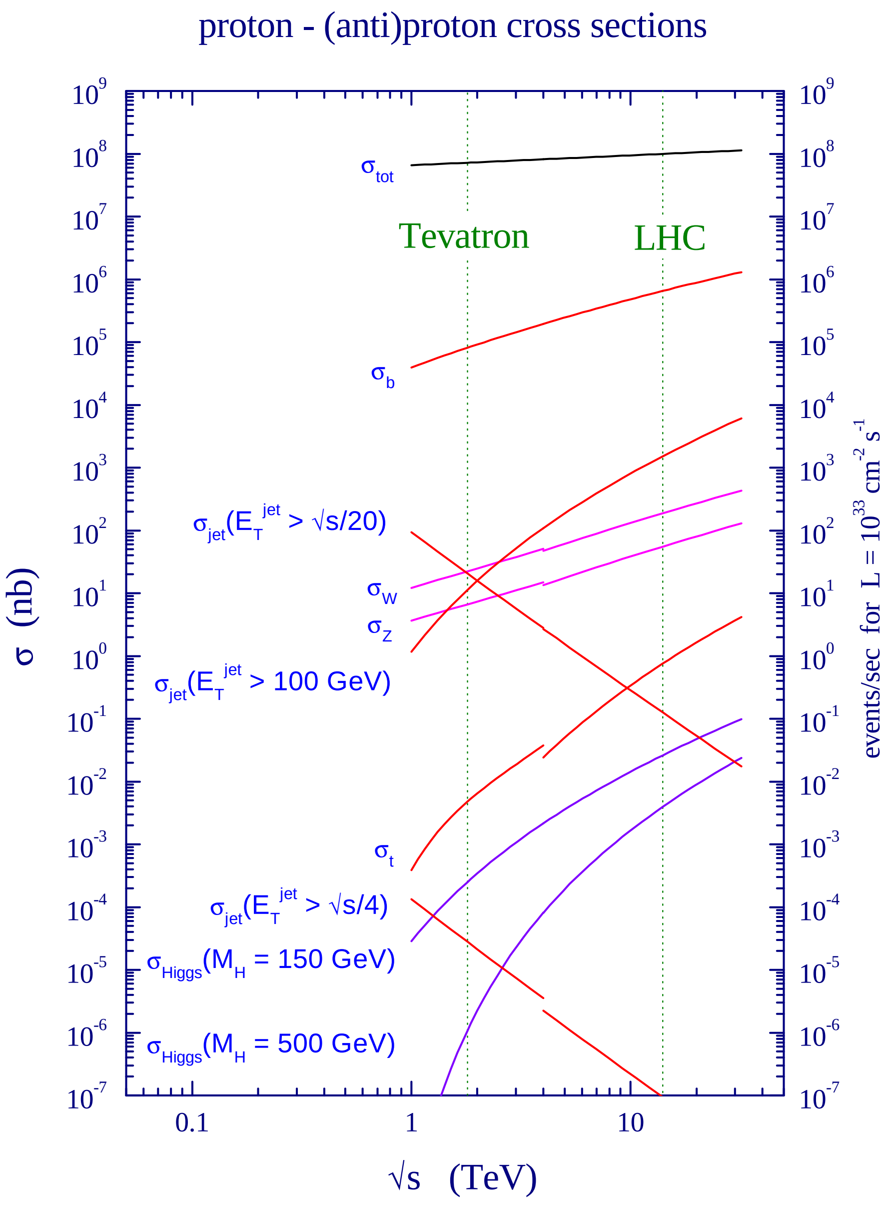
Particle decays

- KK decay chain for $n = 1$ with dominant (solid) and sub-dominant (dotted) transitions
  - heavier $n = 1$ states cascade decay into stable LKP $B^{(1)}$ under emission of soft SM particles
  - LKP escapes detection, leading to missing energy signature



