Probing Quantum Gravity in the Lab

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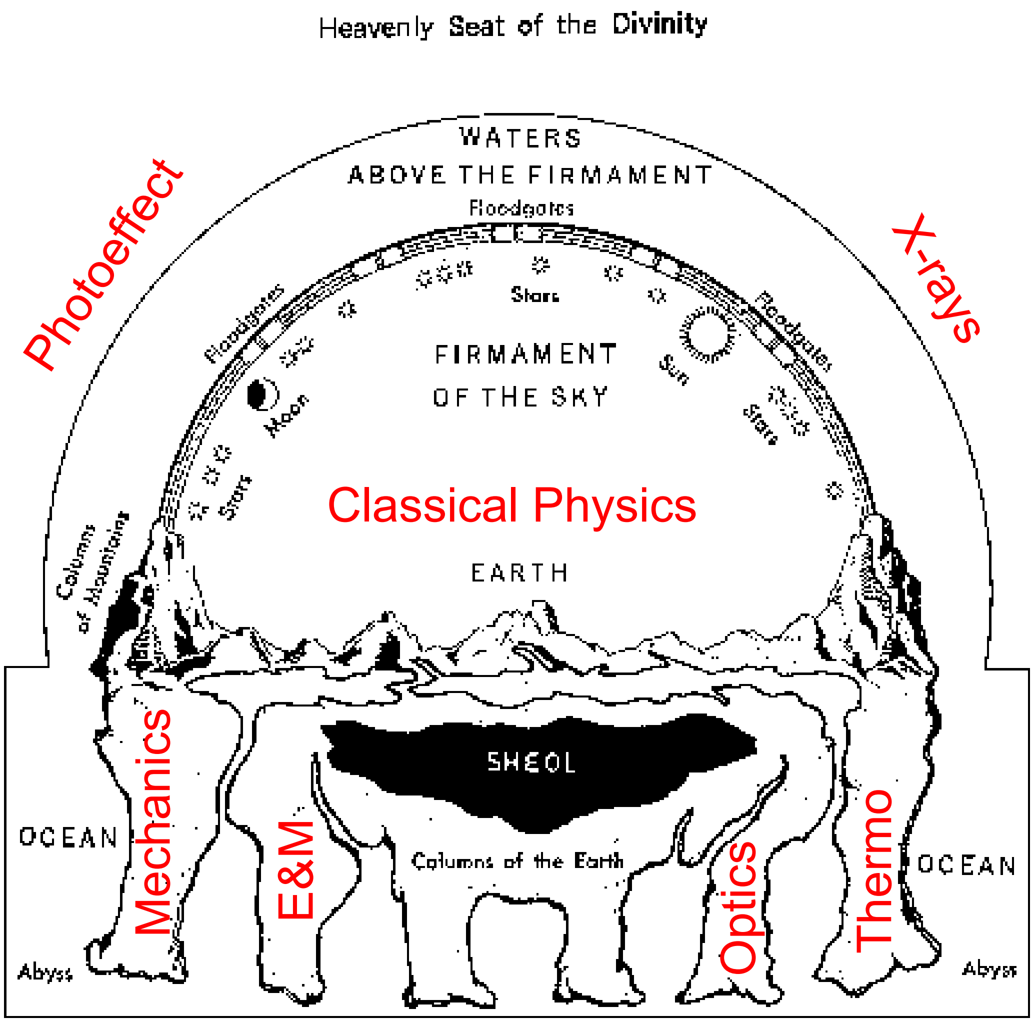
String Phenomenology Workshop

August 4, 2003

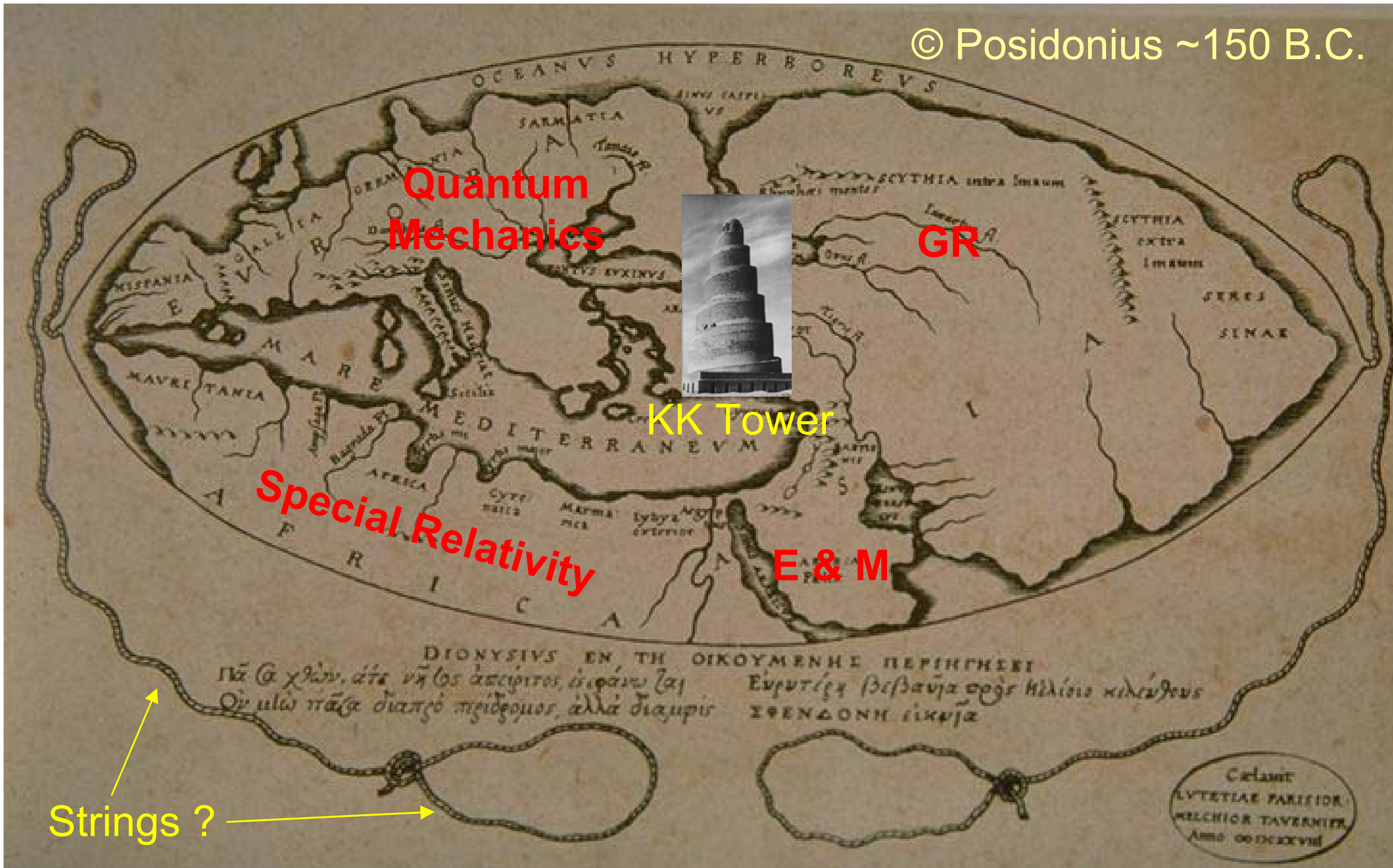
Outline

- Brief History of Strings
- More Fun in Extra Dimensions
  - ADD Model
  - TeV^{-1} Scenario
  - RS Model
  - Universal Extra Dimensions
- Current Constraints on Models with Extra Dimensions
  - Gravity at Short Distances
  - Cosmology and Astrophysics
  - Collider Probes
- Conclusions

