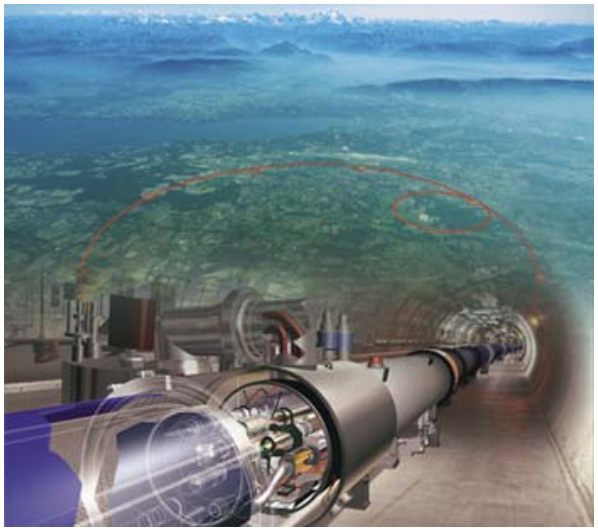
Requirements for Extra Dimension Analyses from LHC Experiments

Albert De Roeck
CERN
Les Houches 2005



EuroGDR Supersymmetry
4th meeting
Frascati 25-27 November 2004

Tev4LHC

Thanks to: B. Heineman, K. Matchev, L. Pape, G. Polesello, Y. Sirois, M. Spiropulu

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

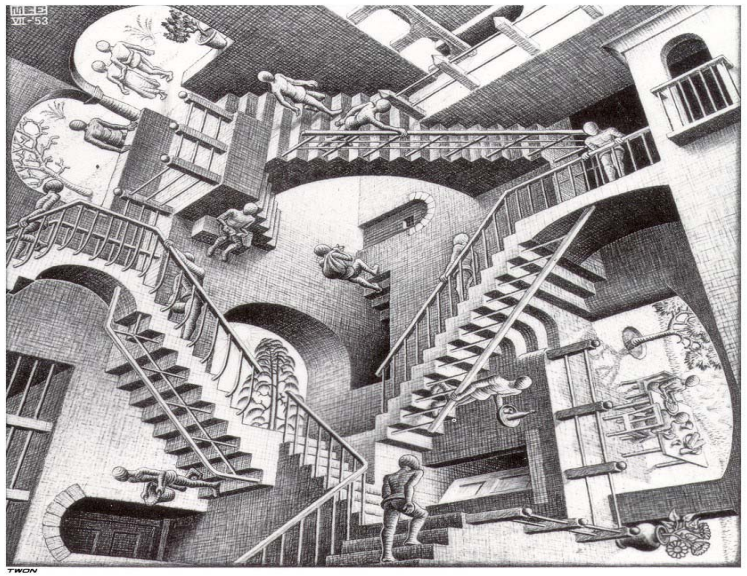
  $\Rightarrow$extended for 2005-2009 but format/convenors change under discussion
- The goal is to enhance discussions and collaborations among members of the community, especially between experimentalists and theorists; to identify promising new lines of research; and possibly to provide scientific expertise 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/

The TeV4LHC Workshop

- Transfer of experience, techniques,…
- Test that can be done with Tevatron data
- Develop further tools/MCs for these colliders

Started: September 2004 FNAL
Final Meeting: 20-22 October 2005 FNAL

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

$$ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2 \ ,$$ k = 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↔UED, Z' ↔ 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 (~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 formalisme in the models, e.g for the definiton of the effective M_{plank} (see G. Landsberg efforts)

Needed: a Forum to discuss/develop these tools & standards?

ED Monte Carlo Generators

Monte Carlo Generators for LHC (Tevatron) analyses

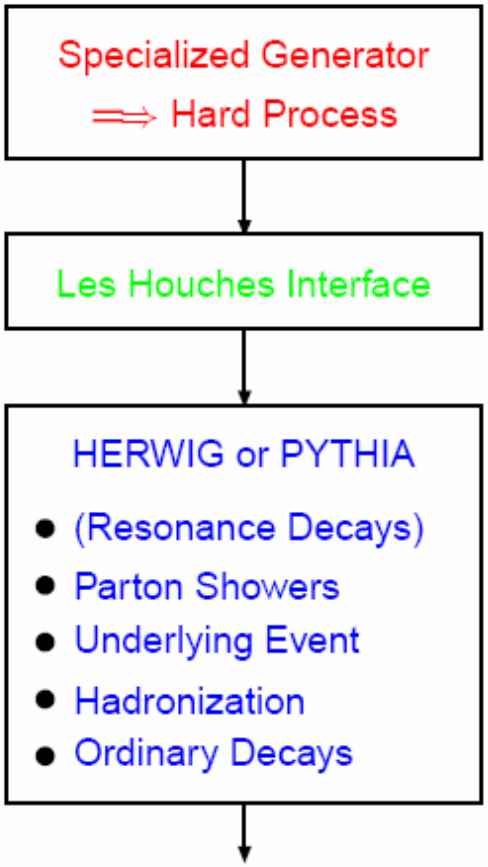
- RS included in standard working horses HERWIG and PYTHIA
  - Spin correlations not complete in PYTHIA e.g. for $G \rightarrow \gamma\gamma$ ZZ, WW (now added: Pythia version 6.226)
- ADD: several private codes for both the graviton radiation and graviton exchange processes, for PYTHIA or HERWIG
  - Recently improved by SHERPA which contains complete ADD FeynmanRules (Gleisberg, Kraus, Matchev) → 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/intitiative

