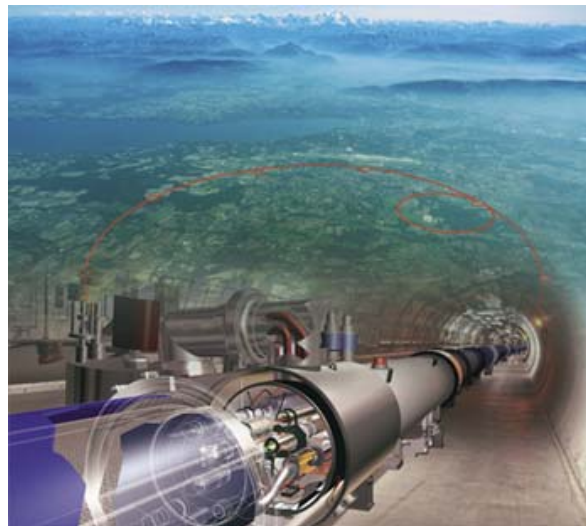




# Requirements for Extra Dimension Analyses from LHC Experiments

Albert De Roeck  
CERN  
TeV4LHC@BNL Feb 3-5



Thanks to: B. Heineman, K. Matchev, L. Pape, G. Polesello, Y. Sirois, M. Spiropulu  
Albert De Roeck (CERN) 1



# EuroGDR



- The Euro-GDR SUPERSYMMETRY is a four-year program (2001-2004) which aims at gathering theorists, high energy experimentalists and astrophysicists around the general topic of supersymmetry and related theories beyond the Standard Model of fundamental interactions
  - ⇒ extended for 2005-2009 but format/convenors change under discussion
- The goal is to enhance discussions and collaborations among members of the community, especially between experimentalists and theorists; to identify promising new lines of research; and possibly to provide scientific expertise when needed by the community at large.
- Working groups
  - Supersymmetric models for colliders
  - Flavours (including neutrinos)
  - Strings, branes and extra dimensions
  - Particle astrophysics and cosmology
  - Tools (supersymmetric spectra, generators, dark matter abundance, CMBcodes, ...)
- One general meeting/year. Several WG meetings/year
- Web page: <http://susy.in2p3.fr/EuroGDR/General/>



# Large Extra Dimensions

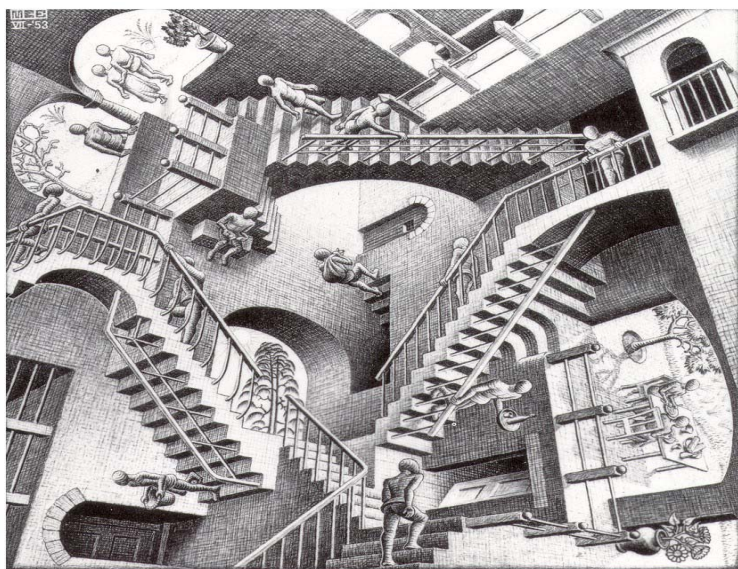


## Large Extra dimensions (ADD)

Gravity in bulk / flat space

Missing energy/interference/black holes

$$ds^2 = G_{IJ}dx^I dx^J = \eta_{\mu\nu}dx^\mu dx^\nu + h_{ij}(y)dy^i dy^j ,$$



## Warped Extra Dimensions (RS)

Gravity in bulk / curved space

Spin 2 resonances > TeV range

$$ds^2 = e^{-2ky} \eta_{\mu\nu} dx^\mu dx^\nu - dy^2, \quad k = \text{warp factor}$$

## TeV Scale Extra Dimensions

Gauge bosons/Higgs in the bulk

Spin 1 resonances > TeV range

Interference with Drell-Yan

## Special case: Universal Extra Dimensions UED

Everybody in the bulk!

Fake SUSY spectrum of KK states

+ many combinations/variations



# Extra Dimensions Analyses



## Issues for Extra Dimension analyses for experimentalists

- Include processes on Monte Carlo Generators for LHC (Tevatron) analyses. Hence they become a 'standard' which can be compared in between experiments
- Include complete information into Monte Carlo Generators, such as spin correlations. Study of measurability of spin effects (e.g.  $SUSY \leftrightarrow UED$ ,  $Z' \leftrightarrow KK...$ )
- Cross checks between codes/Monte Carlo results are important (problems have been found in the past)
- Agree on phase space available for EDs at LHC (& ILC, CLIC, Tevatron). Under which conditions do e.g. astrophysical and other limits apply. How can certain scenarios (e.g. MSLED) escape these limits...? Info is scattered...
- Agree on a number of benchmark scenarios, like we have for SUSY and successfully used e.g. in LHC/ILC studies
- Time to think about K factors? See hep-ph/0411018 for ADD/RS. The K factors can be large ( $\sim 1.6$  in that case) and affect the search reach.
- Accuracy of the background understanding important (e.g. Drell-Yan, Z+jet, PDFs..). Important for distr. tails where statistics & experimental checks will be limited.
- Use the same formalism in the models, e.g. for the definition of the effective  $M_{\text{plank}}$  (see G. Landsberg efforts)

Needed: a Forum to discuss/develop these tools & standards? (CERN) 4



# ED Monte Carlo Generators



## Monte Carlo Generators for LHC (Tevatron) analyses

- RS included in standard working horses HERWIG and PYTHIA
  - Spin correlations not complete in PYTHIA e.g. for  $G \rightarrow \gamma\gamma$  ZZ, WW (now added: Pythia version 6.226)
- ADD: several private codes for both the graviton radiation and graviton exchange processes, for PYTHIA or HERWIG
  - Recently improved by SHERPA which contains complete ADD FeynmanRules (Gleisberg, Kraus, Matchev)  $\rightarrow$  now used in ATLAS/CMS
- UEDs exist in a private code for COMHEP (Matchev et al.)
- **Wish:** have processes combinable with main working horse MCs, at present PYTHIA and HERWIG. Thanks to the Les Houches accord(\*) of 2001, an agreed exchange format exists in the Monte Carlo world such that one can think of a tool kit of ED processes to be combined with these MCs for the fragmentation/ hadronization (which is done e.g. for SM and SUSY processes)

(\*) GENERIC USER PROCESS INTERFACE FOR EVENT GENERATORS.