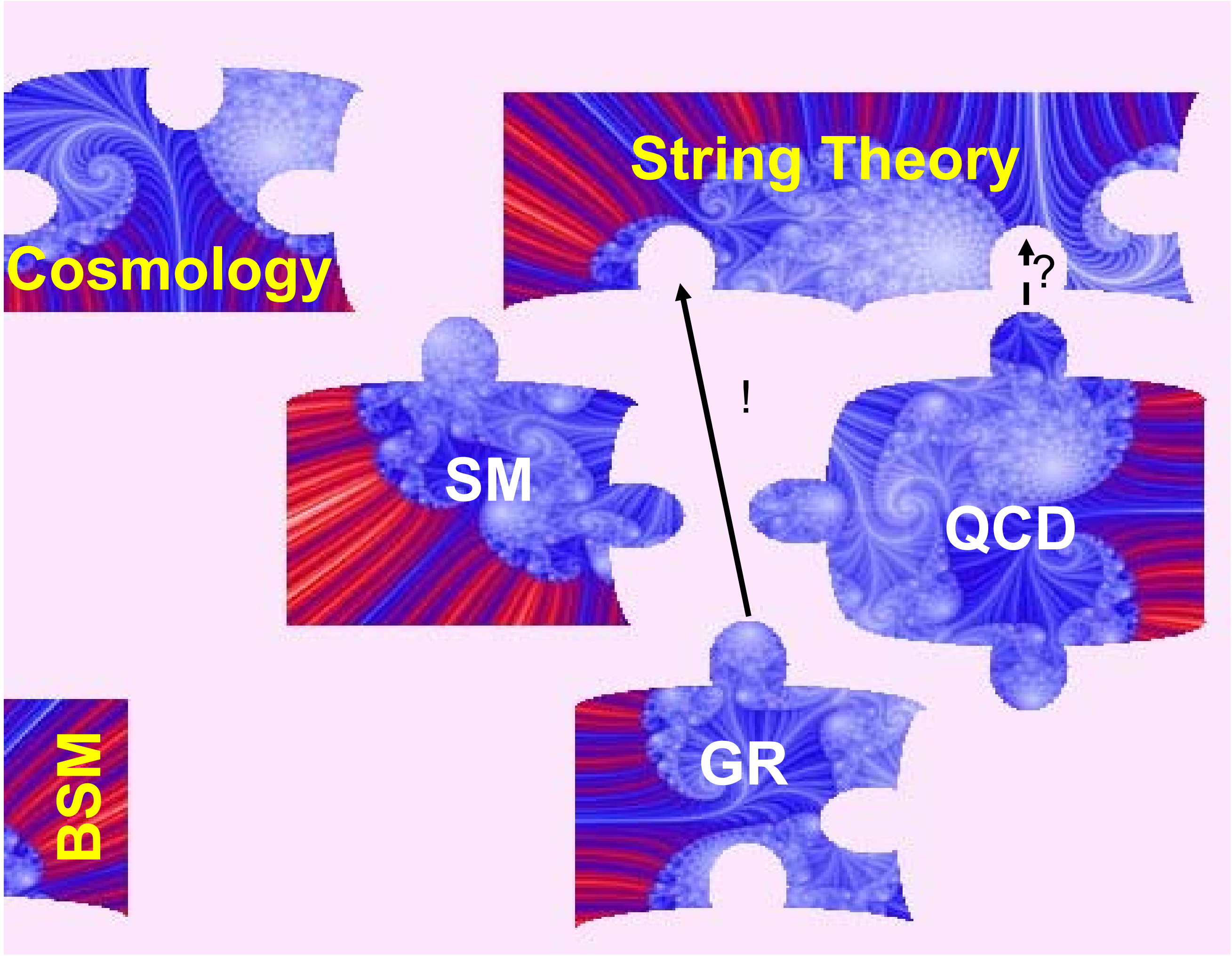
Just A Century Ago…



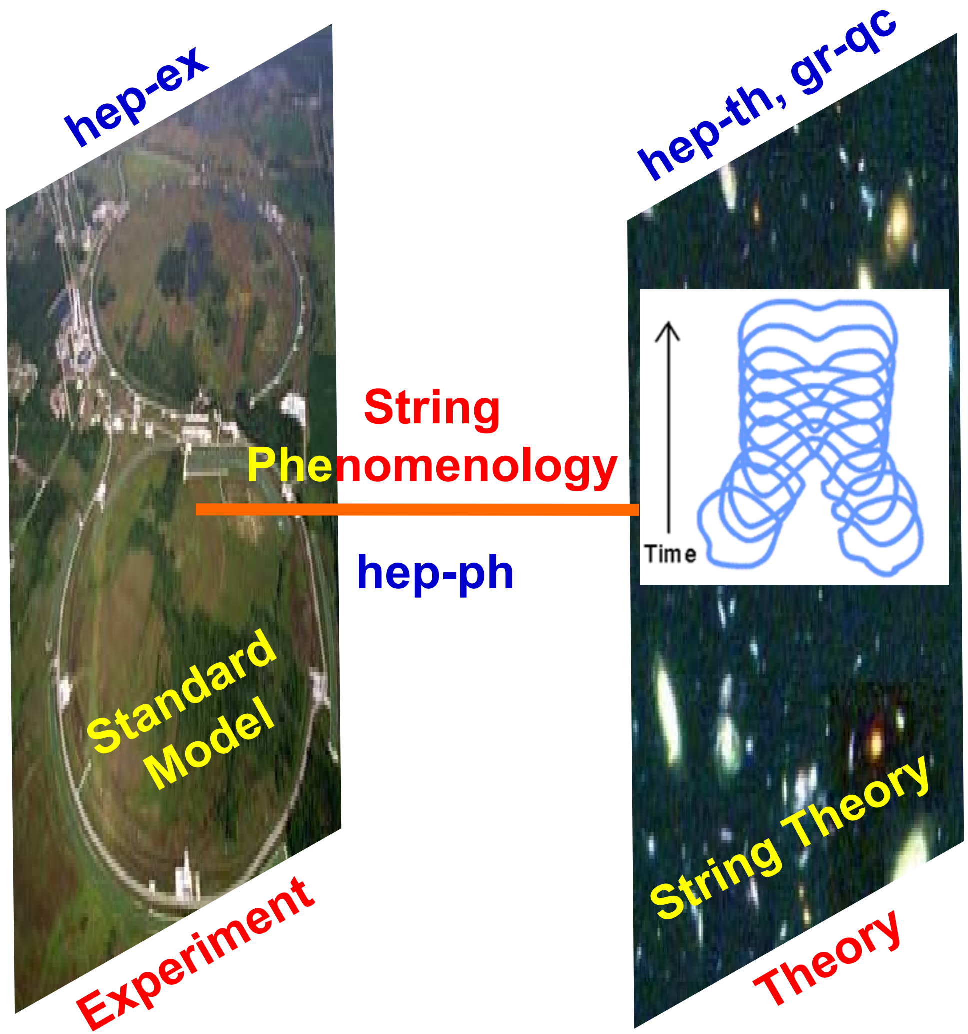
The Thirties



The Seventies

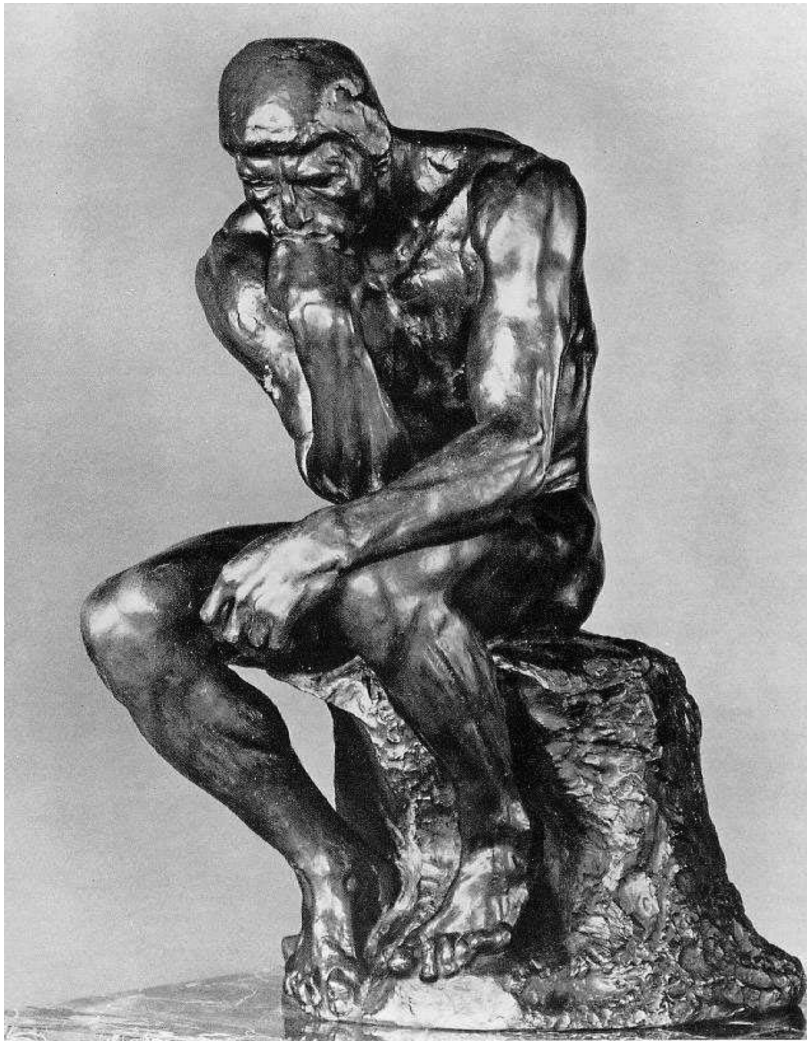


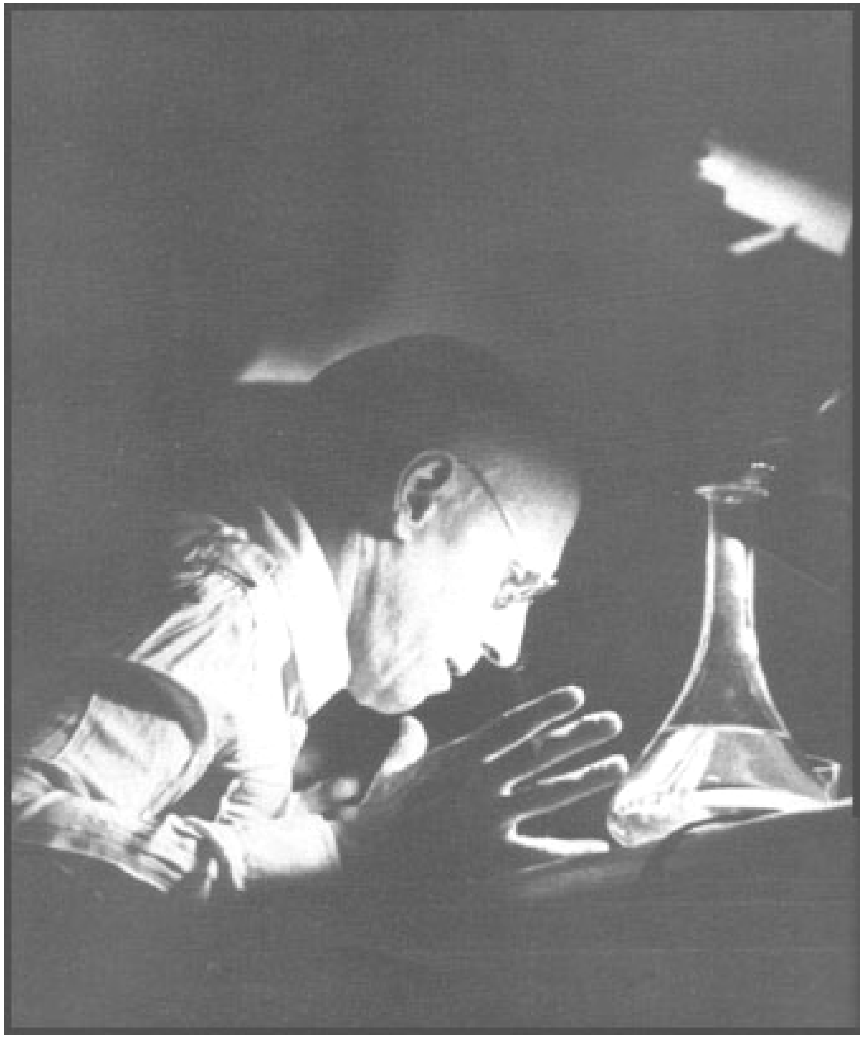
The Nineties



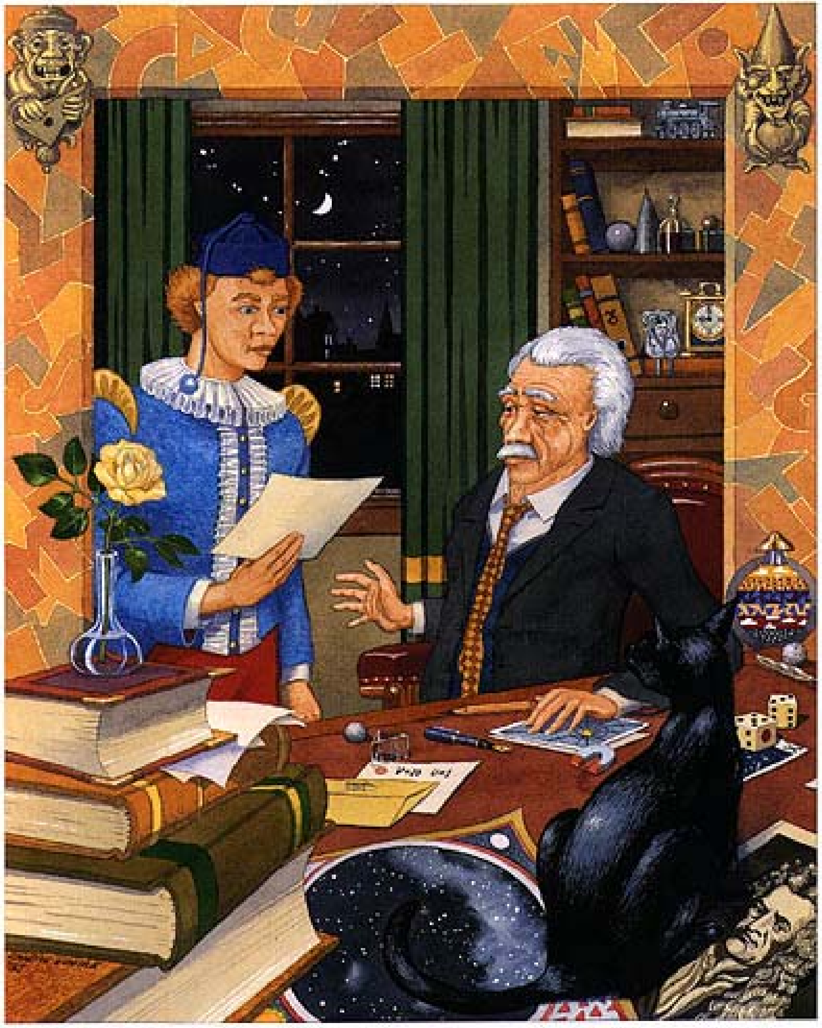
- Late nineties: “Velvet” Revolution in String Theory
  - Large and TeV-size Extra Dimensions
  - Randall-Sundrum
  - NCQFT
  - …
- Not noticed by string theorists for some time
  - Revolution in psychology: string theory meets the experiment
- Birth of String Phenomenology
  - Glasgow BSM Meeting (Y2K)