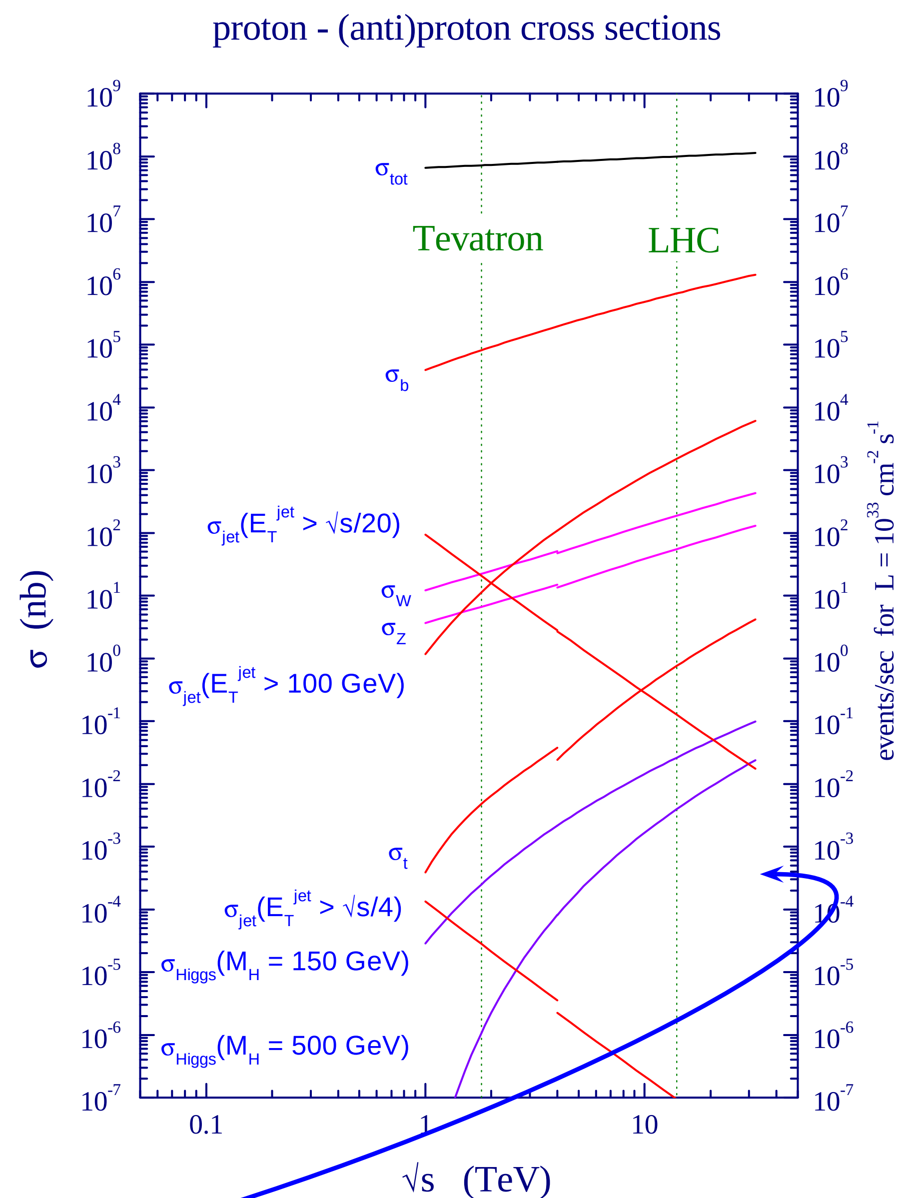
LHC phenomenology

- Expected production rates strongly depend on compactification scale R^{-1}
  - assume minimal UED with $\Lambda R = 20$ (boundary couplings flavor-conserving, boundary terms vanish at cutoff Λ)
  - radiative corrections lift KK mass degeneracy
  - decay cascades terminate with stable LKP
  - generic missing energy signatures



LHC phenomenology

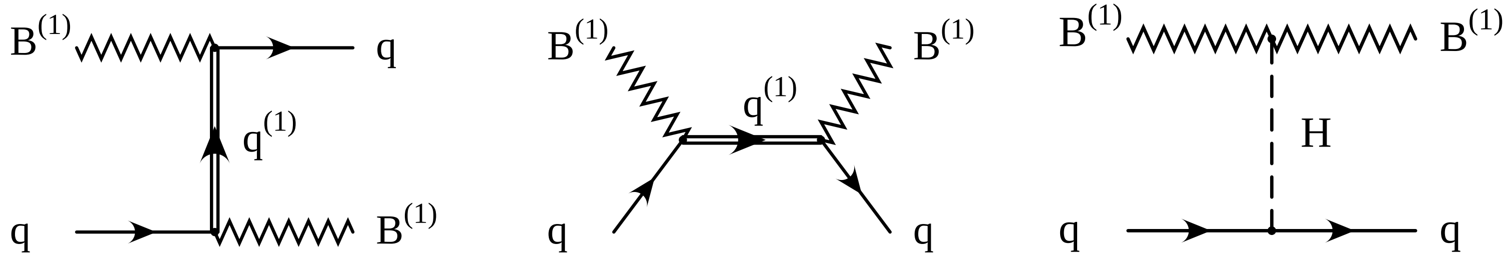
- Expected production rates strongly depend on compactification scale R^{-1}
  - assume minimal UED with $\Lambda R = 20$ (boundary couplings flavor-conserving, boundary terms vanish at cutoff Λ)
  - radiative corrections lift KK mass degeneracy
  - decay cascades terminate with stable LKP
  - generic missing energy signatures



Search here !

Collider signatures

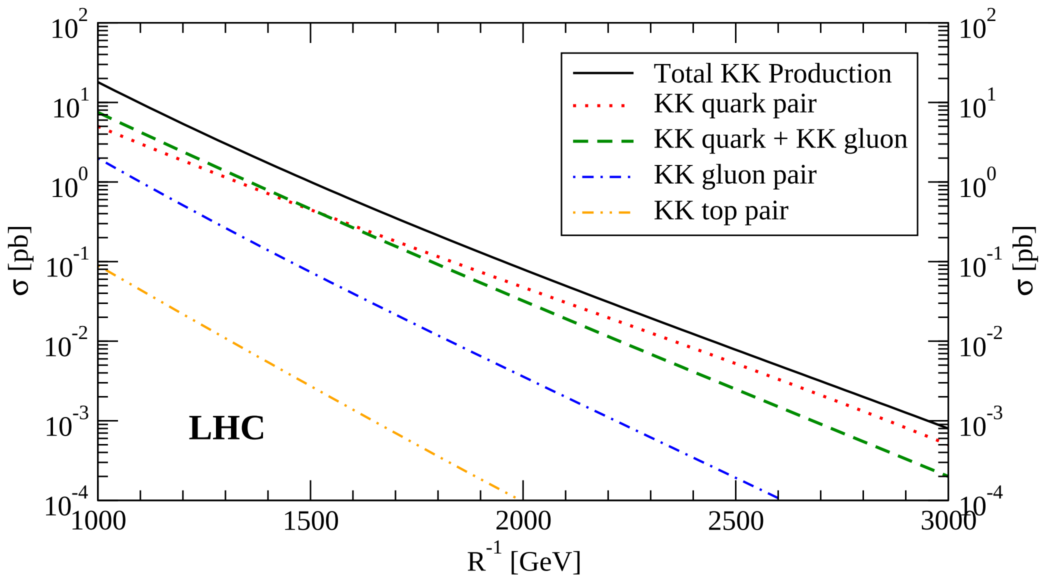
- Feynman diagrams for LKP production
  - $B^{(1)}$-quark scattering
  - $B^{(1)}$-gluon scattering (through quark/KK-quark loop)



- LHC: predominantly production of colored KK-particles
  - pair-production of KK quarks, KK gluons and KK top-quarks