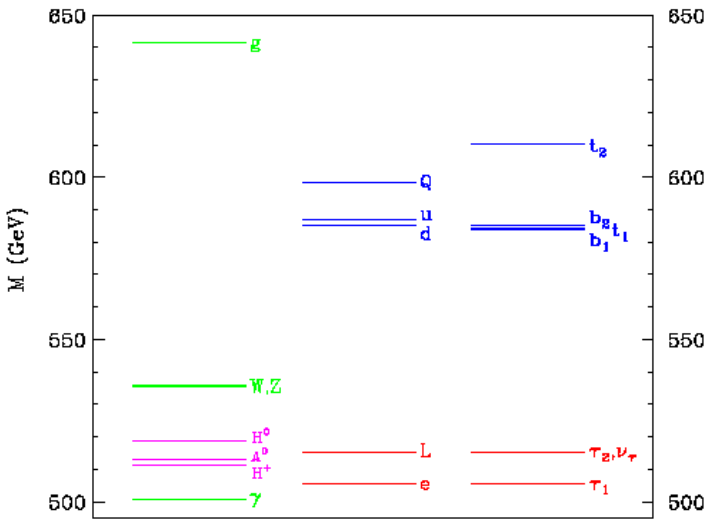
Future ⇒ ThePEG?: a toolkit/framework for HEP event generators
Lonnblad, Gieske, Ribon, Richardson

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^{-1} and RS models, which include many resonances, effects of brane kinematic terms (hep-ph0212279). TeV^{-1} 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_T 2 jet production
  - SUSY+ ED scenarios (modify the phenomenology as in)
  - Thick branes, brain 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

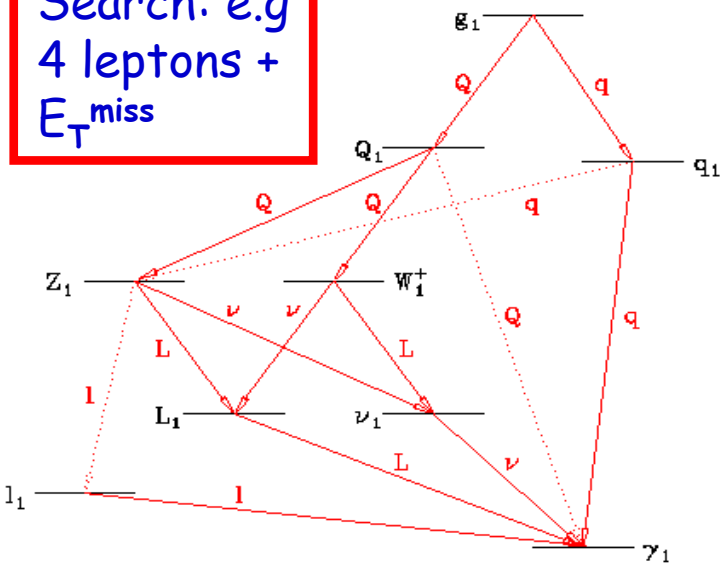


e.g. Cheng, Matchev, Schmaltz hep-ph/0205314

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?

Tools: spin of the "sparticles"/ No heavy higgses/ mass splitting small/pattern repeates at higher energies…

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



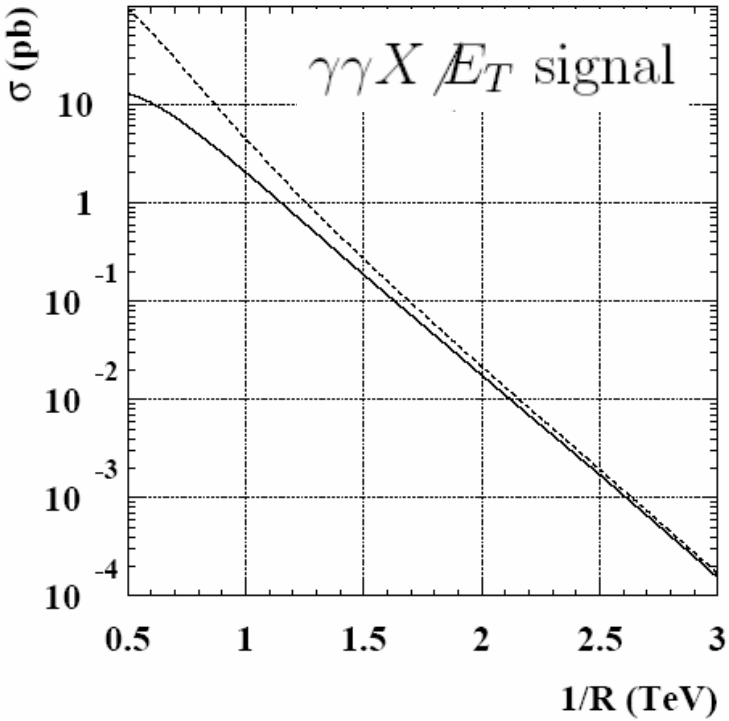
Present implementation in Comphep (Matchev et al.)
Problem: for long decay chain e.g. up to 10 particles/partons in the final state it is difficult to compute with all the spin correlations correctly and time consuming. Some tricks to improve being explored (E. Boos)