String Theory Meets the Experiment

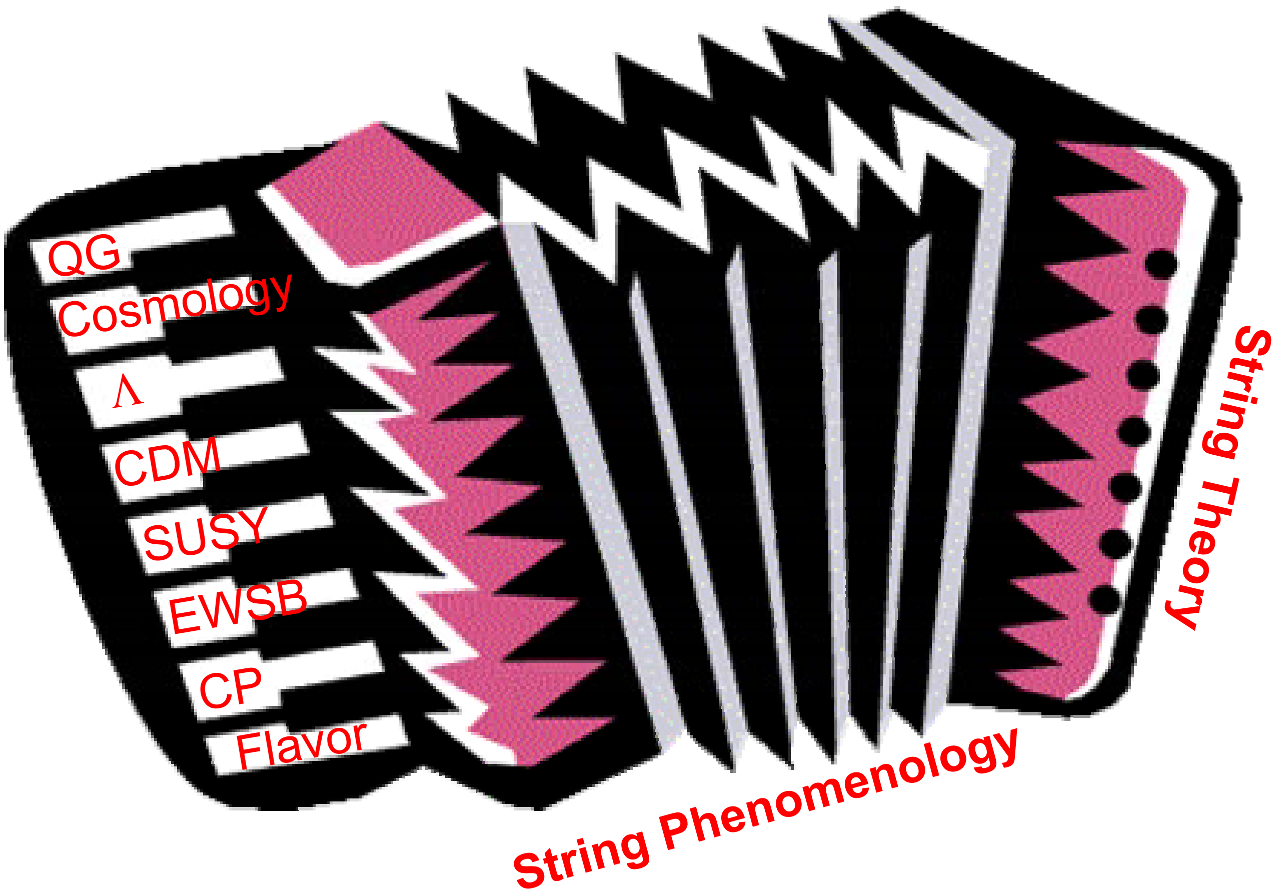




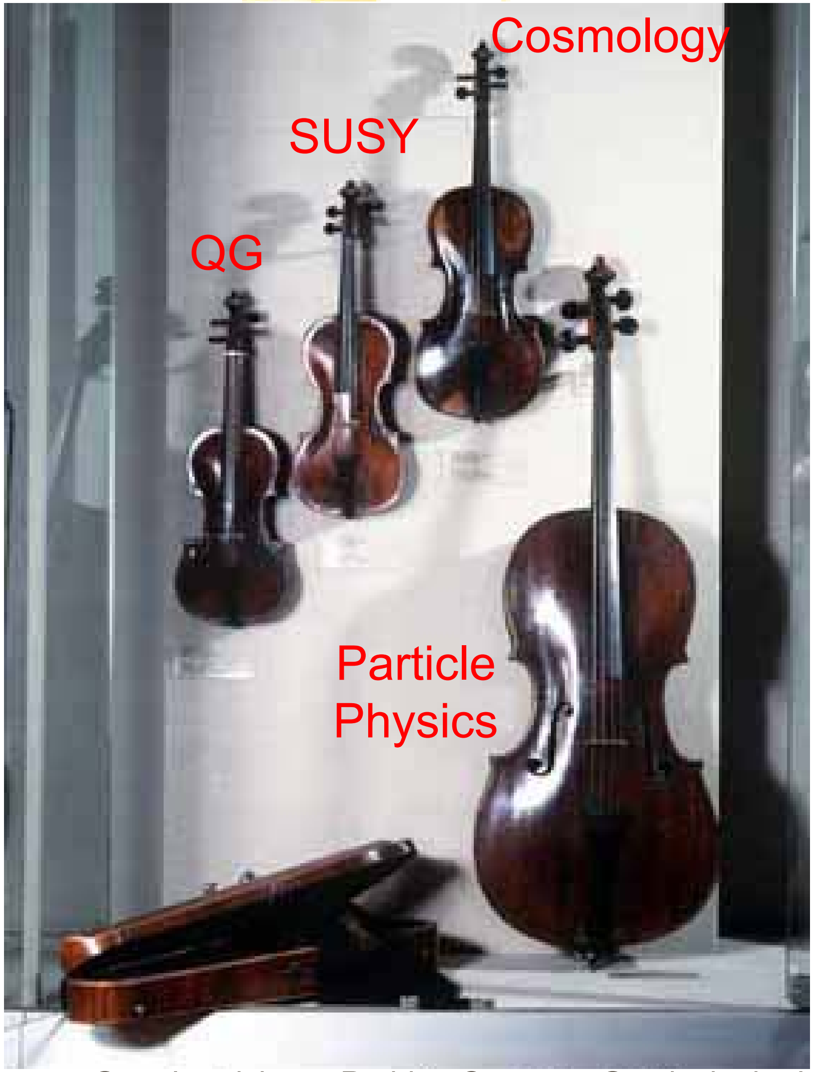
String Theory Meets the Experiment



The 20??-ies?


QG
Cosmology
Λ
CDM
SUSY
EWSB
CP
Flavor
String Phenomenology
String Theory

The 20??-ies?



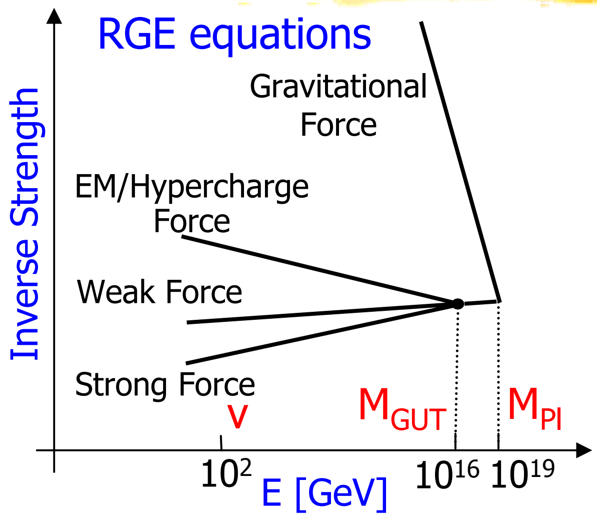
Math Meets Physics?

- Math physics: some dimensionalities are quite special
- Example: Laplace equation in two dimensions has logarithmic solution; for any higher number of dimensions it obeys power law instead
- Some of these peculiarities exhibit themselves in condensed matter physics, e.g. diffusion equation solutions allow for long-range correlations in 2D-systems (cf. flocking)
- Modern view in topology: one dimension is trivial; two and three spatial dimensions are special (properties are defined by the topology); any higher number is not
- Do we *live* in a special space, or only *believe* that we are special?

A $1B Question

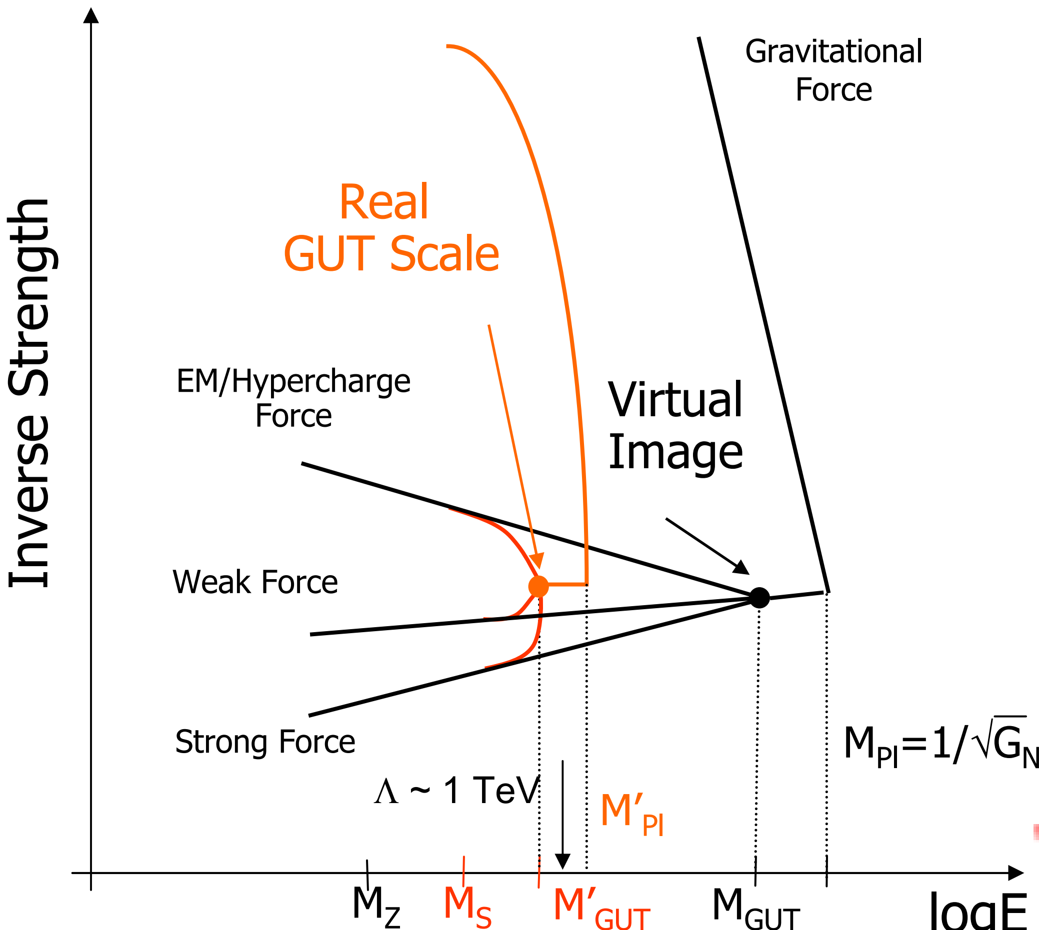
- Can we use extra dimensions of string theory to solve the hierarchy problem?