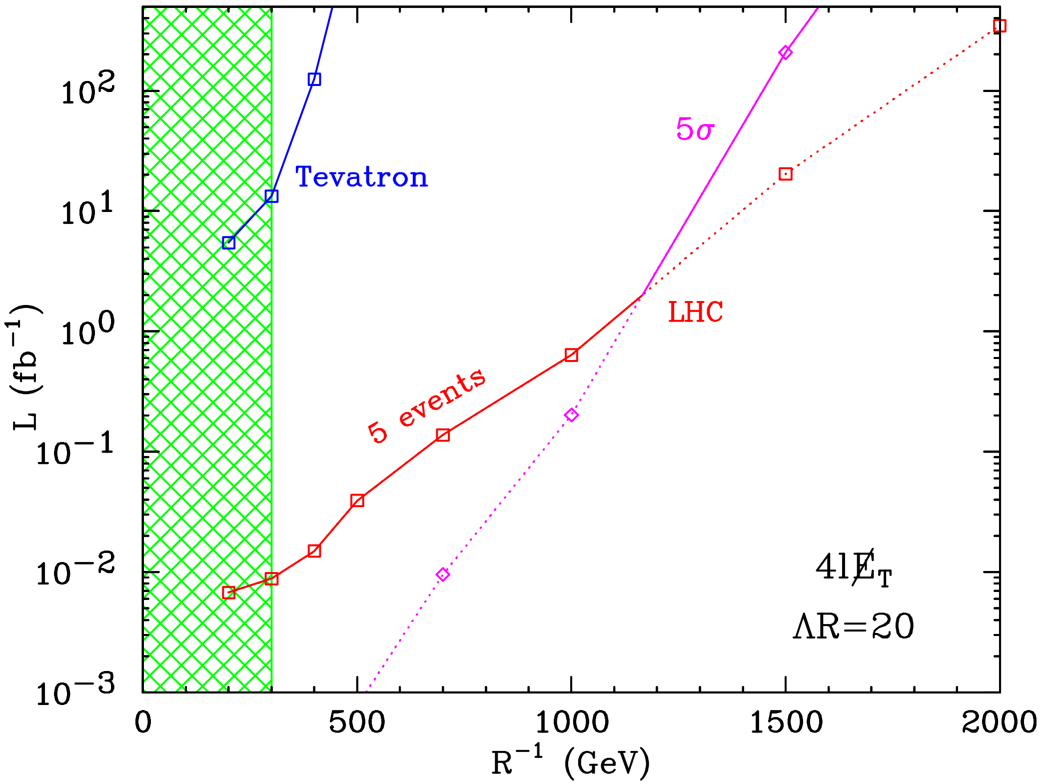
LHC cross section

- Production cross section of KK quarks and KK gluons at LHC as function of compactification radius R^{-1}
  - separate contributions Macesanu, McMullen, Nandi ‘02
    - KK quark pairs
    - KK quark + KK gluon
    - KK gluon pairs
    - KK top pairs



LHC reach

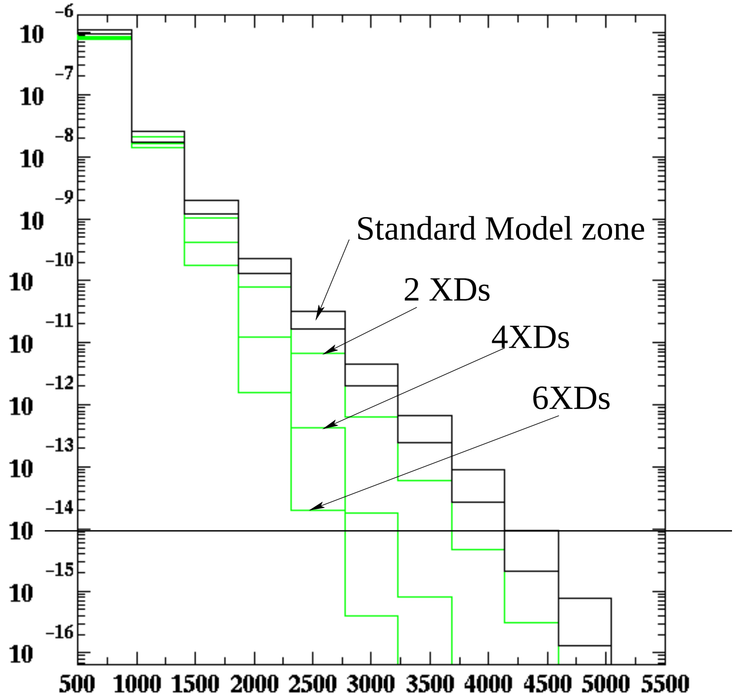
- Discovery reach for minimal UED scenario in $4l + \not{E}_T$ channel as function of luminosity (fb^{-1}) and compactification radius R^{-1}
  - Tevatron (blue) and at the LHC (red) for $\Lambda R = 20$
    Cheng, Matchev, Schmaltz ‘02
- Reach contours correspond to 5σ excess (or observation of 5 signal events)



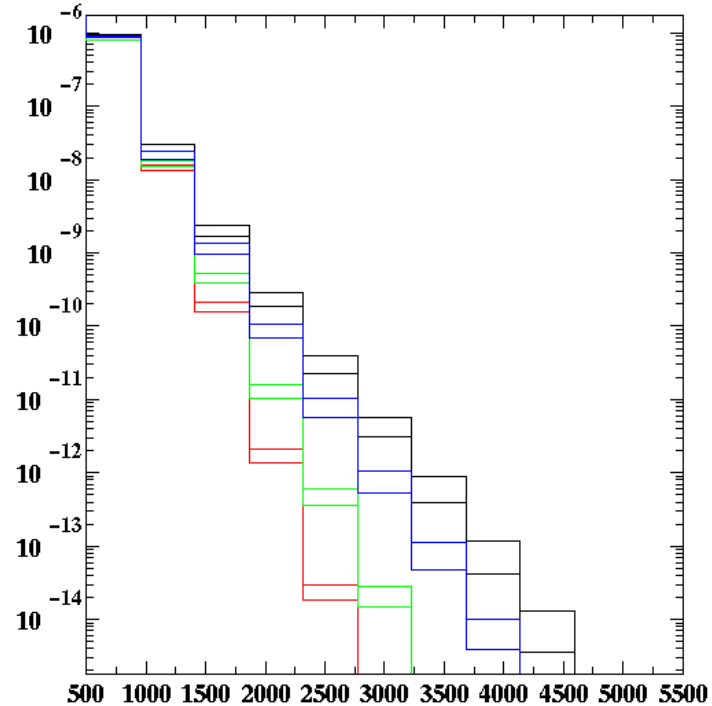
Sensitivity to PDFs

- Sensitivity of LHC dijet cross section to large extra dimensions Ferrag '04
  - large extra dimensions accelerate running of α_s as compactification scale M_c is approached
- PDF uncertainties
  - potential sensitivity to M_c reduced from 6 TeV to 2 TeV

$M_c = 2$ TeV no PDF error



$M_c = 2$ TeV with PDF error



UED vs. SUSY

- *Bosonic supersymmetry? Getting fooled at LHC*
  Cheng, Matchev, Schmaltz '02
- Common features of extra dimensions and supersymmetry
  - lightest new state is neutral and stable
  - collider signatures with missing transverse momentum (energy) plus jets/leptons
  - same couplings for the SM particles and their heavier counterparts