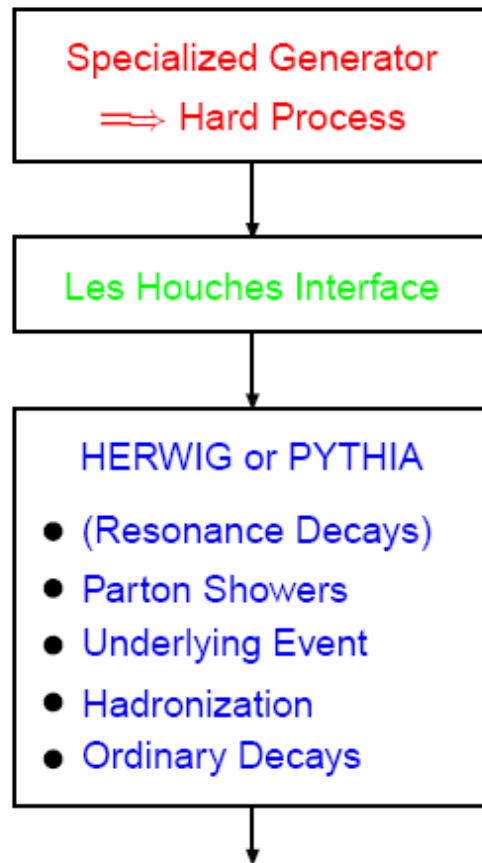
E. Boos et al. Workshop on Physics at TeV Colliders, Les Houches, 2001. hep-ph/0109068



# Monte Carlo Generators



T. Sjostrand      The Les Houches Accord



Some Specialized Generators:

- AcerMC:  $t\bar{t}b\bar{b}$ , ...
- ALPGEN:  $W/Z+ \leq 6j$ ,  
 $nW + mZ + kH+ \leq 3j$ , ...
- AMEGIC++: generic LO
- CompHEP: generic LO
- GRACE+Bases/Spring:  
generic LO+ some NLO loops
- GR@PPA:  $b\bar{b}b\bar{b}$
- MadCUP:  $W/Z+ \leq 3j$ ,  $t\bar{t}b\bar{b}$
- MadGraph+HELAS: generic LO
- MCFM: NLO  $W/Z+ \leq 2j$ ,  
 $WZ, WH, H+ \leq 1j$
- O'Mega+WHIZARD: generic LO
- VECBOS:  $W/Z+ \leq 4j$

Apologies for all unlisted programs

Can we have a toolkit for ED processes?

Needs organization  
EuroGDR? TeV4LHC  
SPA-like project?  
Les Houches 2005?

A combination of the above?  
Core group needed to take the lead/initiative

Future => ThePEG: a toolkit/framework for HEP event generators  
Lonnblad, Gieske, Ribon, Richardson



# LHC Experimentalist Generator Wish List



- **Have more processes available:** compiled list from CMS/ATLAS
  - Universal extra dimensions with KK number conservation
  - Universal extra dimensions without KK number conservation
  - Bulk scalars with Higgs interference
  - Radions and interference with the Higgs (now hack in HDECAY)
  - Implementation of different running couplings (see hep-ph9807522)
  - More flexible/complete generation of KK resonances in TeV<sup>-1</sup> and RS models, which include many resonances, effects of brane kinematic terms (hep-ph0212279). TeV<sup>-1</sup> matrix elements in 'standard toolkit'
  - Branons
  - More sophisticated black hole generators...? (remnant, radiation phases, spin)
  - String ball effects (black hole-like but different radiation/lower mass)
  - Transplankian effects, especially high E<sub>T</sub> 2 jet production
  - SUSY+ ED scenarios (modify the phenomenology as in )
  - Thick branes, brane tension, rigid and soft branes
  - Even more recent scenarios (such as intersecting branes, Higgsless EWSB)

At this stage, for LHC: MCs of new scenarios are important if these imply new signatures and require new sorts of experimental checks

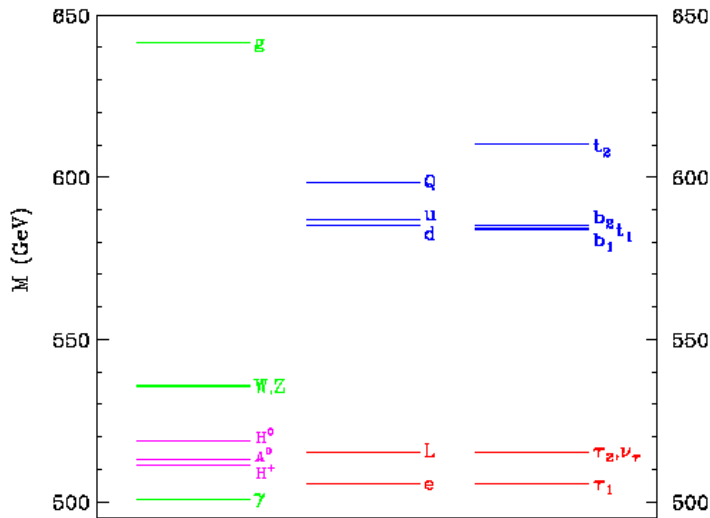


# Example: Universal Extra Dimensions

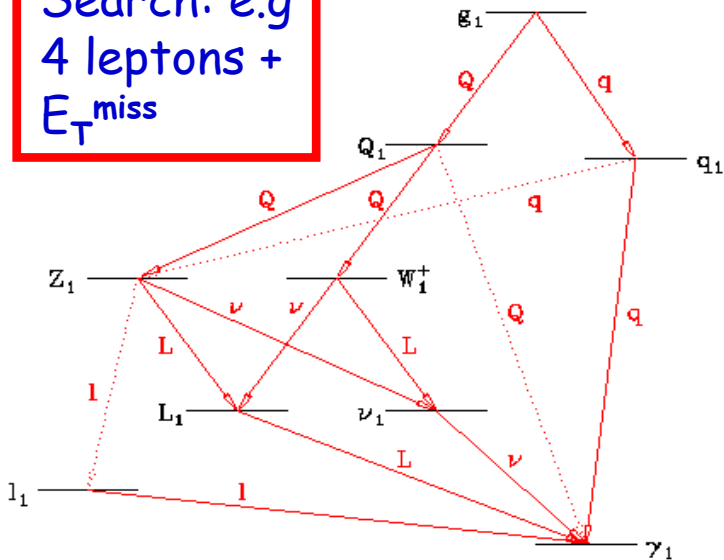


e.g. Cheng, Matchev, Schmaltz hep-ph/0205314

This is a "what if?" scenario!  
What if we have a KK tower pattern from ED's which look like supersymmetry:  
**Can the LHC tell distinguish?**



**Search: e.g**  
4 leptons +  
 $E_T^{miss}$



**Tools: spin of the "sparticles"/ No heavy higgses/  
mass splitting small/pattern repeats at higher  
energies...**

Present implementation in **Comphep** (Matchev et al.)  
Problem: for long decay chain e.g. up to 10  
particles/partons in the final state it is difficult  
to compute with all the spin correlations  
correctly and time consuming. Some tricks to  
improve being explored (E. Boos)