Example: UED without KK conservation

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

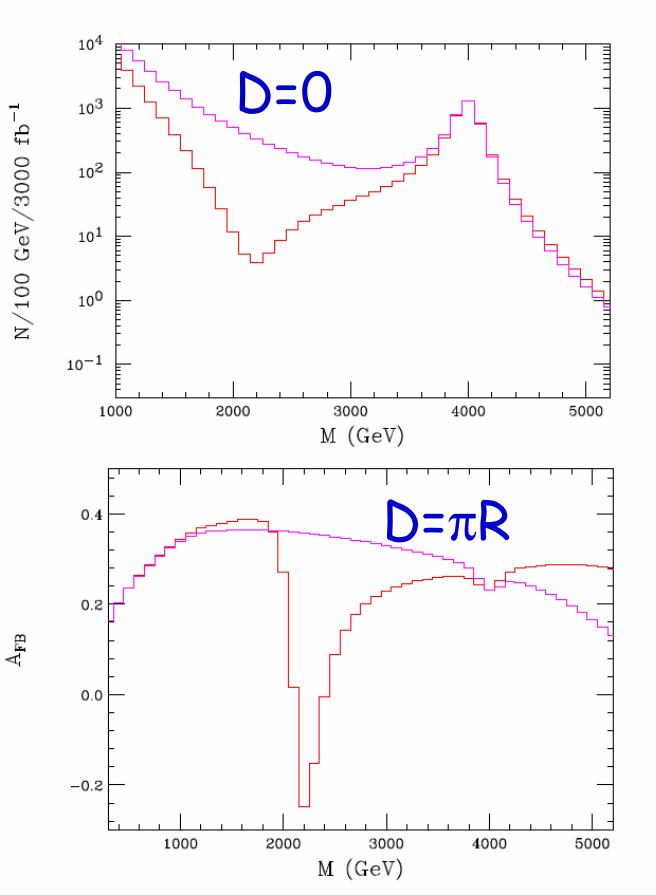
- Pair production
  - E.g. $\gamma^* \rightarrow \gamma$ + KK graviton
  - Signal for LHC 2 photons + large missing ET
- Single production
  - E.g. $gg \rightarrow gg^* \rightarrow gg$+KK graviton
  - Signal for LHC: 2 jets + large missing ET
- Useful to check sensitivity/reach for the LHC by experiments,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

Macesanu, McMullen, Nandi

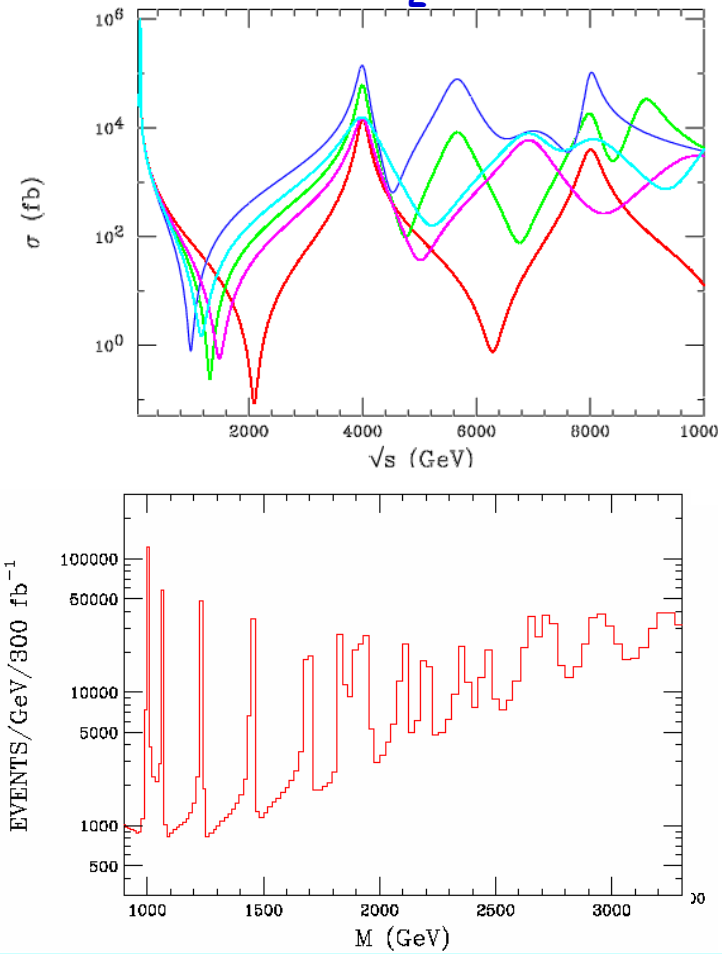


Example: Z'/KK studies in TeV^{-1} EDs

Different γ/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)