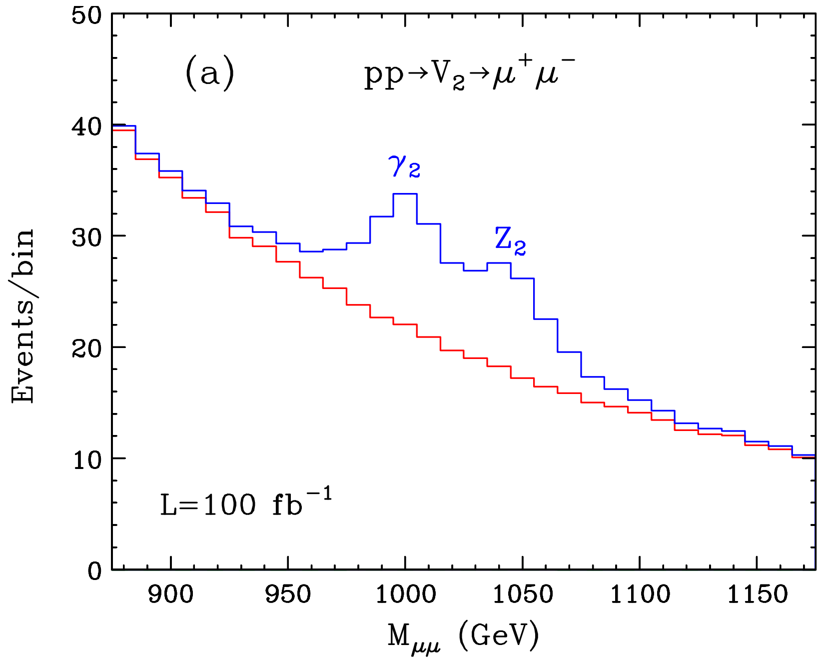
Differences

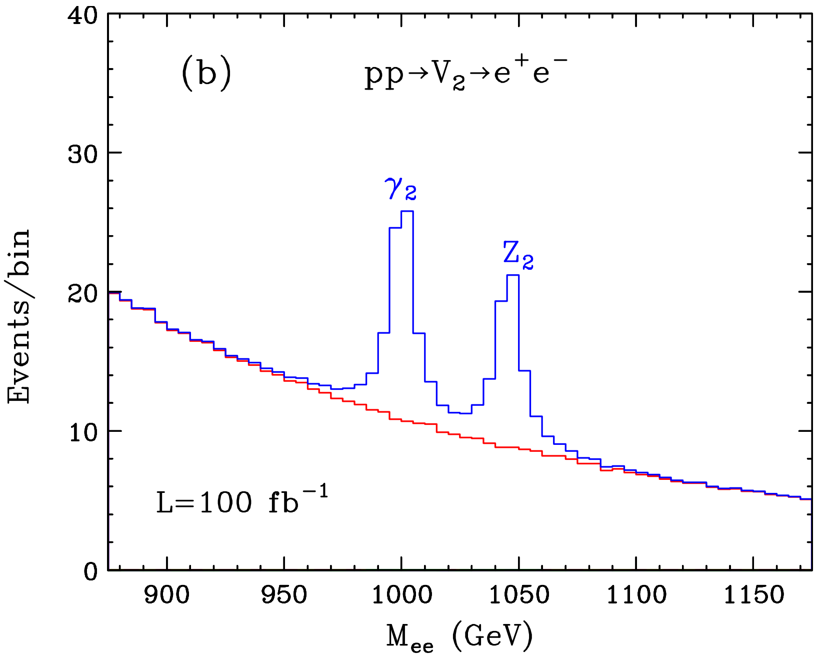
- KK first level states in UED have same spin as SM counterparts
  - SUSY partners have opposite spin
- Higgs sector of UED has different KK parity assignment than heavy Higgs bosons in MSSM (H, A, $H^{\pm}$)
  - Higgs sectors in SUSY and UED share same gauge quantum numbers
  - UED Higgses more similar to SUSY *higgsinos*,
- UED feature higher level KK modes (unlike supersymmetry)

Spin correlations

- second level KK states
- $B^{(2)} - Z^{(2)}$ di-resonance structure with $R^{-1} = 500$ GeV at LHC with $\mathrm{L} = 100\ \mathrm{fb}^{-1}$

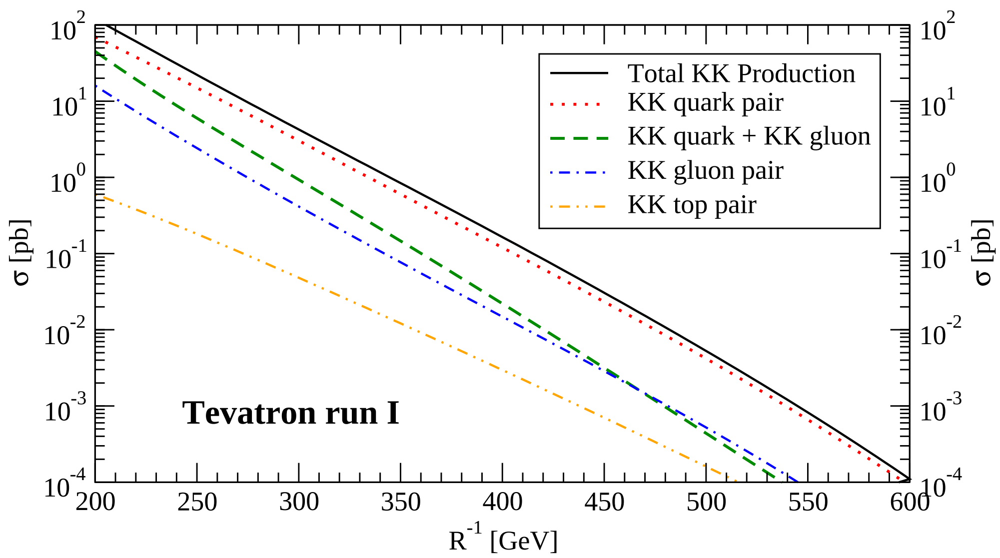
  Datta, Kong, Matchev '05
  - di-muon channel (left)
  - di-electron channel (right)
  - SM background (red)