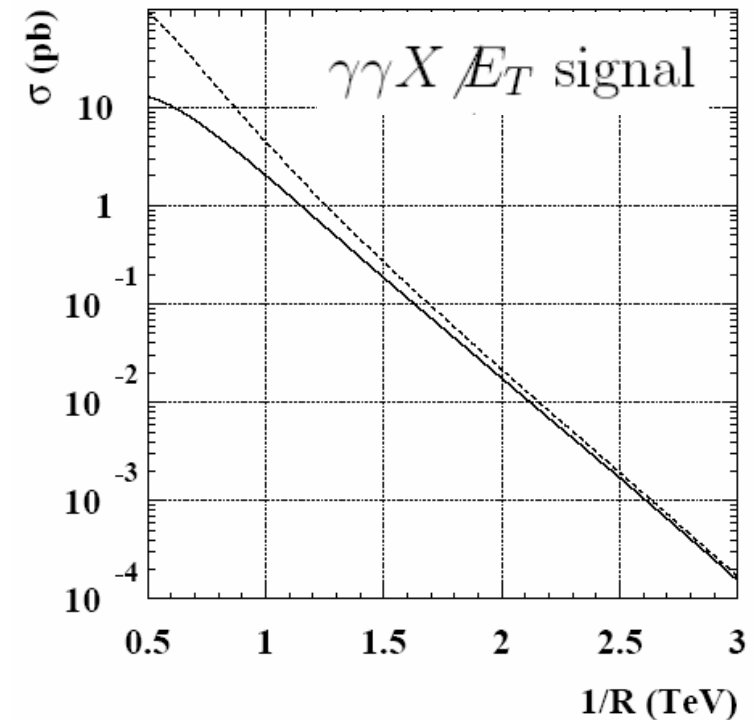
# Example: UED without KK conservation



Add KK violating interactions mediated by gravity to allow KK excitations to decay into a SM particle + KK graviton

- Pair production
  - E.g.  $\gamma^* \rightarrow \gamma + \text{KK graviton}$
  - Signal for LHC: 2 photons + large missing  $E_T$
- Single production
  - E.g.  $gg \rightarrow gg^* \rightarrow gg + \text{KK graviton}$
  - Signal for LHC: 2 jets + large missing  $E_T$
- Useful to check sensitivity/reach for the LHC by experiments, but generator needed to do a good job (including acceptances, smearing, trigger etc...)

Macesanu, McMullen, Nandi

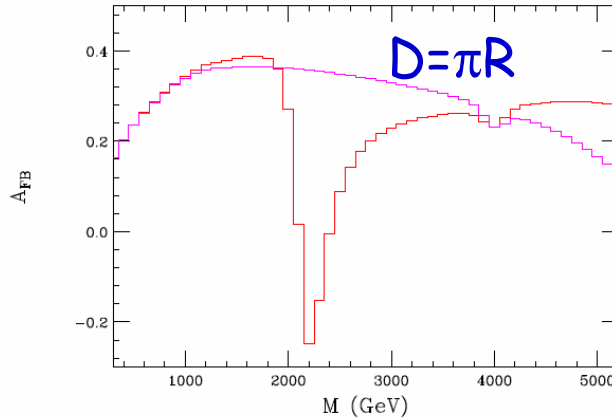
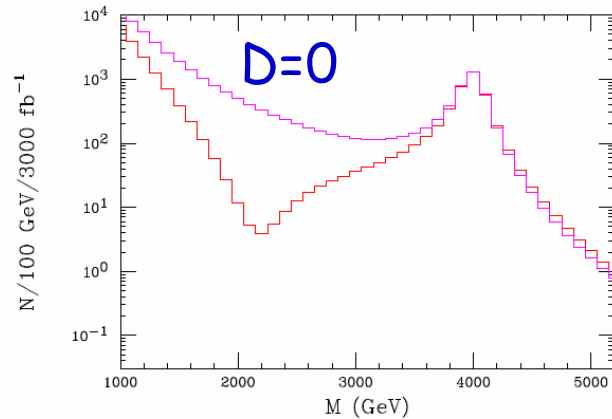




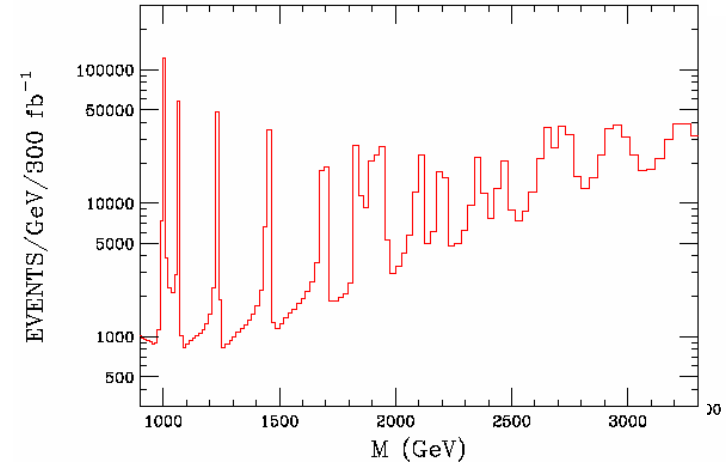
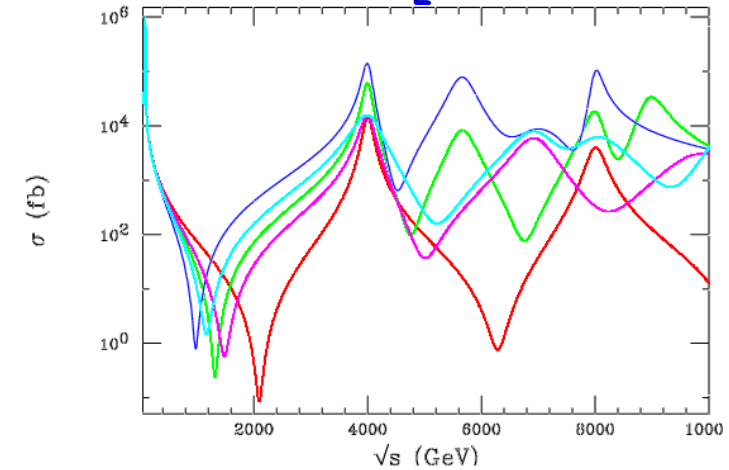
# Example: $Z'/KK$ studies in $TeV^{-1}$ EDs



## Different $\gamma/Z$ KK resonances



## $RS \otimes S^1/Z_2$ orbifold



Can we distinguish scenarios at the LHC? Important to have flexible couplings, interference effects available in the event generators etc.