Example: Rigid/Soft Branes

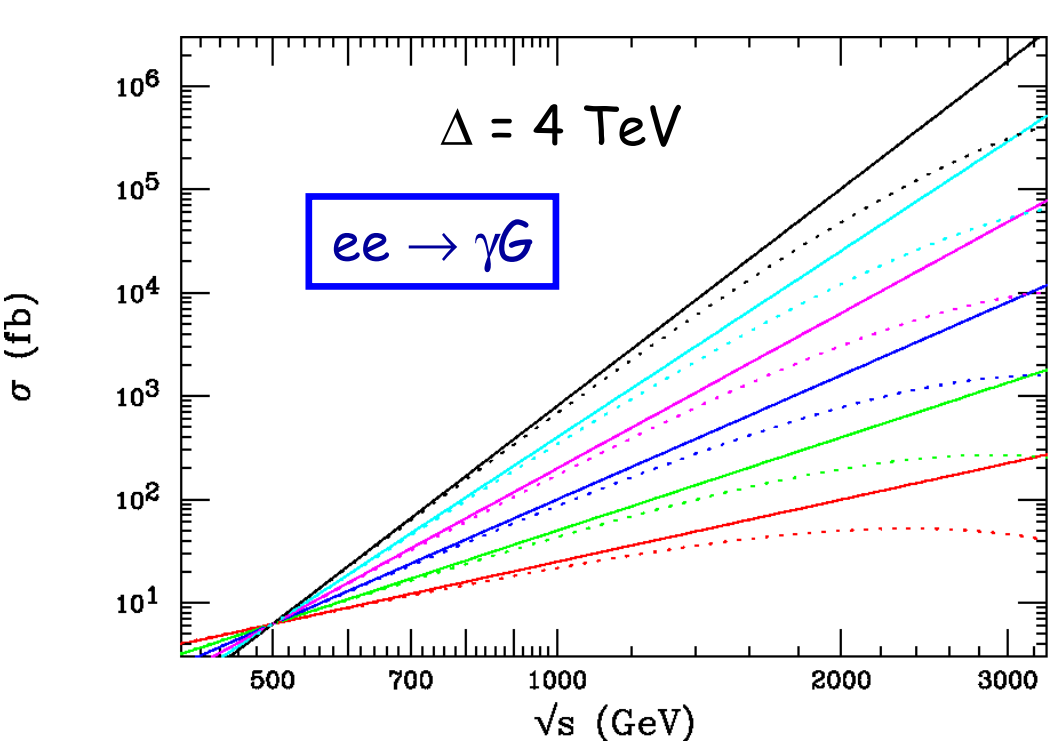
ADD Models

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

Soft branes: Coupling of higher mass KK towers reduced

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

could have any value but expected ~ O(TeV)



n = 7

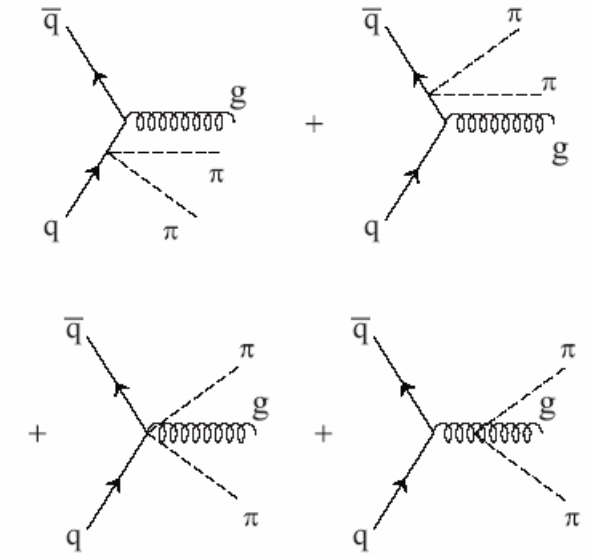
n = 2

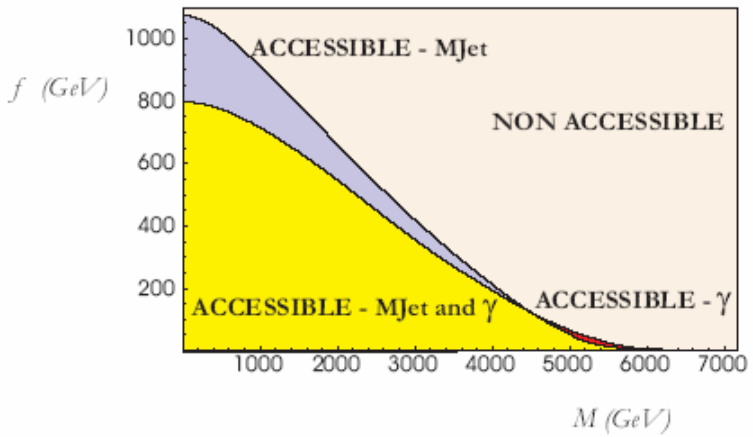
M_D's fixed to agree with M_D=5 TeV, n=2