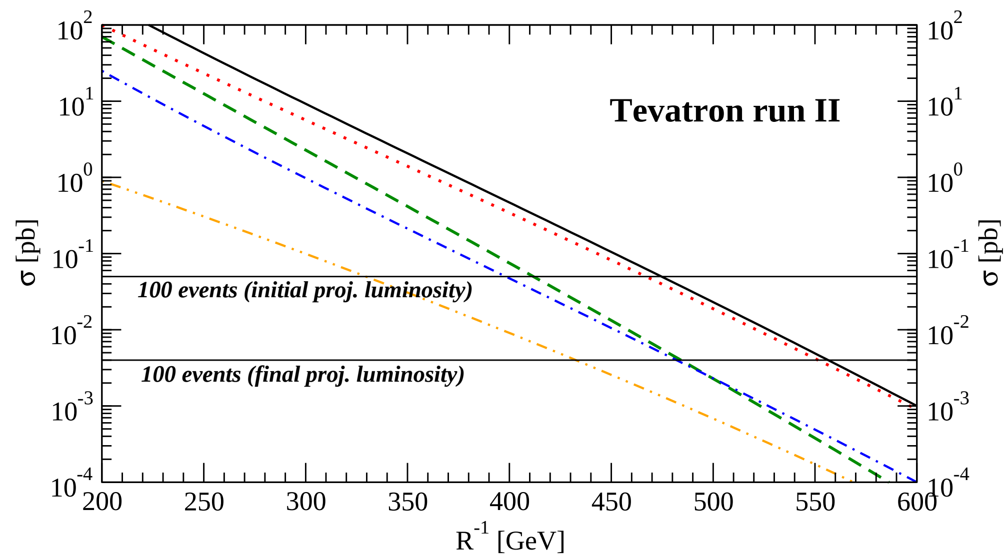




Tevatron cross section

- Production cross section of KK quarks and KK gluons at Tevatron as function of compactification radius R^{-1}
  - run I $\sqrt{s} = 1.8$ TeV, run II $\sqrt{s} = 1.96$ TeV
  - channels: Macesanu, McMullen, Nandi '02
    KK quark pairs, KK quark + KK gluon KK gluon pairs, KK top pairs
- Tevatron run II sensitivity limits

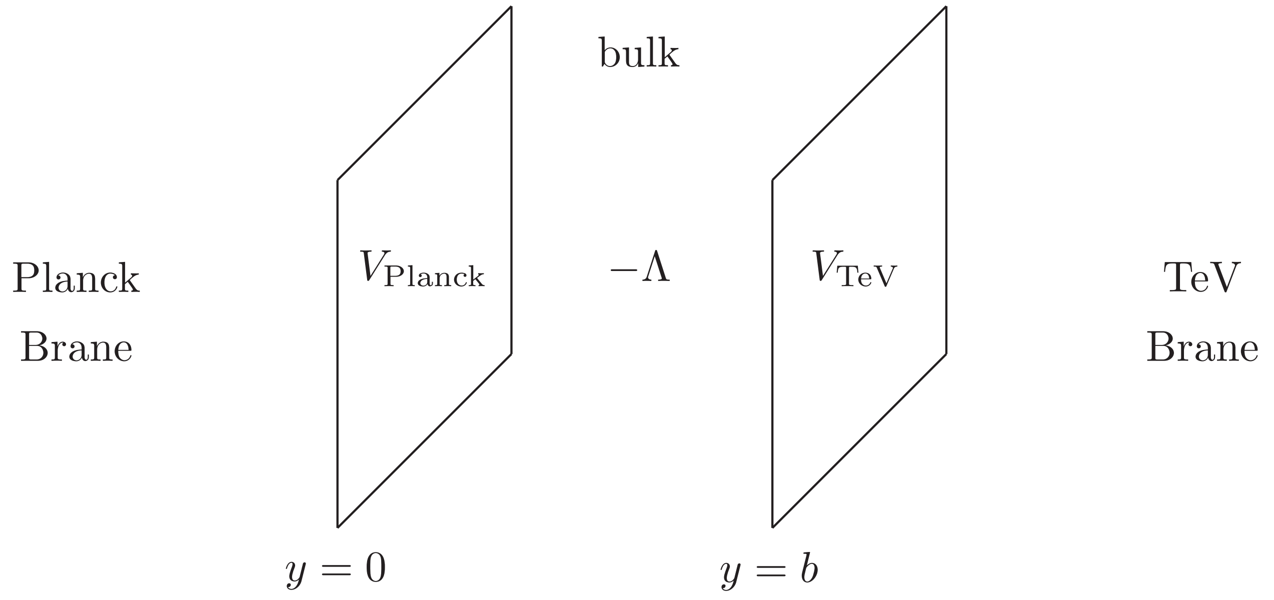




Randall-Sundrum models

RS cartoon

- The world according to RS
  - only gravity exists in the warped extra dimension
  - Standard Model confined to 3-brane
  - all dimensionful SM parameters scaled to the TeV scale



Randall-Sundrum models

- One extra spatial dimension (space $\mathbf{S}_1/\mathbf{Z}_2$) and "warped" five-dimensional geometry
  - "branes" extend infinitely in usual three spatial dimensions (sufficiently thin in warped direction)
- Metric non-factorizable

$$ds^2 = e^{-2kr_c\phi}\eta_{\mu\nu}dx^\mu dx^\nu + r_c^2 d\phi^2$$

  - "warp" factor in four-dimensional metric (rapidly changing function of additional dimension)
  - coordinates x^μ in familiar four dimensions
  - $0 \leq \phi \leq \pi$ parameter of extra dimension of radius r_c ($\mathbf{S}_1/\mathbf{Z}_2 \longrightarrow$ identification of (x,ϕ) with $(x,-\phi)$)
  - $k \sim \mathcal{O}(M_{\rm Planck})$
- Upshot
  - four-dimensional mass scales related to five-dimensional input mass parameters and warp factor $e^{-2kr_c\phi}$

Action for RS models

- Orbifold fixed points at $\phi = 0, \pi$ support two 3-branes (boundaries of the five-dimensional spacetime)
  - 3-branes support $(3+1)$-dimensional field theories
  - classical action $S = S_{gravity} + S_{vis} + S_{hid}$
- Matter field Lagrangian
  - example a fundamental Higgs field with mass parameter v_0

$$S_{vis} \supset \int d^4x \sqrt{-g_{vis}} \{ g_{vis}^{\mu\nu} D_\mu H^\dagger D_\nu H - \lambda (|H|^2 - v_0^2)^2 \}$$