Private code for  $TeV^{-1}$  resonances: Polesello, Azuelos, (Rizzo) 0



# Example: Rigid/Soft Branes



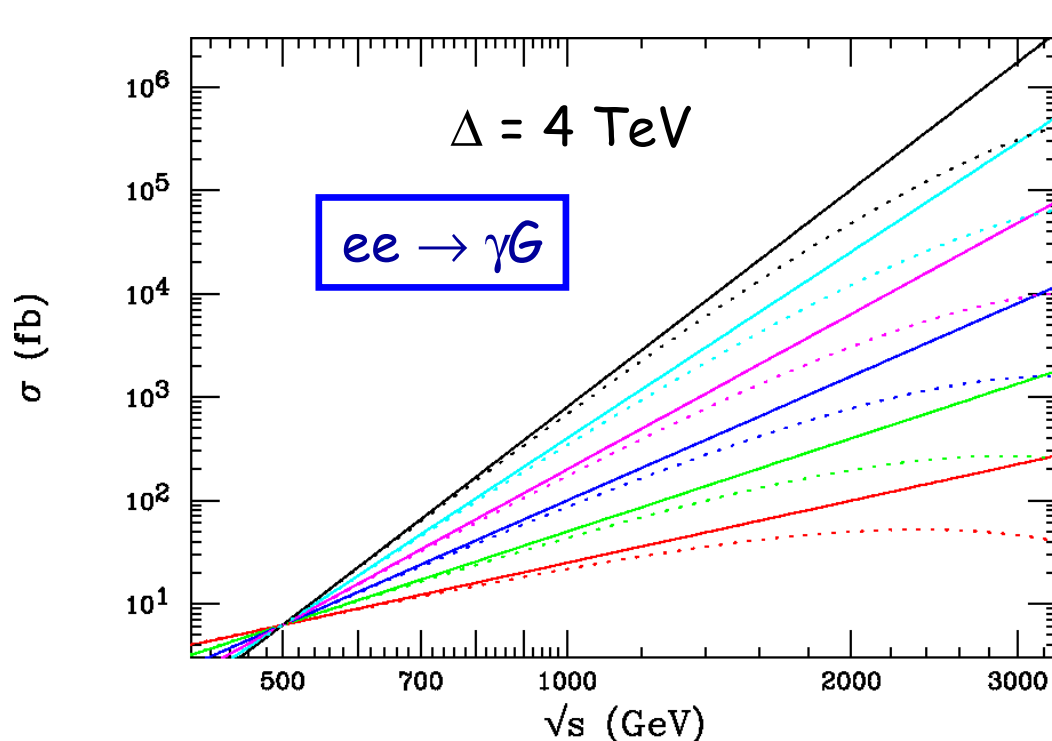
## ADD Models

Rigid brane: Coupling of massive KK towers is exactly the same for less massive towers

Soft branes: Coupling of higher mass KK towers reduced

$$g_n^2 \rightarrow g_n^2 e^{-(m/\Delta)^2} \quad \Delta = \text{wall tension}$$

could have any value but expected  $\sim O(\text{TeV})$



$n = 7$



$n = 2$

$M_D$ 's fixed to agree with  $M_D = 5 \text{ TeV}, n = 2$

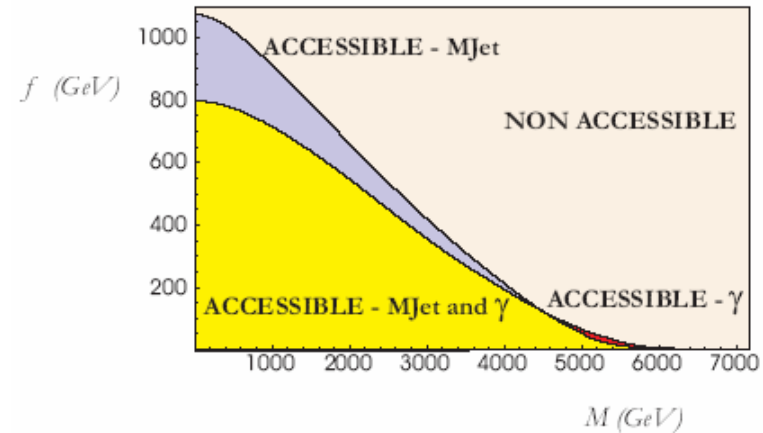
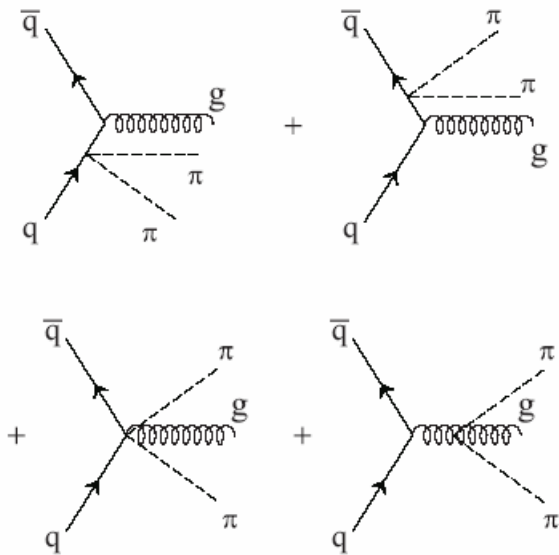
No generator exists, but formulae for cross sections and kinematics available



# Example: Branons



Branons: scalar particles, associated to brane fluctuations couple to SM particles by pairs.



$$\frac{d\sigma(q\bar{q} \rightarrow g\pi\pi)}{dk^2 dt} = \frac{4\alpha_s N}{3} \frac{(k^2 - 4M^2)^2}{184320 f^8 \pi^2 \hat{s}^3 tu} \sqrt{1 - \frac{4M^2}{k^2}} (\hat{s}k^2 + 4tu)(2\hat{s}k^2 + t^2 + u^2), \quad (10)$$

No generator available, but formulae for cross sections and kinematics available



# Example: Black Holes

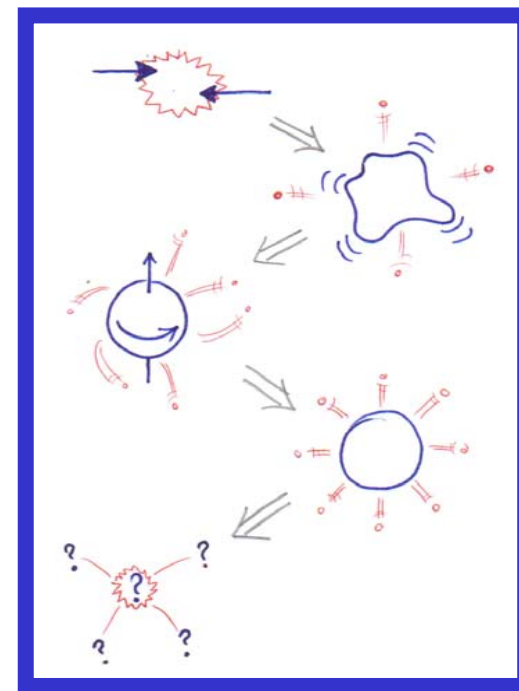


$\sqrt{s} \gg M_{\text{planck}} \Rightarrow$  Black Hole production

Ch. Lester/Prague 2003

Stage	Need a Quantum Theory of Gravity?	Scale	In Event Generators ?
Production	Yes and No	$>M_p$	$\pi r^2$
"Hair Loss"	No	$>M_p$	No
Spin Down	No	$>M_p$	No
Hawking Radiation	Yes and No	$>M_p$ $\sim M_p$	Yes
Remnant Decay	Yes	$<M_p$	Many options

- Several MC on the market
- **Not all radiation phases included yet** (important?)
- Truenoir (Lansberg)
- Charybdis (Harris et al.)
- "BlackHole" (Tanaka et al)