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

Example: Branons

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





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

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

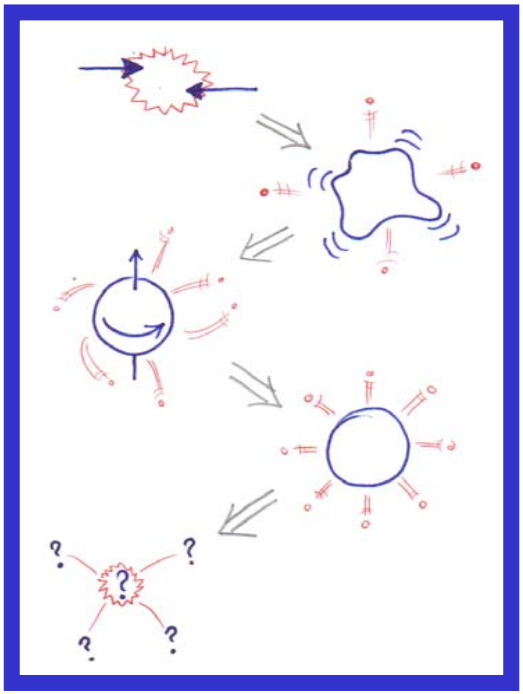
Example: Black Holes

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

Ch. Lester/Prague 2003

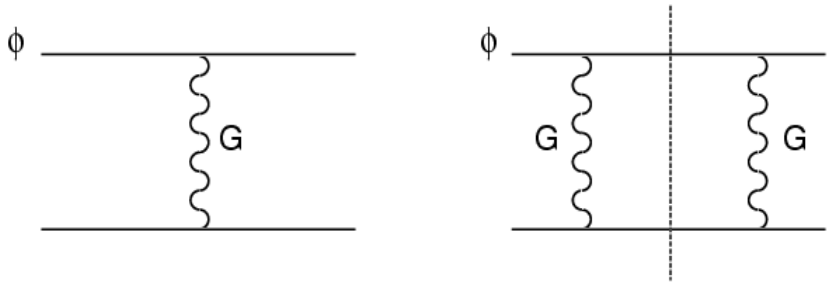
Stage	Need a Quantum Theory of Gravity?	Scale	In Event Generators ?
Production	Yes and No	$>M_P$	πr^2
"Hair Loss"	No	$>M_P$	No
Spin Down	No	$>M_P$	No
Hawking Radiation	Yes and No	$>M_P$ $\sim M_P$	Yes
Remnant Decay	Yes	$<M_P$	Many options