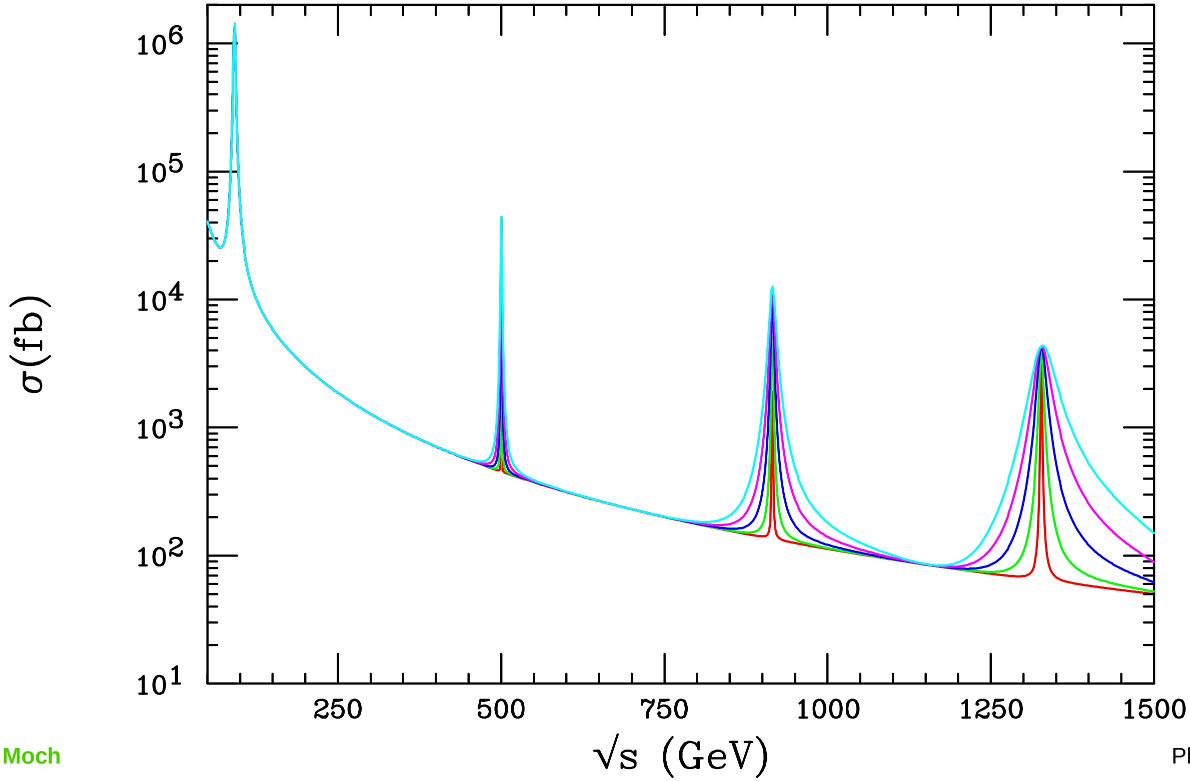
- Substitution of metric and rescaling of Higgs field $H \to e^{k r_c \pi} H$

$$S_{eff} \supset \int d^4x \sqrt{-\overline{g}} \{ \overline{g}^{\mu\nu} D_\mu H^\dagger D_\nu H - \lambda (|H|^2 - e^{-2 k r_c \pi} v_0^2)^2 \}$$

- Upshot
  - physical scale set by symmetry-breaking scale $v \equiv e^{-k r_c \pi} v_0$
  - any mass parameter m_0 on visible 3-brane in fundamental higher-dim. theory corresponds physical mass $m \equiv e^{-k r_c \pi} m_0$

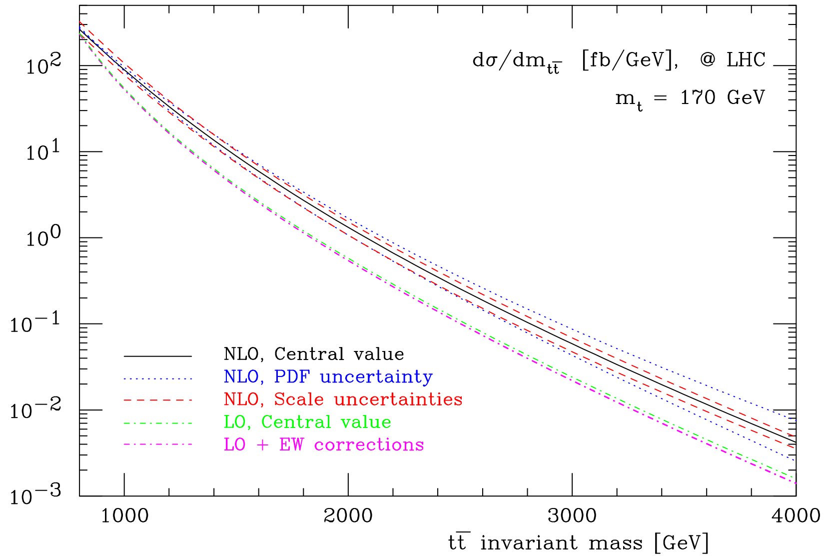
Resonances

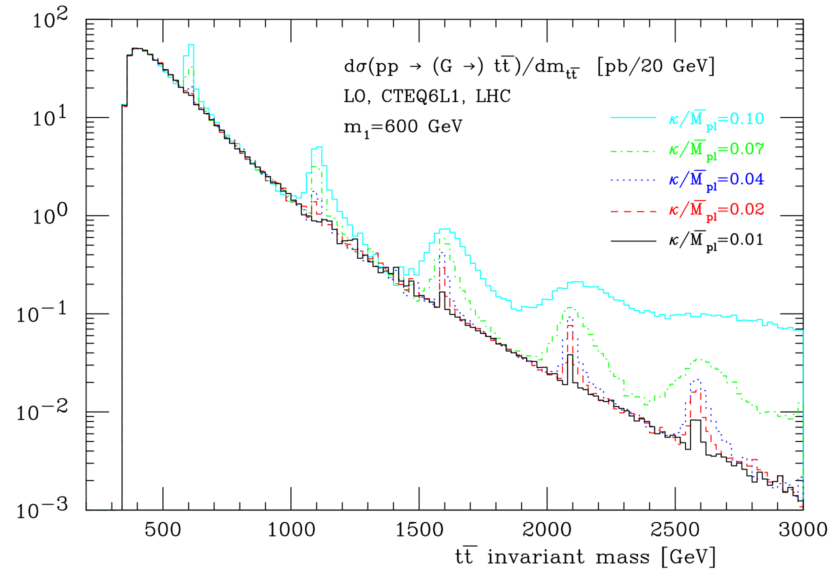
- RS-I scenario predicts di-fermion or di-bosons resonances at LHC from KK gravitons
  - in RS-I coupling of each KK graviton mode is only suppressed by $\mathcal{O}$(TeV) (unlike KK gravitons of ADD)
  - width of these resonances is controlled by ratio $c = k/M$
- Example: cross section for $e^+e^- \to \mu^+\mu^-$ including KK graviton exchange Hewett, Spiropulu ‘02