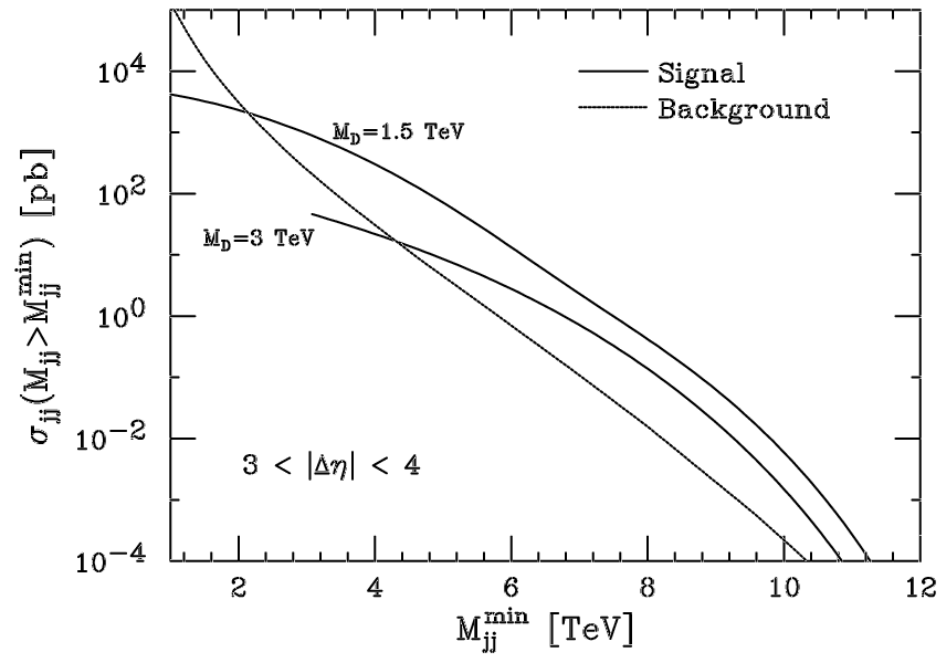
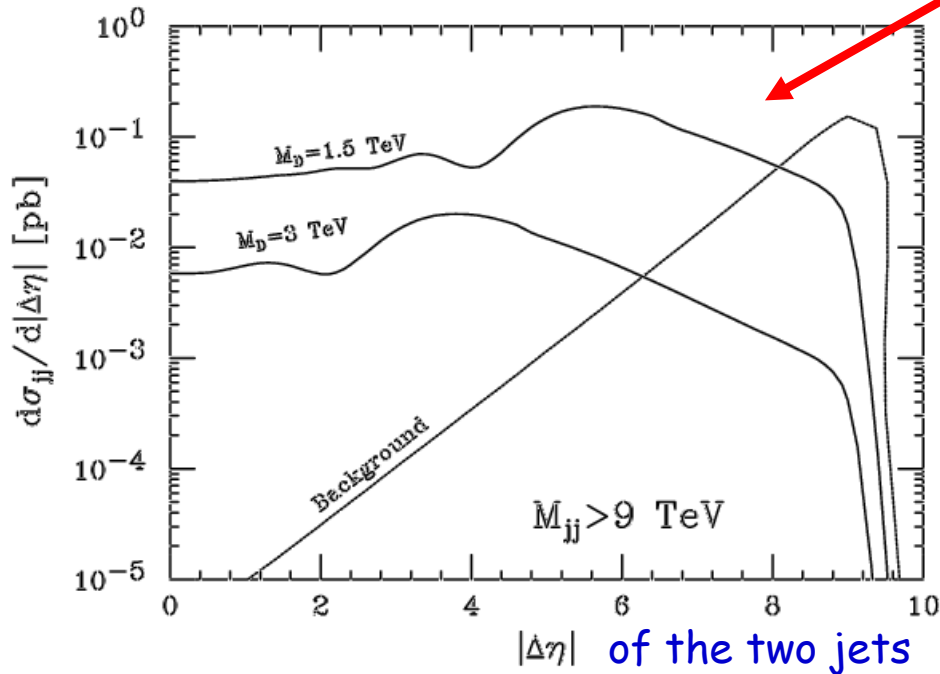
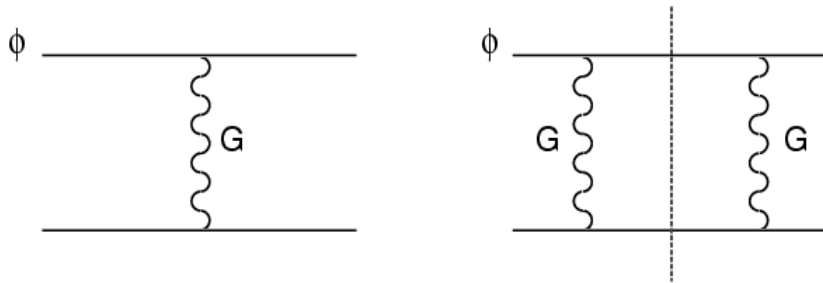
# Example: Transplanckian Effects



Once you pass the Planck scale  $\sqrt{s} \gg M_D \dots$

Processes with small momentum transfer e.g. :  
Elastic transplanckian collisions:  
Study gravity propagation in ED's  
**Signal: dijets with large  $M_{jj}$**

Giudice, Rattazzi, Wells



Phenomenology (formulae) worked out but no generator available!!

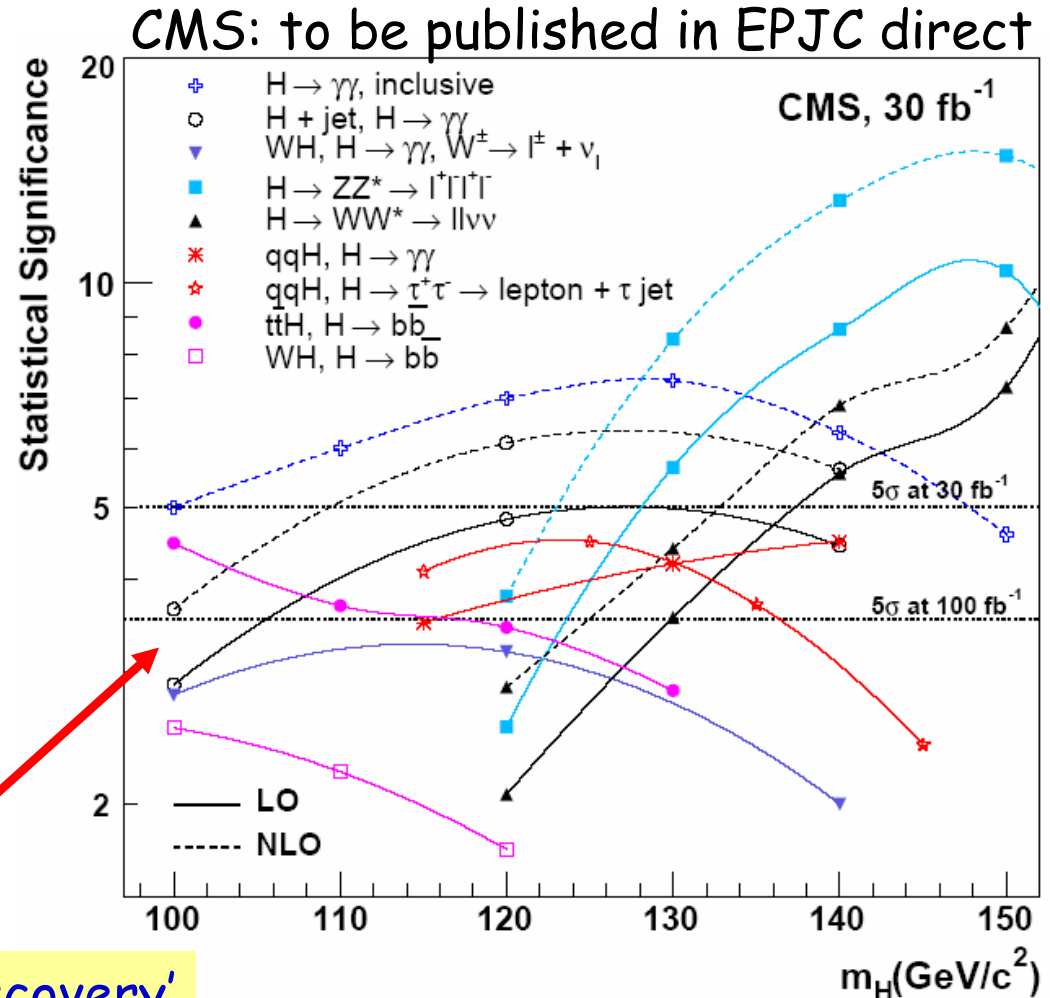


# Higher QCD corrections/K factors



- D. Rainwater (TH) at Les Houches 2003:  
 ⇒ Critique to the experiments:  
 "Where possible the experiments should include NLO results (if nothing better via K factors) in their experimental assessment of their sensitivity. Sometimes important effects on the sensitivity which may reclassify a process as being accessible (or vice versa)"