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



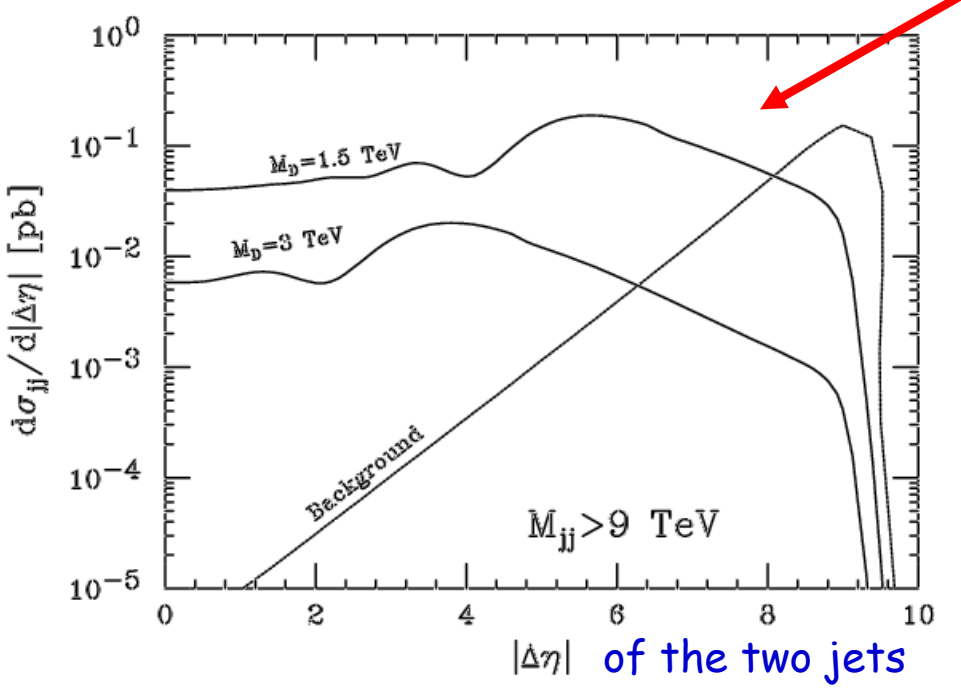
Example: Transplanckian Effects

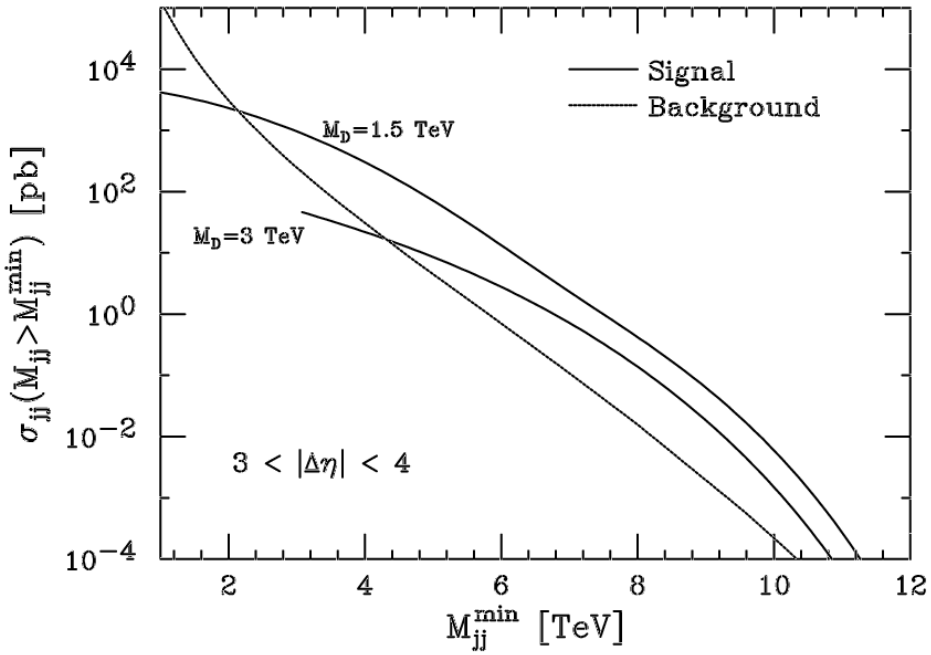
Once you pass the Planck scale $\sqrt{s} >> M_D$...



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!!

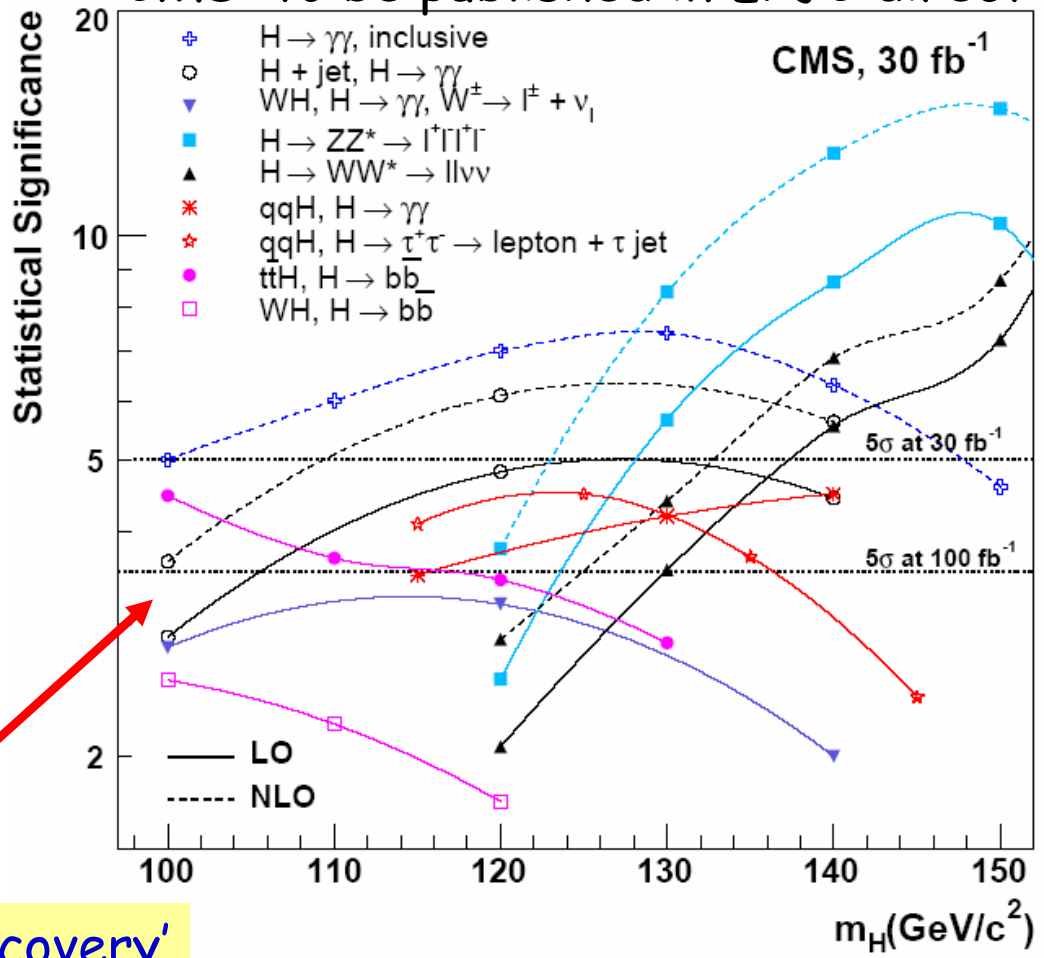
Higher QCD corrections/K factors

- 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 there sensitivity. Sometimes important effects on the sensitivity which may reclassify a process as being accessible (or vice versa)