Life Beyond the Standard Model



- The natural m_H value is Λ, where Λ is the scale of new physics; if SM is the ultimate theory up to GUT scale, an extremely precise $(\sim(v/m_{GUT})^2)$ fine-tuning is required
- We must conclude that the SM is an effective theory, i.e. a low-energy approximation of a more complete model that explains things only postulated in the SM
- This new theory takes over at a scale Λ comparable to the mass of the Higgs boson, i.e. $\Lambda \sim 1$ TeV
- But: the large hierarchy of scales picture is based *solely* on the log extrapolation of gauge couplings by some 14 decades in energy
  - How valid is that?
- 1998: abstract mathematics meets phenomenology. Extra spatial dimensions have been first used to:
  - "Hide" the hierarchy problem by making gravity as strong as other gauge forces in (4+n)-dimensions (Arkani-Hamed, Dimopoulos, Dvali) – ADD
  - Explore modification of the RGE in (4+n)-dimensions to achieve low-energy unification of the gauge forces (Dienes, Dudas, Gherghetta)

Extra Dimensions at Work



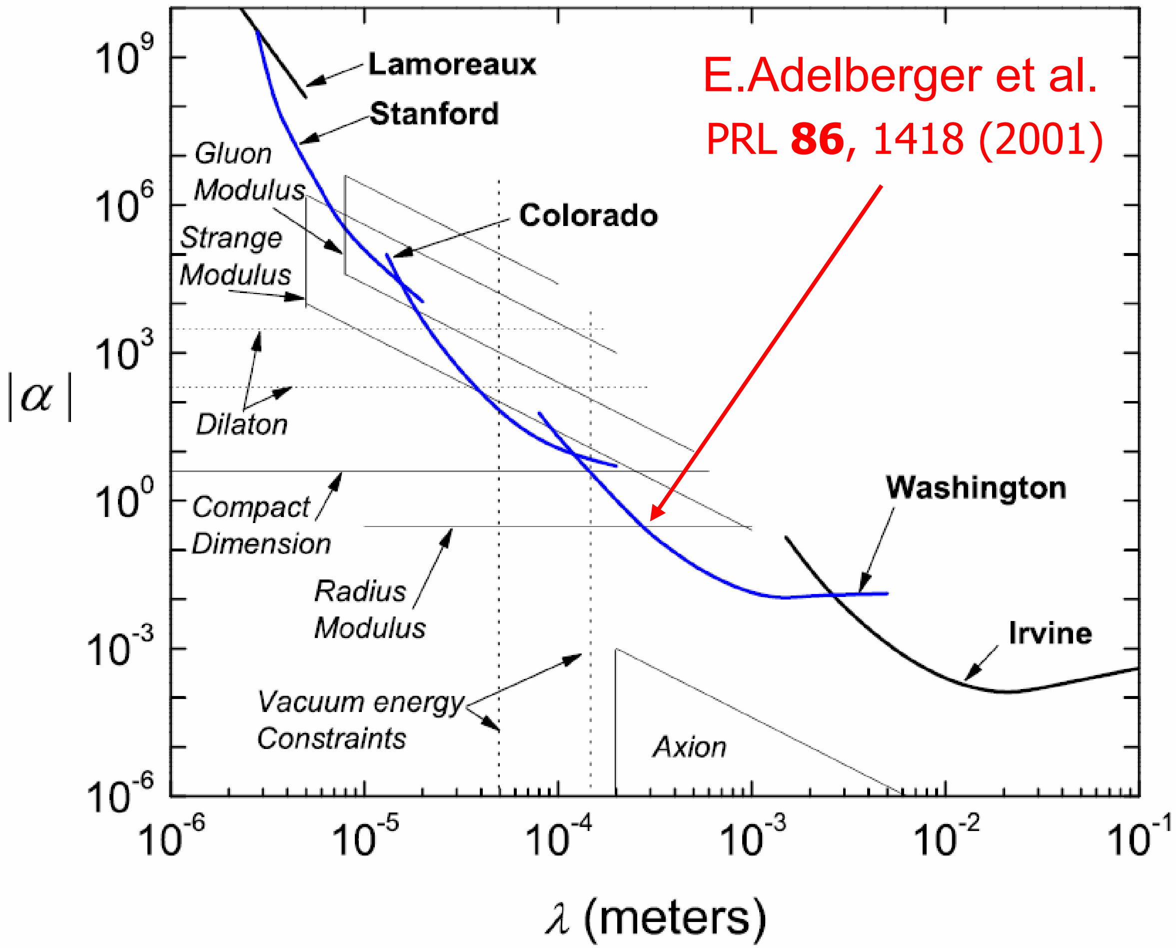
- Burst of the ideas to follow:
  - 1999: possible *rigorous* solution of the hierarchy problem by utilizing metric of curved anti-deSitter space (Randall, Sundrum)
  - 2000: “democratic” (universal) extra dimensions, equally accessible by all the SM fields (Appelquist, Chen, Dobrescu)
  - 2001: “contracted” extra dimensions – use them and then lose them (Arkani-Hamed, Cohen, Georgi)
- All these models result in rich low-energy phenomenology

Using the Extra Dimension Paradigm

- EWSB from extra dimensions:
  - Hall, Kolda [PL **B459**, 213 (1999)] (lifted Higgs mass constraints)
  - Antoniadis, Benakli, Quiros [NP **B583**, 35 (2000)] (EWSB from strings in ED)
  - Cheng, Dobrescu, Hill [NP **B589**, 249 (2000)] (strong dynamics from ED)
  - Mirabelli, Schmaltz [PR **D61**, 113011 (2000)] (Yukawa couplings from split left- and right-handed fermions in ED)
  - Barbieri, Hall, Namura [hep-ph/0011311] (radiative EWSB via t-quark in the bulk)
- Flavor/CP physics from ED:
  - Arkani-Hamed, Hall, Smith, Weiner [PRD **61**, 116003 (2000)] (flavor/CP breaking fields on distant branes in ED)
  - Huang, Li, Wei, Yan [hep-ph/0101002] (CP-violating phases from moduli fields in ED)
- Neutrino masses and oscillations from ED:
  - Arkani-Hamed, Dimopoulos, Dvali, March-Russell [hep-ph/9811448] (light Dirac neutrinos from right-handed neutrinos in the bulk or light Majorana neutrinos from lepton number breaking on distant branes)
  - Dienes, Dudas, Gherghetta [NP **B557**, 25 (1999)] (light neutrinos from right-handed neutrinos in ED or ED see-saw mechanism)
  - Dienes, Sarcevic [PL **B500**, 133 (2001)] (neutrino oscillations w/o mixing via couplings to bulk fields)
- Many other topics from Higgs to dark matter

Constraints from Gravity Experiments

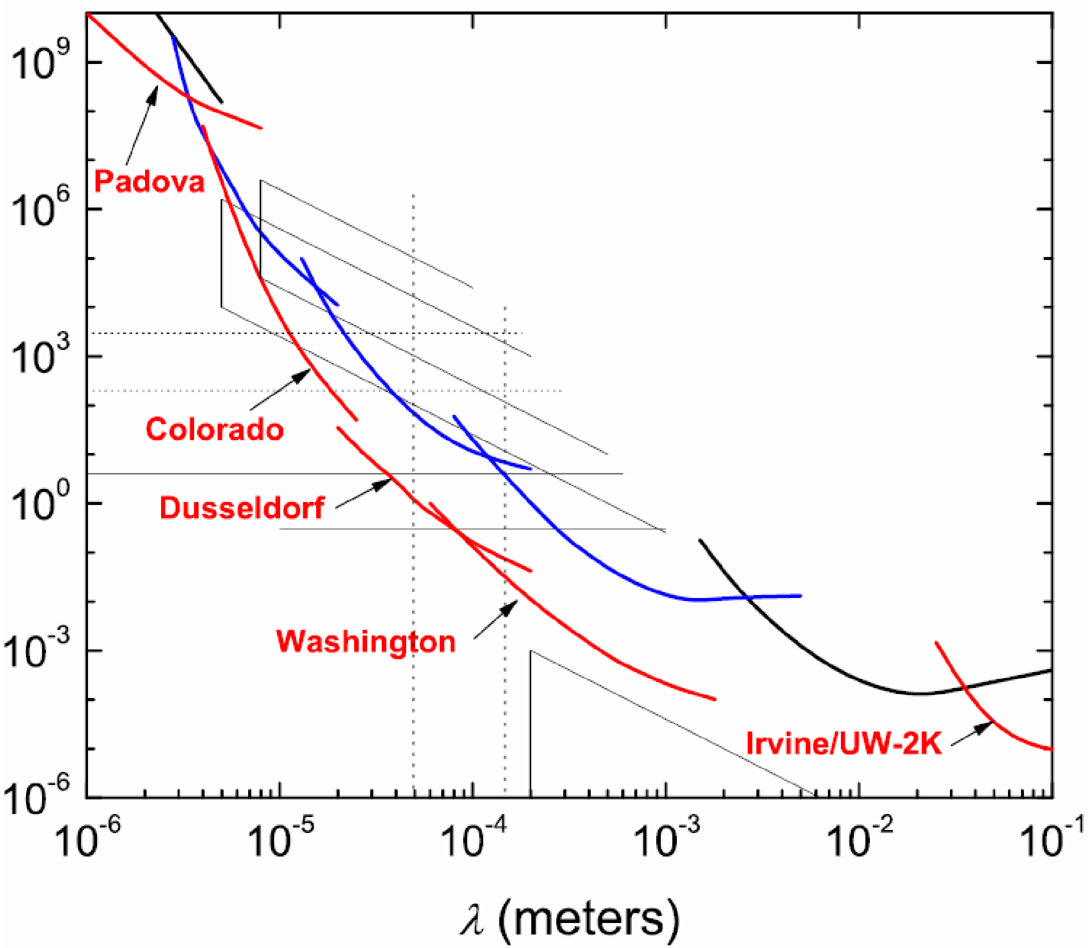
[J. Long, J. Price, hep-ph/0303057]



- Sub-millimeter gravity measurements could probe n=2 case in the ADD hypothesis
- The best sensitivity so far have been achieved in the U of Washington torsion balance experiment – a high-tech "remake" of the 1798 Cavendish experiment
  - $R \lesssim 0.15$ mm ($M_D \gtrsim 4$ TeV)
- Sensitivity vanishes quickly with the distance – can't push limits further down significantly
- Started restricting ADD with 2 extra dimensions; can't probe any higher number
- Ultimately push the sensitivity by a factor of two in terms of the distance

Constraints from Gravity Experiments: Future

[J. Long, J. Price, hep-ph/0303057]



Astrophysical and Cosmological Constraints

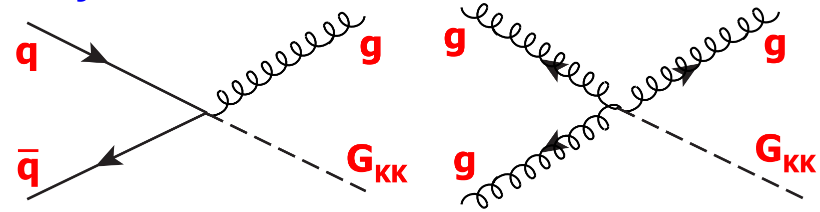
- Supernova cooling due to graviton emission – an alternative cooling mechanism that would decrease the dominant cooling via neutrino emission
  - Tightest limits on any additional cooling sources come from the measurement of the SN1987A neutrino flux by the Kamiokande and IMB
  - Application to the ADD scenario [Cullen and Perelstein, PRL **83**, 268 (1999); Hanhart, Phillips, Reddy, and Savage, Nucl. Phys. **B595**, 335 (2001)]:
  - M_D > 25-30 TeV (n=2)
  - M_D > 2-4 TeV (n=3)
- Distortion of the cosmic diffuse gamma radiation (CDG) spectrum due to the $G_{KK} \to \gamma\gamma$ decays [Hall and Smith, PRD **60**, 085008 (1999)]:
  - M_D > 100 TeV (n=2)
  - M_D > 5 TeV (n=3)
- Overclosure of the universe, matter dominance in the early universe [Fairbairn, Phys. Lett. **B508**, 335 (2001); Fairbairn, Griffiths, JHEP 0202, **024** (2002)]
  - M_D > 86 TeV (n=2)
  - M_D > 7.4 TeV (n=3)
- Neutron star γ-emission from radiative decays of the gravitons trapped during the supernova collapse [Hannestad and Raffelt, PRL **88**, 071301 (2002)]:
  - M_D > 1700 TeV (n=2)
  - M_D > 60 TeV (n=3)
- Caveat: there are many known (and unknown!) uncertainties, so the cosmological bounds are reliable only as an order of magnitude estimate
- Still, n=2 is largely disfavored