Top-quark invariant mass distristribution

- Invariant mass distribution of top-quark pair invariant $M_{t\bar{t}}$





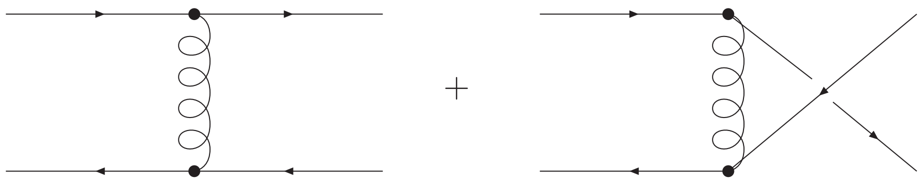
- Left: the $t\bar{t}$ invariant mass spectrum at LHC with NLO electroweak corrections
- Right: s-channel graviton exchange in $t\bar{t}$ invariant mass spectrum at LHC Frederix, Maltoni '07
  - Kaluza-Klein resonances in RS model

Hadronic di-jets

- Di-jet differential cross section for scattering
  $\mathrm{parton}_i(k_1) + \mathrm{parton}_j(k_2) \rightarrow \mathrm{parton}_k(k_3) + \mathrm{parton}_l(k_4)$

$$\frac{d^3\sigma}{dy_3 dy_4 dp_t^2} = \frac{1}{16\pi s^2} \sum_{i,j,k,l=q,\bar{q},g} \frac{f_i(x_1)}{x_1} \frac{f_j(x_2)}{x_2} \overline{\sum} \frac{1}{1+\delta_{kl}} |\mathcal{A}(ij \rightarrow kl)|^2$$

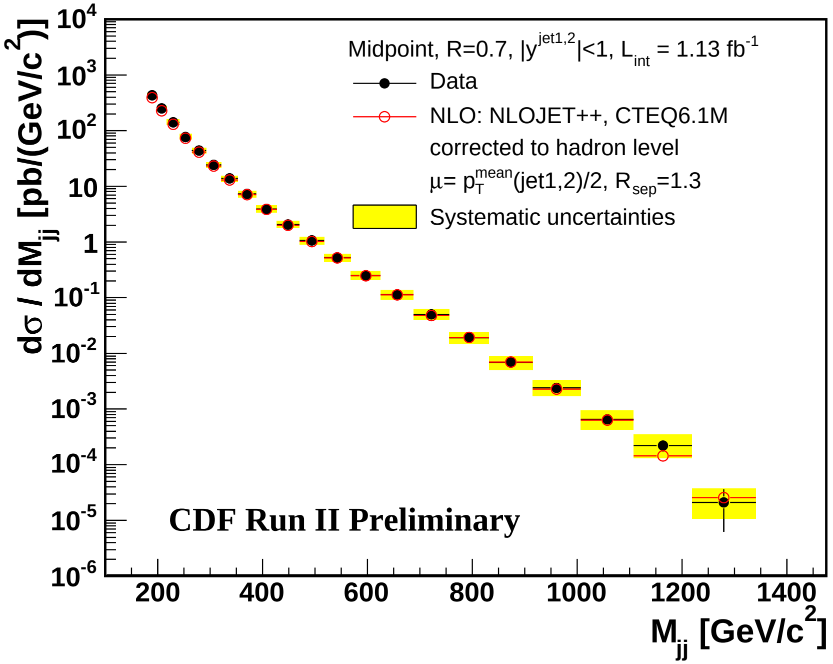
- Example: $\hat{\sigma}^{ud}$ with
  $\overline{\sum} |\mathcal{A}|^2 = (4\pi\alpha_s)^2 \frac{4}{9} \frac{s^2+u^2}{t^2}$

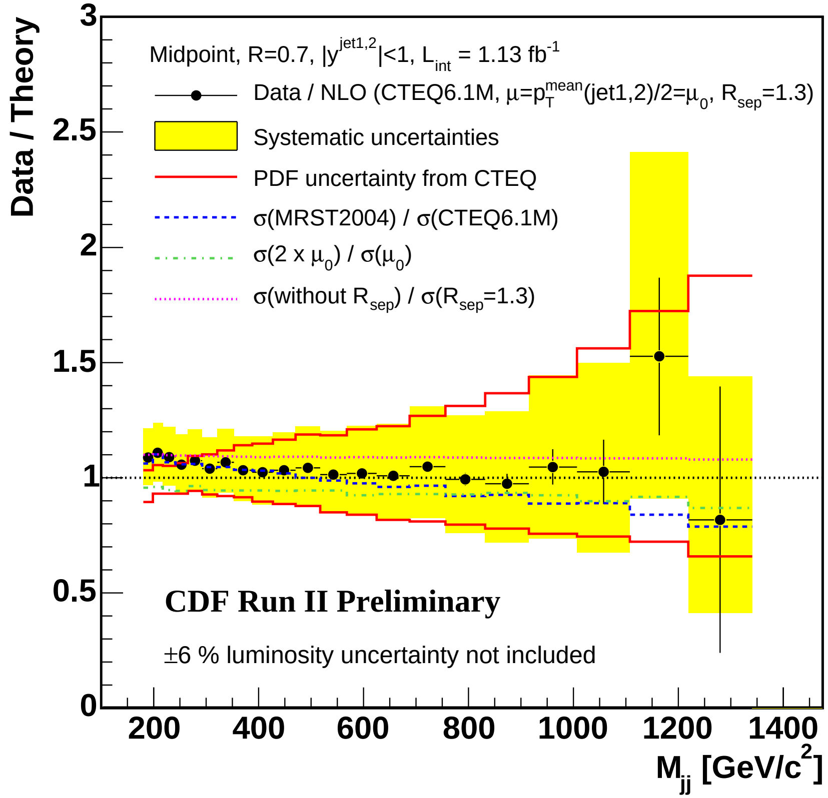


- Kinematics in di-jet cms
  - di-jet rapidity $y^* = \frac{y_3 - y_4}{2}$ determines cms scattering angle
    $\cos\theta^* = \frac{p_z^*}{E^*} = \frac{\sinh y^*}{\cosh y^*} = \tanh\left(\frac{y_3-y_4}{2}\right)$
  - di-jet invariant mass M_{JJ}^2