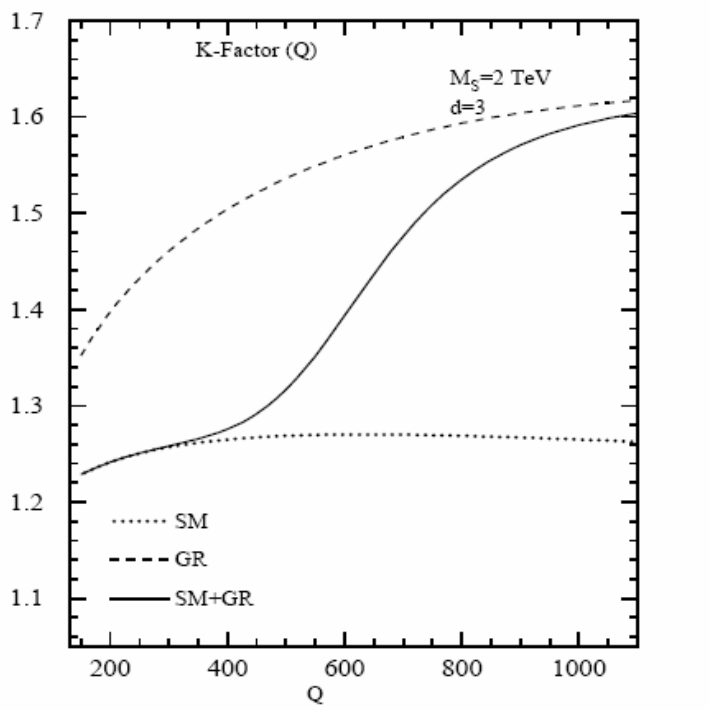
CMS: to be published in EPJC direct



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
$pp \rightarrow G \rightarrow 2$ leptons



Q= invariant mass of the Lepton Pair in DY production

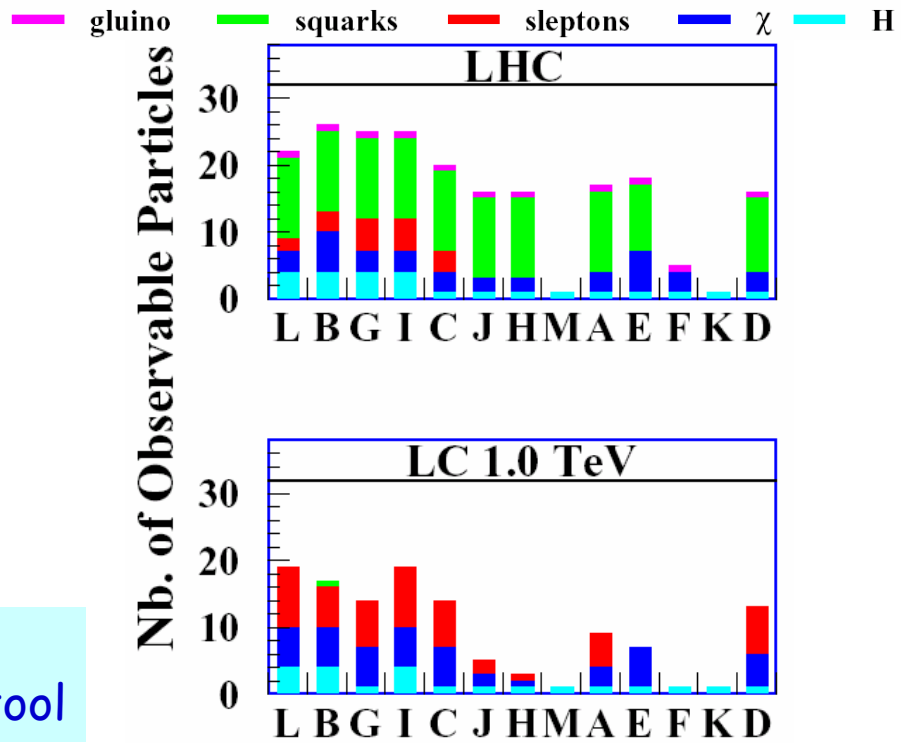
Note:
- K factor for gravity channel is large: ~1.6
- Drell-Yan K factor is lower. Can change the search sensitivity by ~50%

What about RS $G \rightarrow 2$ leptons? same!
What about $G \rightarrow \gamma\gamma$? not same!

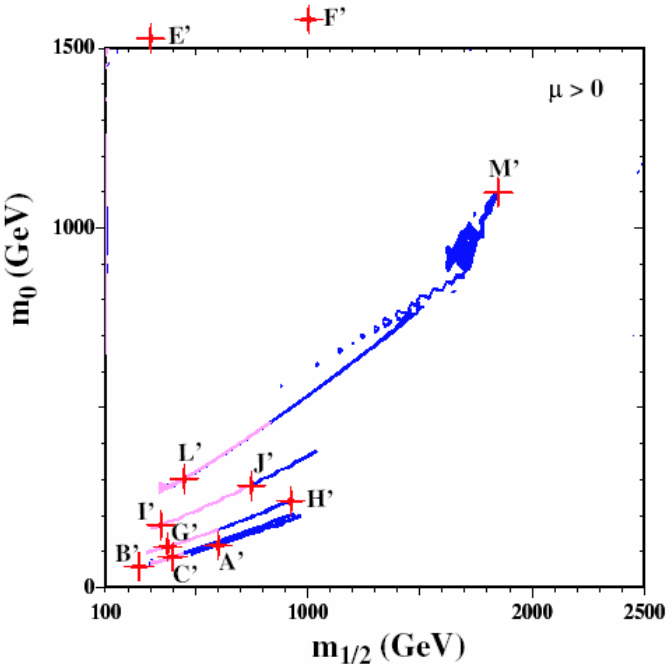
K factors can make a difference!
Already useful now for Tevatron
$\Rightarrow$ We encourage more K-factor determinations

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 ($b \to s\gamma$), g_μ-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?