Collider Signatures for Large Extra Dimensions

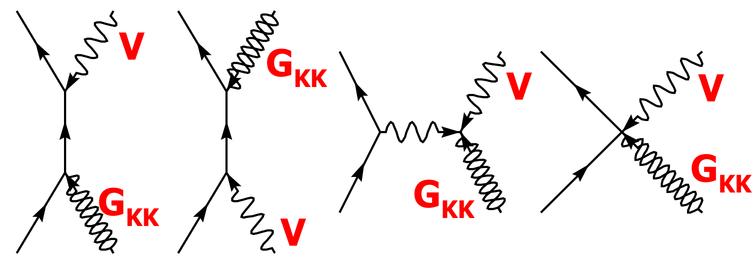
- Kaluza-Klein gravitons couple to the momentum tensor, and therefore contribute to most of the SM processes
- For Feynman rules for G_{KK} see:
  - Han, Lykken, Zhang, PR **D59**, 105006 (1999)
  - Giudice, Rattazzi, Wells, Nucl. Phys. **B544**, 3 (1999)
- Since graviton can propagate in the bulk, energy and momentum are not conserved in the G_{KK} emission from the point of view of our 3+1 space-time
- Since the spin 2 graviton in generally has a bulk momentum component, its spin from the point of view of our brane can appear as 0, 1, or 2
- Depending on whether the G_{KK} leaves our world or remains virtual, the collider signatures include single photons/Z/jets with missing E_T or fermion/vector boson pair production

Real Graviton Emission

Monojets at hadron colliders

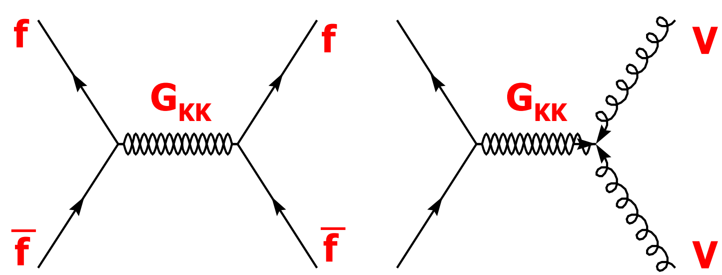


Single VB at hadron or e^+e^- colliders



Virtual Graviton Emission

Fermion or VB pairs at hadron or e^+e^- colliders



LEP2 Constraints

Experiment	$e^+e^- \to \gamma G$					$e^+e^- \to ZG$				
	n=2	n=3	n=4	n=5	n=6	n=2	n=3	n=4	n=5	n=6
ALEPH	1.28	0.97	0.78	0.66	0.57	0.35	0.22	0.17	0.14	0.12
DELPHI	1.38	**1.02**	0.84	**0.68**	0.58					
L3	1.02	0.81	0.67	0.58	0.51	0.60	0.38	0.29	**0.24**	**0.21**
OPAL	1.09	0.86	0.71	0.61	0.53					

Color coding
≤184 GeV
≤189 GeV
>200 GeV
λ=-1 **λ=+1** **GL**

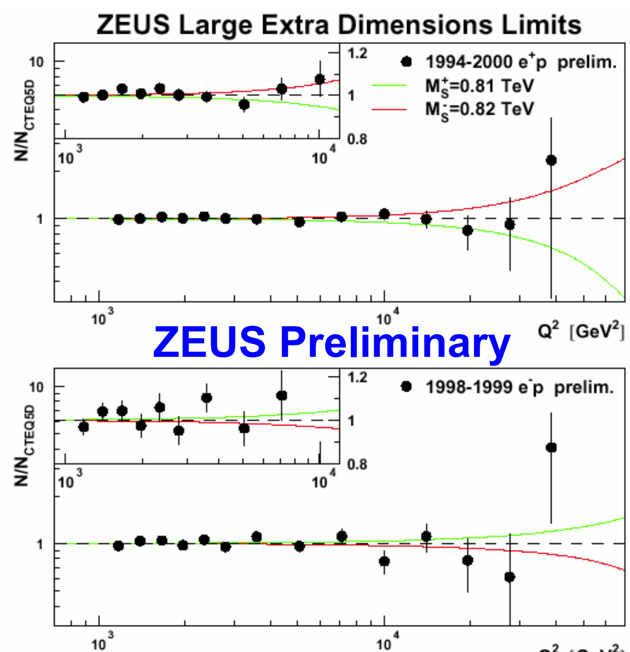
Virtual Graviton Exchange [M_S(Hewett)]

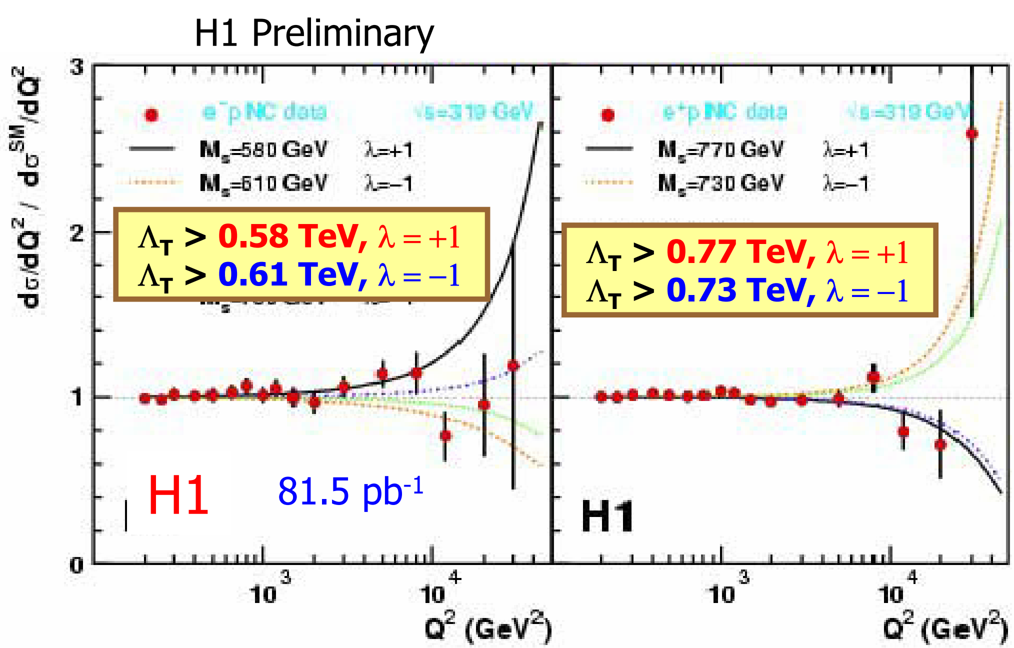
Experiment	e^+e^-	$\mu^+\mu^-$	$\tau^+\tau^-$	qq	ff	$\gamma\gamma$	WW	ZZ	**Combined**
ALEPH	1.04 0.81	0.65 0.67	0.60 0.62	0.53/0.57 0.46/0.46 (bb)	1.05 0.84	0.81 0.82			0.75/1.00 (<189)
DELPHI		0.59 0.73	0.56 0.65		0.60 0.76	0.83 0.91			0.60/0.76 (ff) (<202)
L3	0.98 1.06	0.56 0.69	0.58 0.54	0.49 0.49	0.84 1.00	0.99 0.84	0.68 0.79		1.1/1.0 (<202)
OPAL	1.15 1.00	0.62 0.66			0.62 0.66	0.89 0.83		0.63 0.74	1.17/1.03 (<209)

LEP Combined: 1.2/1.1

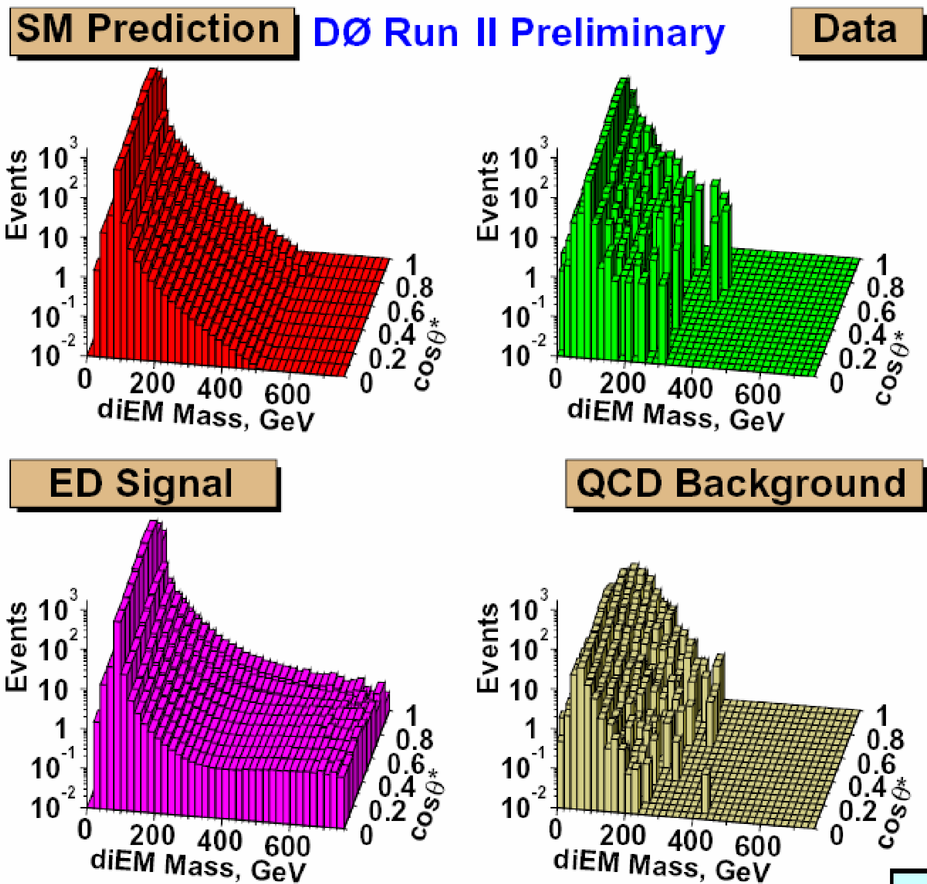
HERA Search for Virtual Graviton Effects

- $e^{\pm}p \rightarrow e^{\pm}p$
  - t-channel exchange, similar to Bhabha scattering diagrams; based on the GRW formalism (both H1 and ZEUS in fact set limits on Λ_T, but call it M_S)
  - Usual SM, Z/γ^* interference, and direct G_{KK} terms
  - Analysis method: fit to the $d\sigma/dQ^2$ distribution
  - Current H1 limits: Λ_T > 0.82/0.78 TeV (M_S > 0.73/0.70 TeV)
  - Current ZEUS limits: Λ_T > 0.81/0.82 TeV (M_S > 0.72/0.73 TeV)
  - Expected sensitivity up to 1 TeV with the ultimate HERA data set