Shown here for Higgs 'discovery'

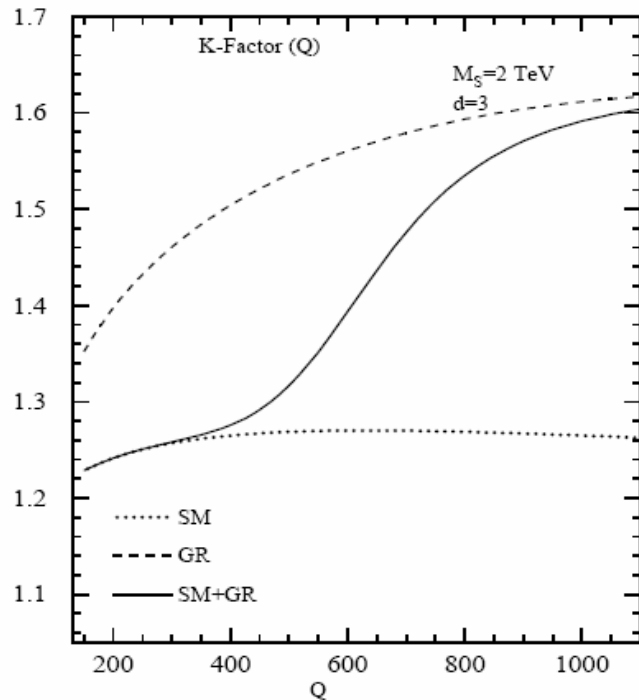




# Higher QCD corrections/K-Factors



P. Mathews, V. Ravindran, K. Shridhar, W.L. van Neerven  
NLO QCD corrections to ADD models hep-ph/0411018  
 $pp \rightarrow G \rightarrow 2 \text{ leptons}$



Q= invariant mass of the Lepton Pair in DY production

Note:

- K factor for gravity channel is large:  $\sim 1.6$
- Drell-Yan K factor is lower. Can change the search sensitivity by  $\sim 50\%$

What about RS  $G \rightarrow 2 \text{ leptons}$ ? **same!**  
What about  $G \rightarrow \gamma\gamma$ ? **not same!**

K factors can make a difference!  
Already useful now for Tevatron  
 $\Rightarrow$  We encourage more K-factor determinations

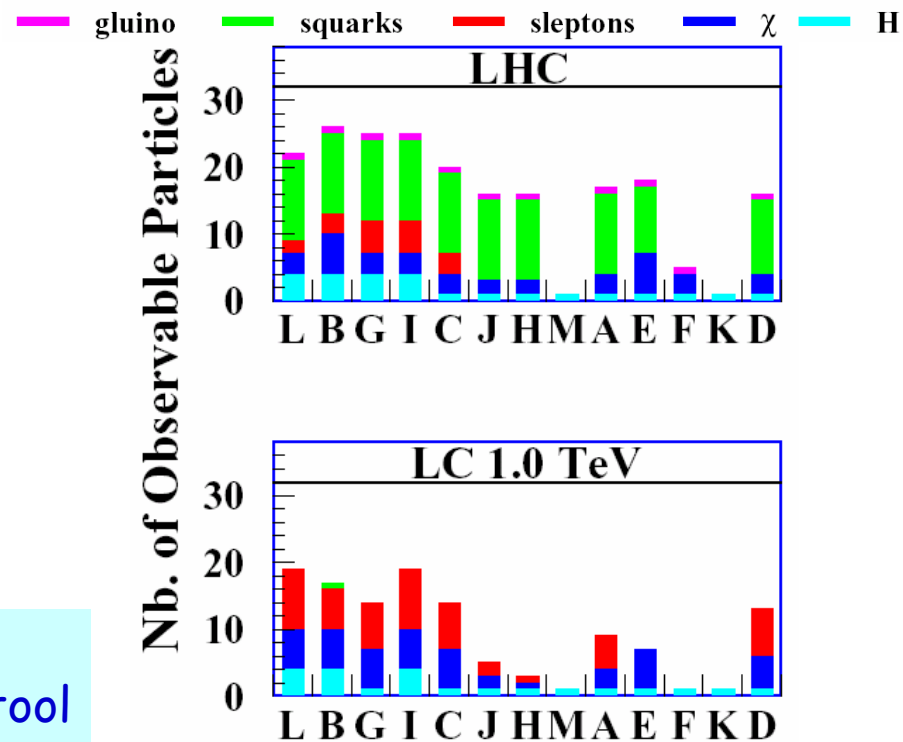




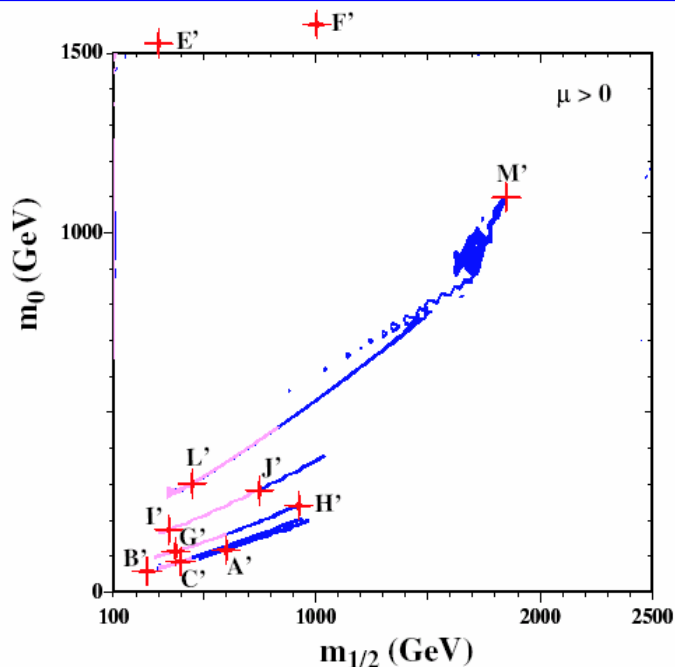
# Benchmarks for EDs: The SUSY example



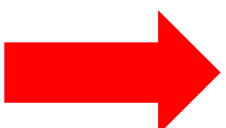
- A number of SUSY (msugra and other) benchmark points to study LHC/LC sensitivity (Battaglia et al, Allanach et al.,...)
- Take into account direct searches at LEP and Tevatron, BR ( $b \rightarrow s\gamma$ ),  $g_{\mu-2}$  (E821), Cosmology:  $0.09 \leq \Omega_{\chi} h^2 \leq 0.13$



Allowed regions in the  $M_0$ - $M_{1/2}$  plane



ISASUGRA as common tool



Very useful for comparisons of analyses, common studies, LHC/ILC studies

We would benefit strongly from defining common ED benchmarks! Working group?