Constrains 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)
- Newtons law works down to 200μm

$\delta = 3$ R= 3 nm

$\delta = 4$ R= 6×10^{-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 $\sim\lambda/M_S^4$(Hewett), where λ 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 Λ_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 $\sim F/M_S^4$(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:

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

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

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

- Rule of thumb:

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

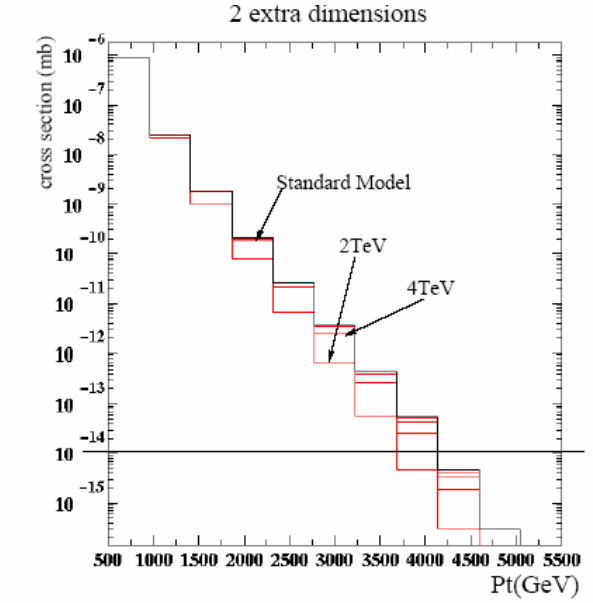
$$\Lambda_T(\text{GRW}) = M_S(\text{HLZ})\big|_{n=4}$$

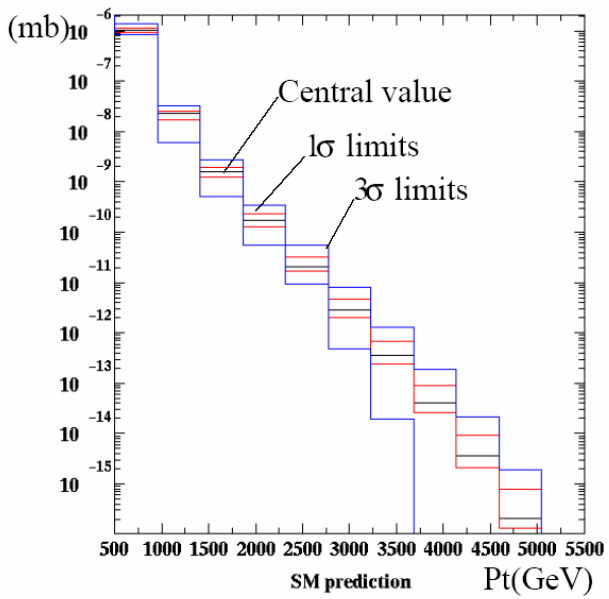
Useful to agree on a unique formalism

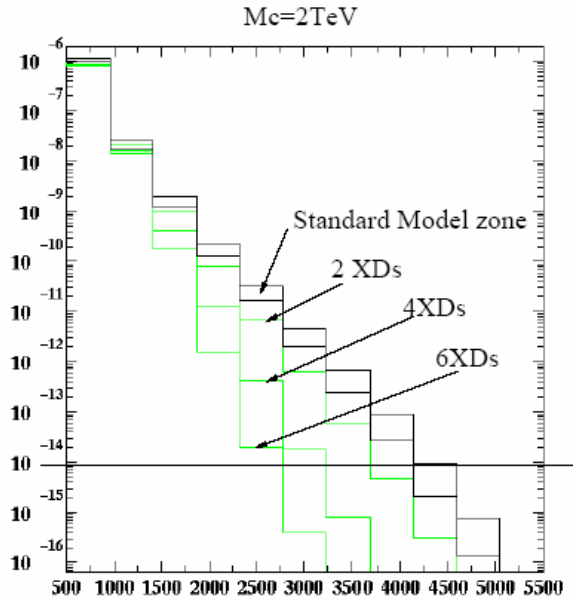
Precise knowledge of the SM background

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

Tev4LHC & HERA/LHC workshop

Other important SM background channel: Drell-Yan production

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

So far

- Good meeting at BNL (February) with a number of interested people (volunteers?)
  - D. Bourlikov
  - T. Han
  - K. Matchev (+ one Florida student?)
  - F. Kraus + one student?
  - T. Tait
  - S. Mrenna
  - M. Besancon
  - + a few others
- No real work started yet: Guess it is time to start.
- Les Houches traditionally excellent place for initiating something like this!