Hadron Colliders: Virtual Graviton Effects



Run II, 130 pb^{-1}

- High-mass, low |cosθ| tail is a characteristic signature of LED [Cheung, GL, PRD **62** 076003 (2000)]
- 2-dimensional method resolves this tail from the high-mass, high |cosθ| tail due to collinear divergencies in the SM diphoton production
- Best limits on the effective Planck scale come from the DØ Run I data:
  - M_S(Hewett) > 1.1/1.1 TeV ($\lambda = +1/-1$)
  - Λ_T(GRW) > 1.3 TeV
  - M_S(HLZ) > 1.0-1.4 TeV (n=2-7)
- Combined with Run I DØ result:
  - Λ_T(GRW) > 1.4 TeV – tightest to date
- Sensitivity in Run II and at the LHC (HLZ):

	Run II, 2 fb^{-1}	Run II, 20 fb^{-1}	LHC, 100 fb^{-1}
$e^+e^- + \mu^+\mu^-$	1.3-1.9 TeV	1.7-2.7 TeV	6.5-10 TeV
$\gamma\gamma$	1.5-2.4 TeV	2.0-3.4 TeV	7.5-12 TeV
$e^+e^- + \mu^+\mu^- + \gamma\gamma$	**1.5-2.5 TeV**	**2.1-3.5 TeV**	**7.9-13 TeV**

Hadron Colliders: Real Graviton Emission

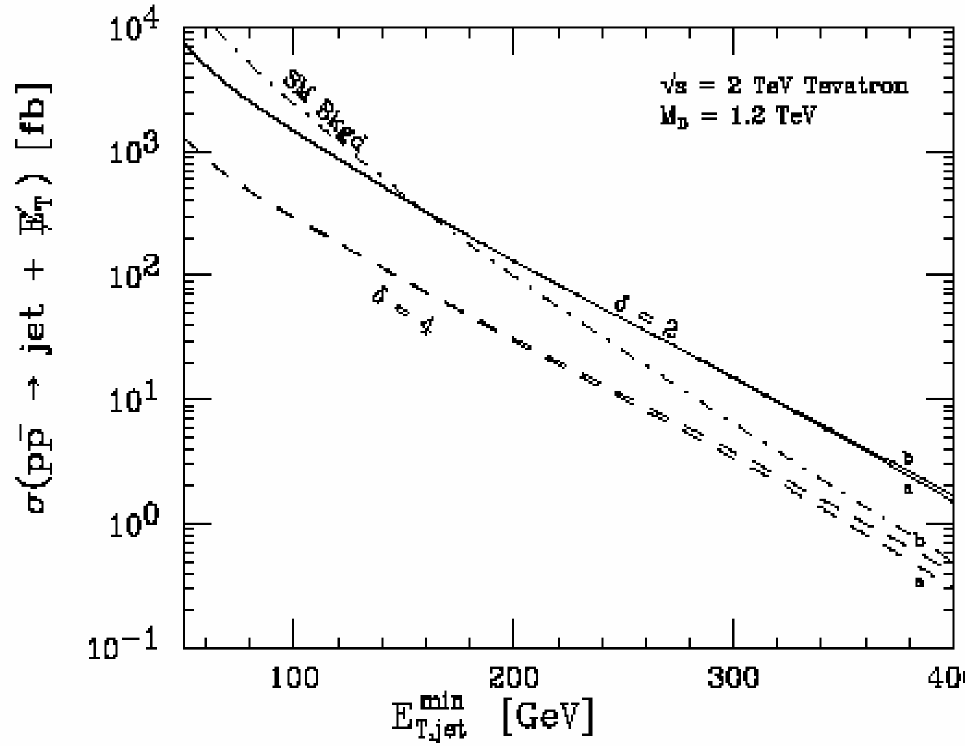
- $q\bar{q}/gg \to q/gG_{KK}$
  - jets + ME_T final state
  - $Z(\nu\nu)$+jets is irreducible background
  - Challenging signature due to large instrumental backgrounds from jet mismeasurement, cosmics, etc.
  - DØ pioneered this search and set limits [hep-ex/0302014] M_D > 0.7-1.1 TeV
  - CDF just announced similar preliminary limits
  - Expected reach for Run II/LHC:

n	M_D reach, Run I	M_D reach, Run II	M_D reach, LHC 100 fb^{-1}
2	1100 GeV	1400 GeV	8.5 TeV
3	950 GeV	1150 GeV	6.8 TeV
4	850 GeV	1000 GeV	5.8 TeV
5	700 GeV	900 GeV	5.0 TeV

Theory:

[Giudice, Rattazzi, Wells, Nucl. Phys. **B544**, 3 (1999) and corrected version, hep-ph/9811291]

[Mirabelli, Perelstein, Peskin, PRL **82**, 2236 (1999)]

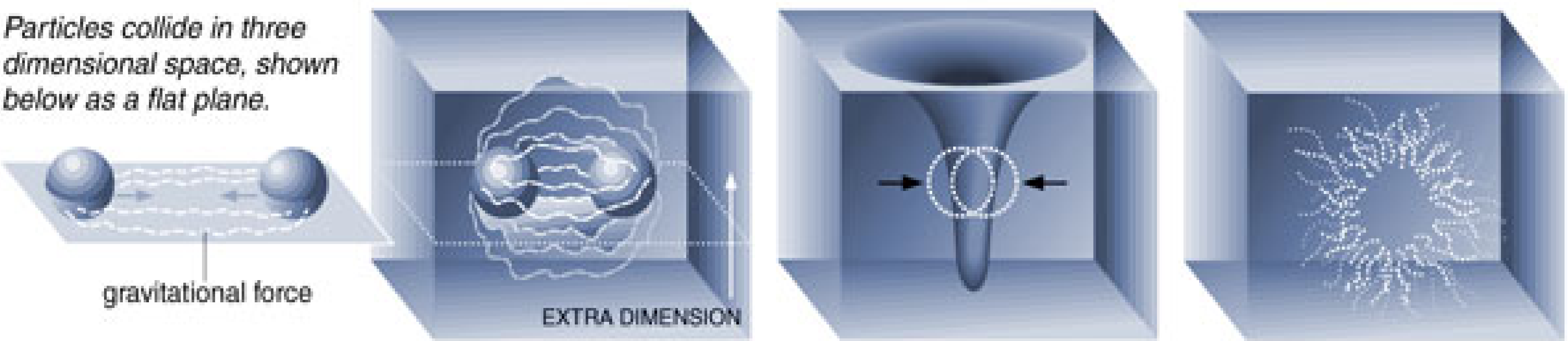


Black Holes at the LHC

NYT, 9/11/01

Black Holes on Demand

Scientists are exploring the possibility of producing miniature black holes on demand by smashing particles together. Their plans hinge on the theory that the universe contains more than the three dimensions of everyday life. Here's the idea:



As the particles approach in a particle accelerator, their gravitational attraction increases steadily.

When the particles are extremely close, they may enter space with more dimensions, shown above as a cube.

The extra dimensions would allow gravity to increase more rapidly so a black hole can form.

Such a black hole would immediately evaporate, sending out a unique pattern of radiation.

Black Hole Production

- Schwarzschild radius is given by Argyres et al., hep-th/9808138 [after Myers/Perry, Ann. Phys. **172** (1986) 304]; it leads to:

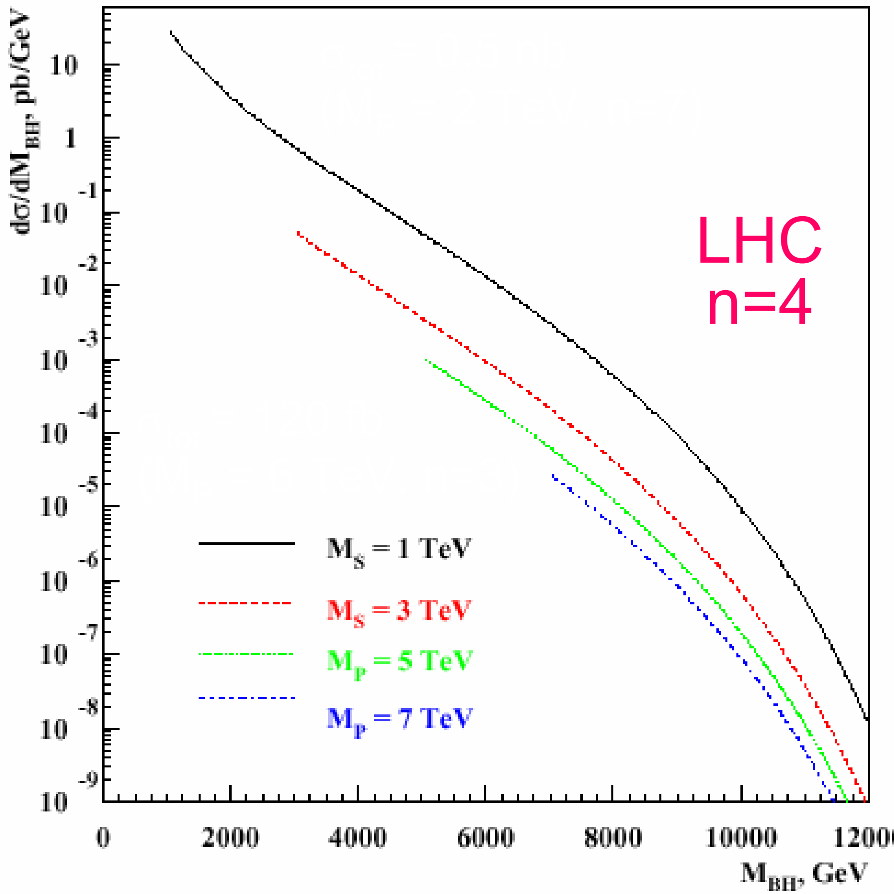
$$\sigma(\hat{s} = M_{BH}^2) = \pi R_S^2 = \frac{1}{M_P^2}\left[\frac{M_{BH}}{M_P}\,\frac{8\Gamma\left(\frac{n+3}{2}\right)}{n+2}\right]^{\frac{2}{n+1}}$$

- Hadron colliders: use parton luminosity w/ MRSD-' PDF (valid up to the VLHC energies)

$$\frac{d\sigma(pp \to BH + X)}{dM_{BH}} = \frac{dL}{dM_{BH}}\hat{\sigma}(ab \to BH)\Big|_{\hat{s}=M_{BH}^2}$$

$$\frac{dL}{dM_{BH}} = \frac{2M_{BH}}{s}\sum_{a,b}\int_{M_{BH}^2/s}^{1}\frac{dx_a}{x_a}f_a(x_a)f_b\left(\frac{M_{BH}^2}{sx_a}\right)$$

[Dimopoulos, GL, PRL **87**, 161602 (2001)]