$$dy_3 dy_4 dp_t^2 = \frac{1}{2} dx_1 dx_2 d\cos\theta^*$$

Jets at Tevatron





- Di-jet invariant mass distribution
  - agreement with perturbative QCD over eight orders of magnitude
  - larger uncertainites for high M_{jj}^2

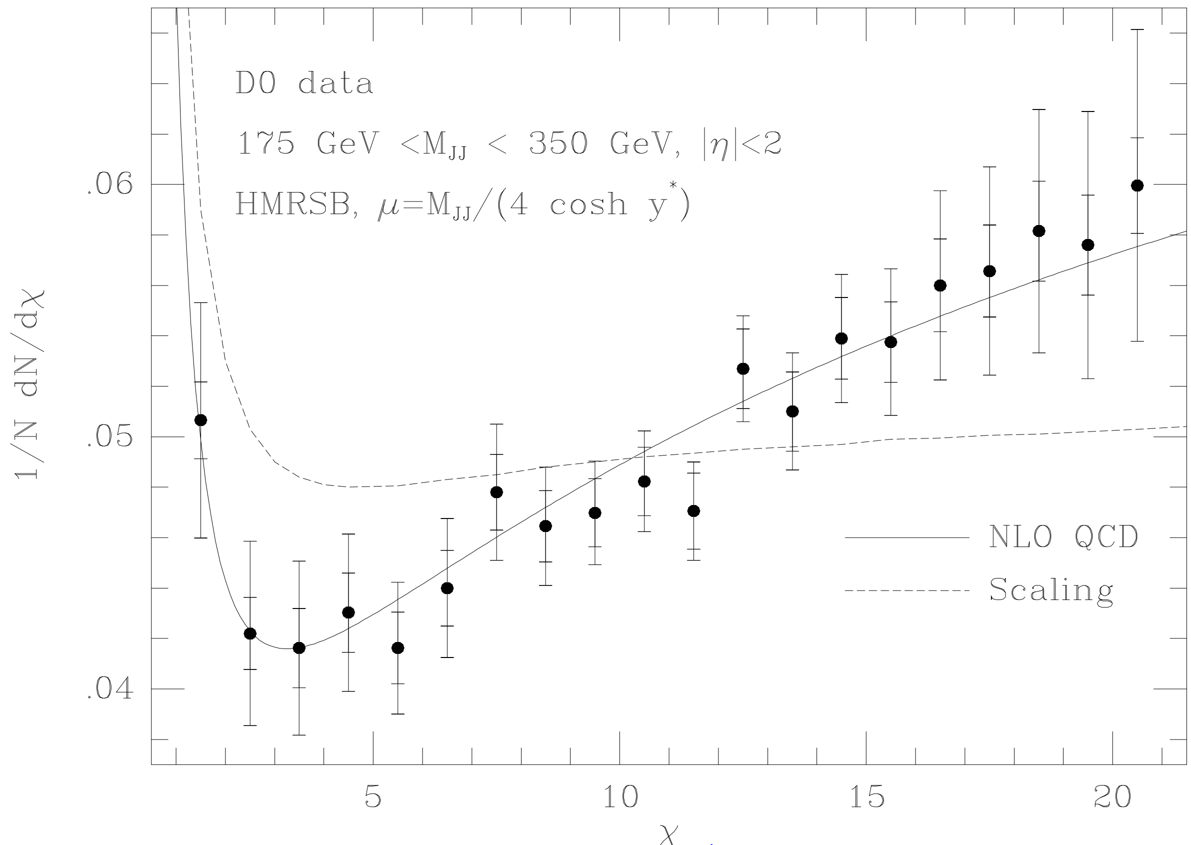
- Cross section σ^{ud} in di-jet cms kinematics

$$\frac{d\hat{\sigma}^{ud}}{d\cos\theta^*} = \frac{\pi\alpha_s^2}{2M_{JJ}^2}\,\frac{4}{9}\left[\frac{4+(1+\cos\theta^*)^2}{(1-\cos\theta^*)^2} + \frac{4+(1-\cos\theta^*)^2}{(1+\cos\theta^*)^2}\right]$$

- Small angles $\dfrac{d\hat{\sigma}^{ud}}{d\cos\theta^*} \sim \dfrac{1}{\sin^4(\theta^*/2)}$ (Rutherford)
  - transform to $\chi = \dfrac{1+\cos\theta^*}{1-\cos\theta^*}$
  - $\dfrac{d\hat{\sigma}^{ud}}{d\chi} \sim \mathrm{const}$
- Scalar colored particle (e.g. scalar gluon)
  - $\dfrac{d\hat{\sigma}^{ud}}{d\cos\theta^*} \sim \mathrm{const}$ transforms to $\dfrac{d\hat{\sigma}^{ud}}{d\chi} \sim \dfrac{1}{(1+\chi)^2}$

Quark substructure

- Searches for quark sub-structure in di-jet angular correlations



$$\frac{d^2\sigma}{dM_{JJ}^2 d\cos\theta^*} = \sum_{i,j=q,\bar{q},g} \int_0^1 f_i(x_1)\, f_j(x_2)\, \delta(x_1 x_2 s - M_{JJ}^2)\, \frac{d\hat{\sigma}^{ij}}{d\cos\theta^*}$$

Summary table

- “Metric” for models with extra dimensions

	SM fields	gravity
ADD	confined to 3-brane	gravity acts on 3-brane and in bulk
RS	confined to 3-brane	gravity acts on 3-brane and in bulk (extra dimension with large curvature)
UED	propagate through all spacetime (not confined to particular brane)	propagates through all spacetime