# Constraints from other data



- It would be useful for LHC (and other studies) to know the available phase space, constrained by other data
  - High energy collider data (usually known)
  - Precision measurements
  - Astrophysical and cosmological constraints (recent: hep-ph/0408320)
  - Other experiments (gravitational measurements etc.)
- Benchmark processes need to take these into account
- Some effort in PDG. Working group?

⇒ Example: ADD Size of the Extra Dimensions:

$\delta = 1$   $R = 10^{13}$  m excluded!

$\delta = 2$   $R = 0.7$  mm essentially excluded

- Results from SN1987A (model dependent)

- Newton's law works down to  $200\mu\text{m}$

$\delta = 3$   $R = 3$  nm

$\delta = 4$   $R = 6 \times 10^{-12}$  m...

Eg. LEP2 data constrains very strongly interacting gravity at the weak scale (Giudice, Strumia hep-ph/0301232)



# Formalism Unification



## Example: Virtual Graviton effects

G. Landsberg...

- ✚ **Hewett**: neither sign of the interference nor the dependence on the number of extra dimensions is known; therefore the **interference term is**  $\sim \lambda/M_S^4(\text{Hewett})$ , where  $\lambda$  is of order 1; numerically uses  $\lambda = \pm 1$
- ✚ **GRW**: sign of the interference is fixed, but the dependence on the number of extra dimensions is unknown; therefore the **interference term is**  $\sim 1/\Lambda_T^4$  (where  $\Lambda_T$  is their notation for  $M_S$ )
- ✚ **HLZ**: not only the sign of interference is fixed, but the  $n$ -dependence can be calculated in the effective theory; thus the **interference term is**  $\sim F/M_S^4(\text{HLZ})$ , where  $F$  reflects the dependence on the number of extra dimensions:

$$F = \begin{cases} \log\left(\frac{M_S^2}{s}\right), & n = 2 \\ \frac{2}{n-2}, & n > 2 \end{cases}$$

- ✚ **Correspondence** between the three formalisms:

$$M_S(\text{Hewett})|_{\lambda=+1} \equiv \sqrt[4]{\frac{2}{\pi}} \Lambda_T(\text{GRW})$$

$$\frac{\lambda}{M_S^4(\text{Hewett})} = \frac{\pi}{2} \frac{F}{M_S^4(\text{HLZ})}$$

$$\frac{1}{\Lambda_T^4(\text{GRW})} = \frac{F}{M_S^4(\text{HLZ})}$$

- ✚ **Rule of thumb**:

$$M_S(\text{Hewett})|_{\lambda=+1} \approx M_S(\text{HLZ})|_{n=5}$$

$$\Lambda_T(\text{GRW}) = M_S(\text{HLZ})|_{n=4}$$

Useful to agree on a unique formalism

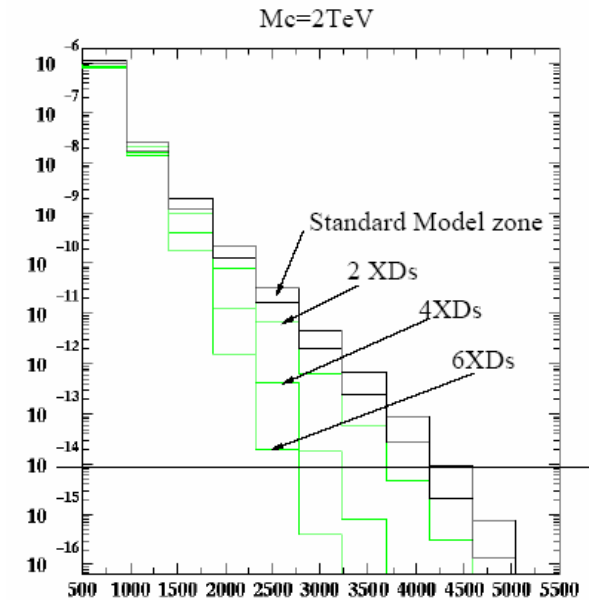
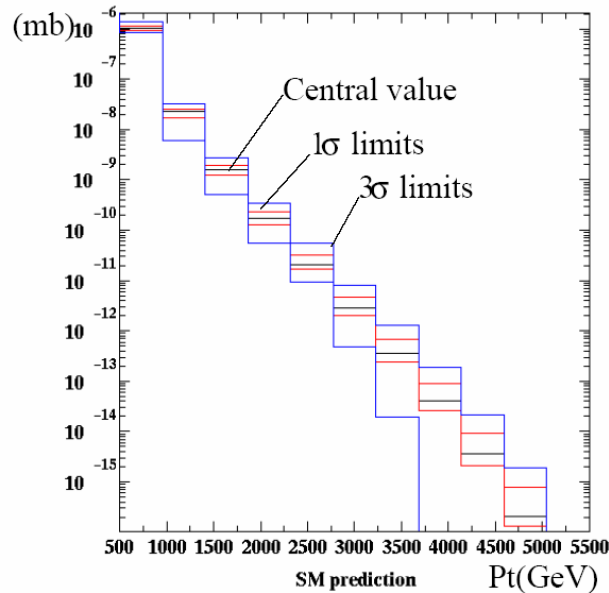
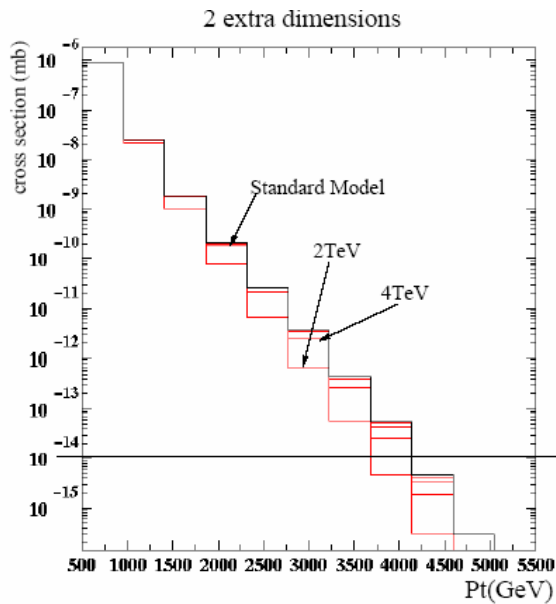


# Precise knowledge of the SM background



Example: effect of PDFs on ADD di-jet final state sensitivity

Graviton exchange contributions reduce the cross section (interference)



S. Ferrag

Reduction of the Sensitivity due to PDF uncertainty (CTEQ6)



	2 extra-dimensions	4 extra-dimensions	6 extra-dimensions
Theoretically	5 TeV	5 TeV	5 TeV
including PDF uncertainties	< 2 TeV	< 3 TeV	< 4 TeV

This workshop and the HERA/LHC workshop

Other important SM background channel: Drell-Yan production

Albert De Roeck (CERN)20



# Conclusions



EuroGDR: plenty of young theorists (strings, branes, ..)

Taken from a colloquium given by K. Matchev at FNAL during the first TeV4LHC workshop September 04  
Konstantin is a theorist!