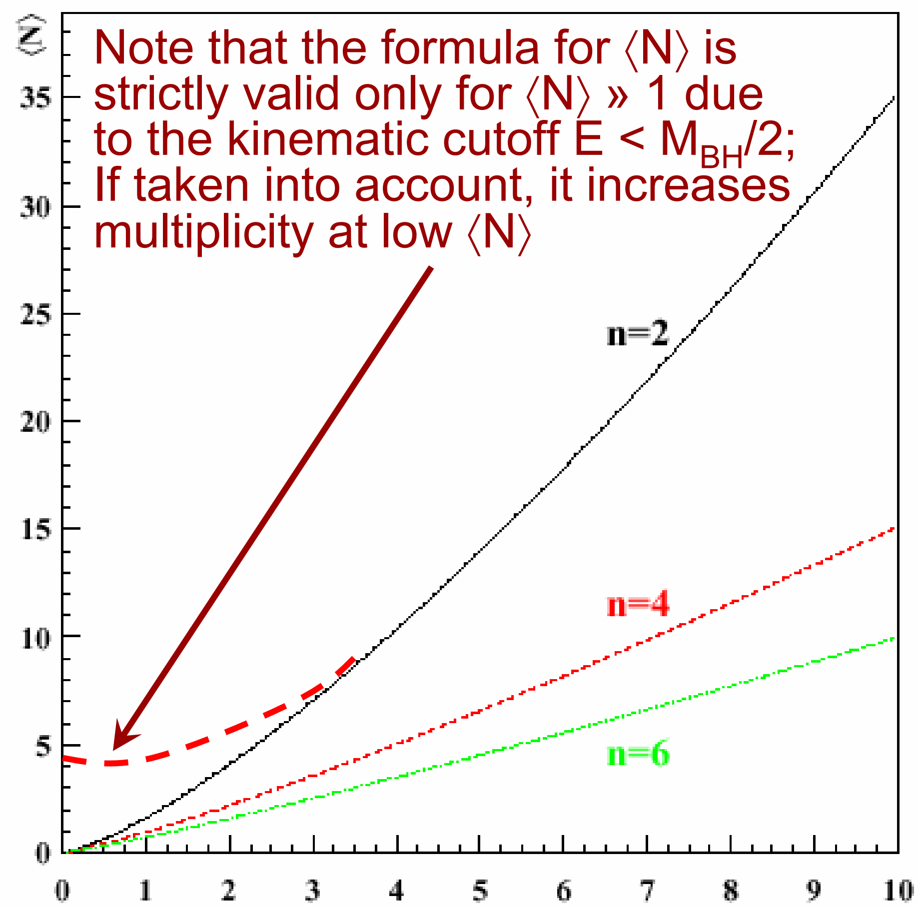


Black Hole Decay

- Hawking temperature: $R_S T_H = (n+1)/4\pi$ (in natural units $\hbar = c = k = 1$)
- BH radiates mainly on the brane [Emparan/Horowitz/Myers, hep-th/0003118]
  - $\lambda \sim 2\pi/T_H > R_S$; hence, the BH is a point radiator, producing s-waves, which depends only on the radial component
  - The decay into a particle on the brane and in the bulk is thus the same
  - Since there are much more particles on the brane, than in the bulk, decay into gravitons is largely suppressed
- Democratic couplings to ~120 SM d.o.f. yield probability of Hawking evaporation into γ, $l^{\pm}$, and ν ~2%, 10%, and 5% respectively
- Averaging over the BB spectrum gives average multiplicity of decay products:

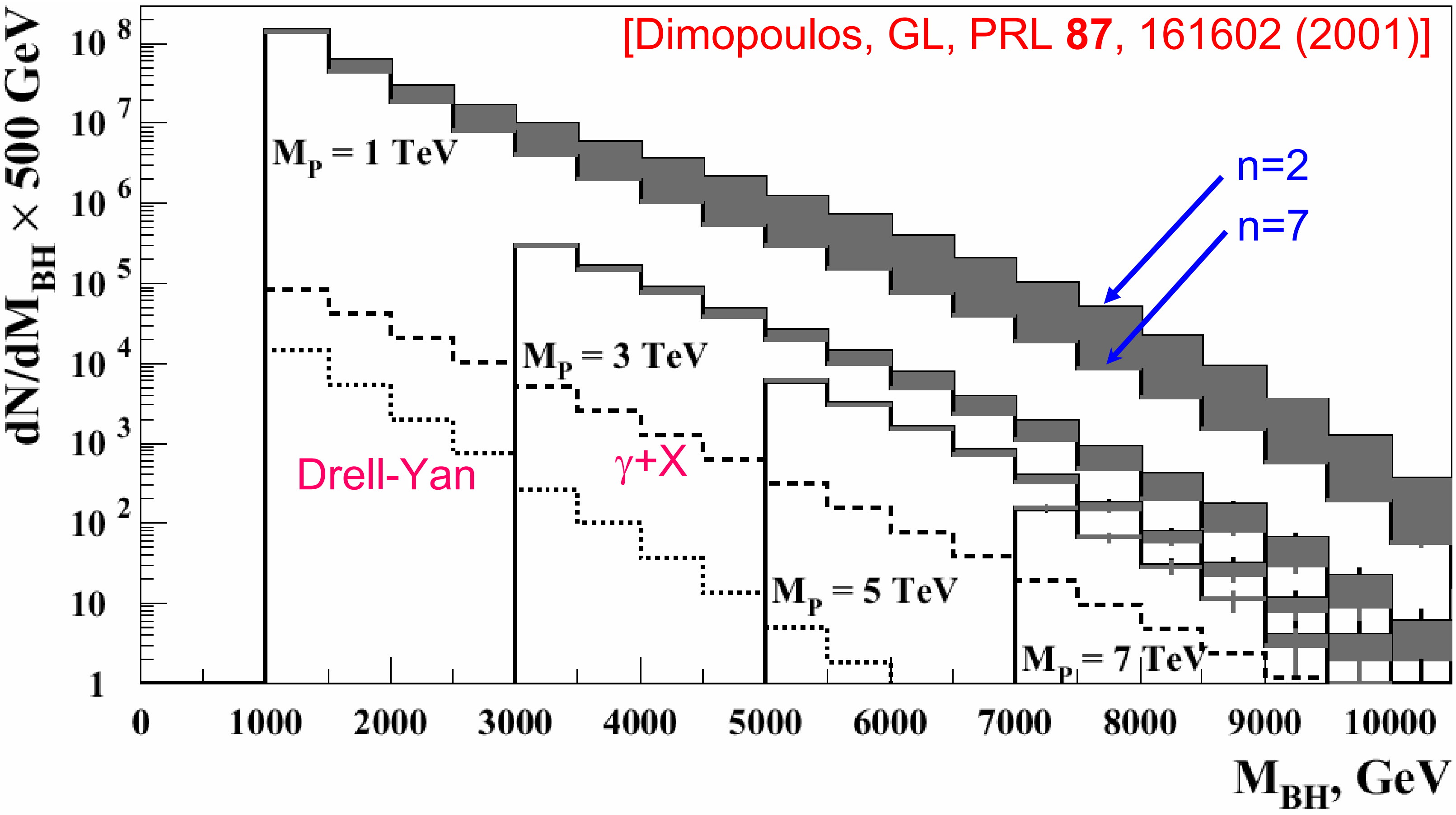
$$\langle N \rangle \approx \frac{M_{BH}}{2T_H}$$

[Dimopoulos, GL, PRL **87**, 161602 (2001)]



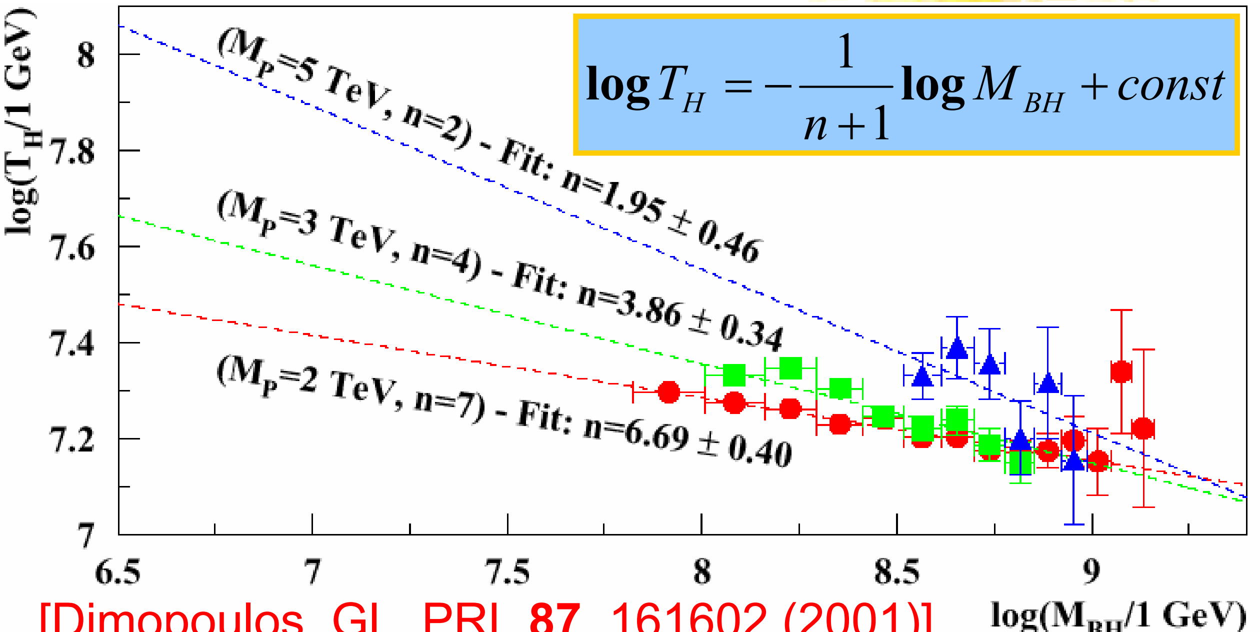
- Stefan's law: $\tau \sim 10^{-26}$ s

LHC: Black Hole Factory



Spectrum of BH produced at the LHC with subsequent decay into final states tagged with an electron or a photon

Space-Probes at the LHC

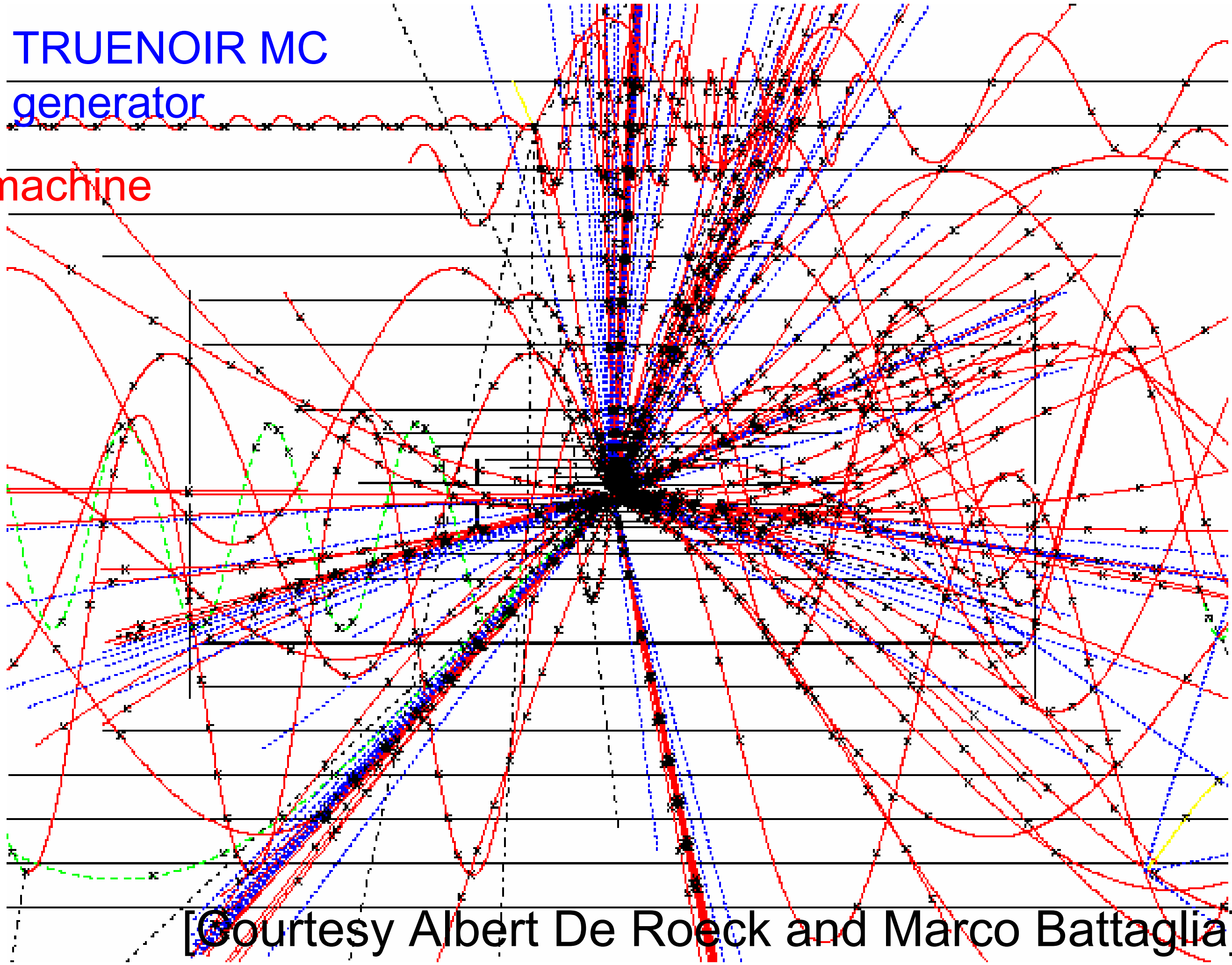


[Dimopoulos, GL, PRL **87**, 161602 (2001)]