- The area of undisciplined theorizing is over!  
What can you do for the LHC/Tevatron/ILC and what can they do for you
- There is a big gap between what even the phenomenologically oriented theorists are doing and
  - What the theorists need to do for TeV/LHC searches
  - What the experimentalists would like them to be doing

⇒ A wish list to this community



## Summary: a list of wishes



- **ED MC process tool box**
  - Complete with (many) missing processes
  - Include details in the MC, eg. spin correlations. These correlations likely to become very important when LHC will discover a new object.
  - In principle easy to contribute with present generator developments (Les Houches accord/ThePEG...)
- **SM background processes: precision needed** (well known at this wkshop).
- Higher order QCD (EW) corrections to processes
- **ED and constraints from existing data**
- Start thinking of benchmark processes.
- **Select a formalism, where (if) needed**

EuroGDR and/or TeV4LHC and LesHouches05 can play an important role driving or organizing this effort, perhaps via working groups on some of these topics

SUSY has the SPA project. Something similar for EDs?

⇒ Result: some useful contacts but work/organization still has to start



# Large Extra Dimensions

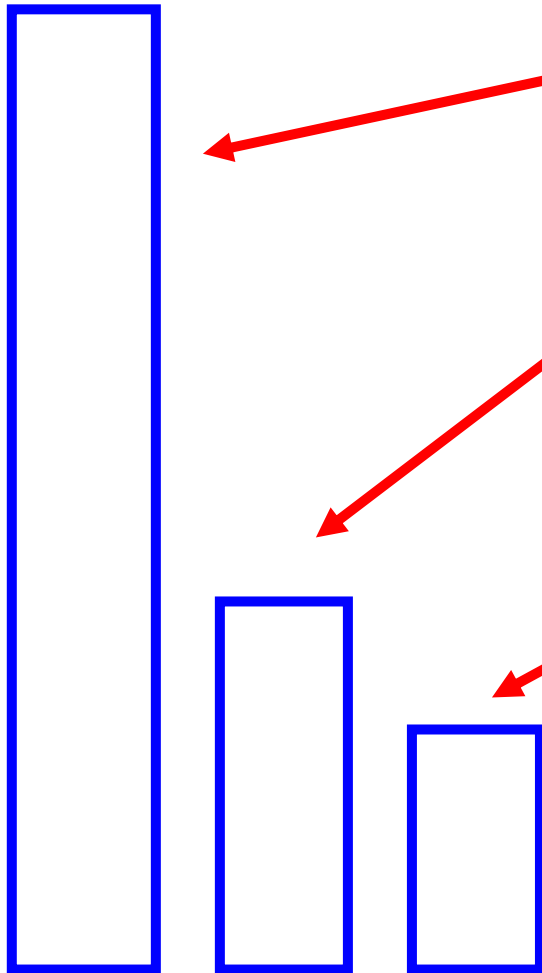


$10^{-3}eV$

100GeV

1 TeV

scale



## Large Extra dimensions (ADD)

Gravity in bulk / flat space

Missing energy/interference/black holes

$$ds^2 = G_{IJ}dx^I dx^J = \eta_{\mu\nu}dx^\mu dx^\nu + h_{ij}(y)dy^i dy^j ,$$

## Warped Extra Dimensions (RS)

Gravity in bulk / curved space

Spin 2 resonances > TeV range

$$ds^2 = e^{-2ky} \eta_{\mu\nu} dx^\mu dx^\nu - dy^2, \quad k = \text{warp factor}$$

## TeV Scale Extra Dimensions

Gauge bosons/Higgs in the bulk

Spin 1 resonances > TeV range

Interference with Drell-Yan

## Special case: Universal Extra Dimensions UED

Everybody in the bulk!

Fake SUSY spectrum of KK states

+ many combinations/variations



# The HERA/LHC and TeV4LHC Workshops!

Optimal understanding of SM backgrounds, e.g. PDF uncertainties discussed here!

**HERA AND THE LHC**  
A workshop on the implications of HERA for LHC physics

March 2004 - Jan 2005

- Parton density functions
- Multijet final states and energy flow
- Heavy quark
- Diffraction
- Monte Carlo tools

**Startup Meeting**  
March 26-27 2004  
CERN, Geneva

**Midterm Meeting**  
October 2004

**Final Meeting**  
Jan 2005  
DESY, Hamburg

Organizing Committee:  
G. Abbiendi (CERN), J. Alkner (CERN),  
M. Bähr (DESY), J. Bijnens (CERN),  
S. Frixione (CERN), G. Grunberg (CERN),  
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S. Weyant (DESY), M. Wulf (DESY)

[www.desy.de/~heralhc](http://www.desy.de/~heralhc) [heralhc.workshop@cern.ch](mailto:heralhc.workshop@cern.ch)

First Meeting 16 - 18 Sept. '04 Fermilab • Midterm meetings at Brookhaven & CERN • Final meeting at Fermilab, Fall '05

**TeV4LHC WORKSHOP**

Using the data & experience from the Tevatron to prepare for the LHC

*TeV4LHC Organizing Committee:*  
Georges Aad (U. Montreal)  
Ulrich Bauer (SUNY at Buffalo)  
Marcela Carena, Chair (FNAL)  
Sally Dawson (BNL)  
Dan Green (FNAL)  
Ian Hinchliffe (LBL)  
Young-Kee Kim (U. Chicago)  
Joe Lykken (FNAL)  
Stephen Mrenna (FNAL)  
Heidi Schellman (Northwestern)  
John Warner (FNAL)

*Working Groups*  
**QCD, Top & Electroweak Physics, Higgs, and Physics Landscape.**

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*Information & Registration:* <http://conferences.fnal.gov/tev4lhc/>

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Next meeting: Jan 17-21 @CERN

Next meetings Feb 3-5 @ BNL



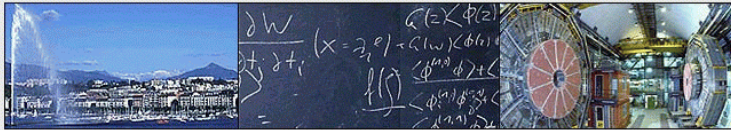


# Preamble: String Theorists @ LHC




July '04: String theory conference at CERN -- O(100) participants

⇒ they got a tour to the LHC experiments...



Strings at CERN  
July 5-7, 2004

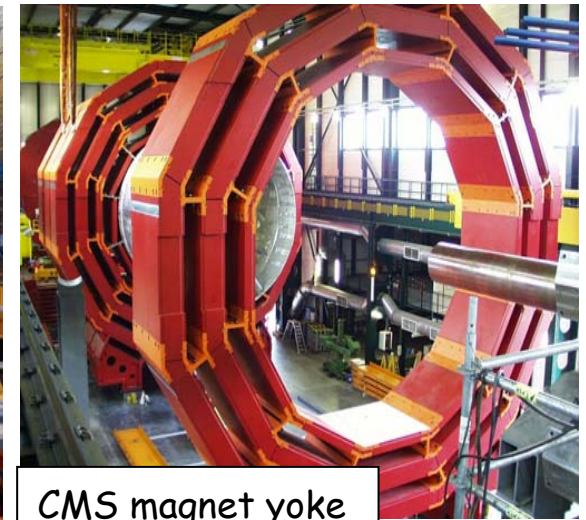


menu

- Home
- Useful
- Information
- Program
- Post-Program
- Participants
- Register
- Theory Division
- Contact
- Admins

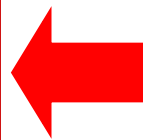


ATLAS cavern



CMS magnet yoke

LHC is coming!  
LHC is inspiring!  
LHC needs good tools!



...after which some string theorists wanted to become experimentalists...  
...and ideas start circulating for a mock data analysis challenge between theorist and experimentalists, on 'LHC data' containing new physics signals...