M_P	1 TeV	2 TeV	3 TeV	4 TeV	5 TeV
$n=2$	1%/0.01	1%/0.02	3.3%/0.10	16%/0.35	40%/0.46
$n=3$	1%/0.01	1.4%/0.06	7.5%/0.22	30%/1.0	48%/1.2
$n=4$	1%/0.01	2.3%/0.13	9.5%/0.34	35%/1.5	54%/2.0
$n=5$	1%/0.02	3.2%/0.23	17%/1.1		
$n=6$	1%/0.03	4.2%/0.34	23%/2.5	Fit fails	
$n=7$	1%/0.07	4.5%/0.40	24%/3.8		

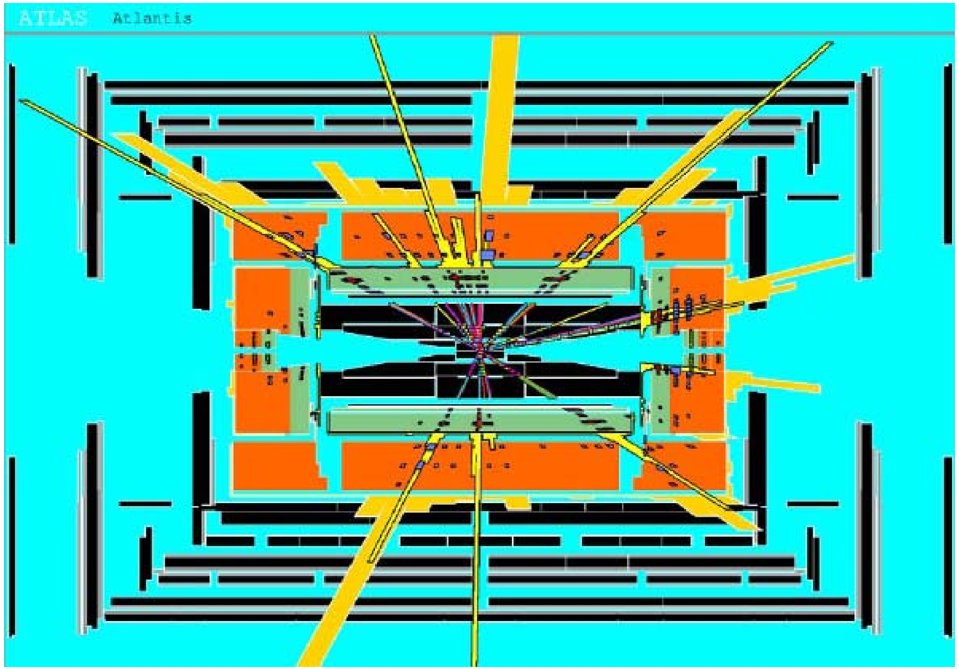
- Relationship between $\log T_H$ and $\log M_{BH}$ allows to find the number of ED,
- This result is independent of their shape!
- This approach drastically differs from analyzing other collider signatures and would constitute a “smoking cannon” signature for a TeV Planck scale

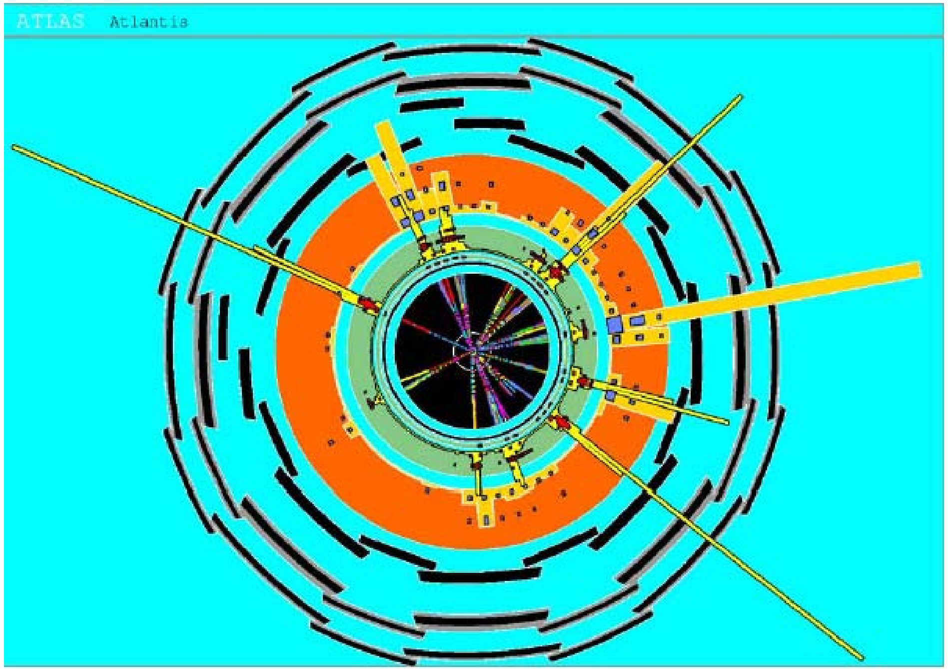
A Black Hole Event Display



First Detailed LHC Studies

- First studies already initiated by ATLAS and CMS
  - ATLAS – Cambridge HERWIG-based generator with more elaborated decay model [Harris/Richardson/Webber]
  - CMS – TRUENOIR [GL]

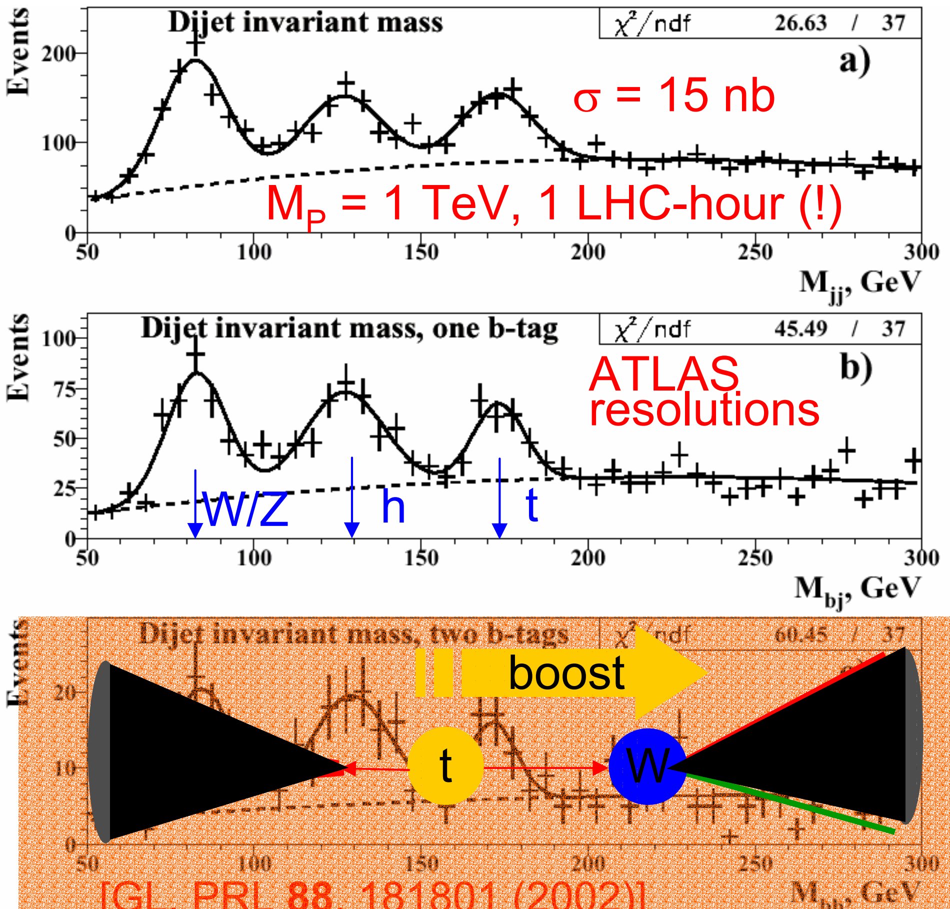




Simulated black hole event in the ATLAS detector [from ATLAS-Japan Group]

Higgs Discovery in BH Decays

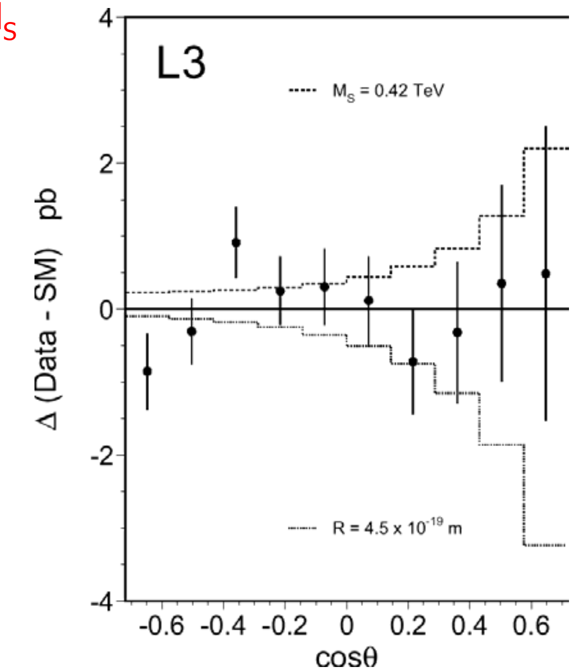
- Example: 130 GeV Higgs particle, which is tough to find either at the Tevatron or at the LHC
- Higgs with the mass of 130 GeV decays predominantly into a bb-pair
- Tag BH events with leptons or photons, and look at the dijet invariant mass; does not even require b-tagging!
- Use a typical LHC detector response to obtain realistic results
- Time required for 5 sigma discovery:
  - M_P = 1 TeV – 1 hour
  - M_P = 2 TeV – 1 day
  - M_P = 3 TeV – 1 week
  - M_P = 4 TeV – 1 month
  - M_P = 5 TeV – 1 year
  - Standard method – 1 year w/ two well-understood detectors!



- An exciting prospect for discovery of other new particles w/ mass ~100 GeV!

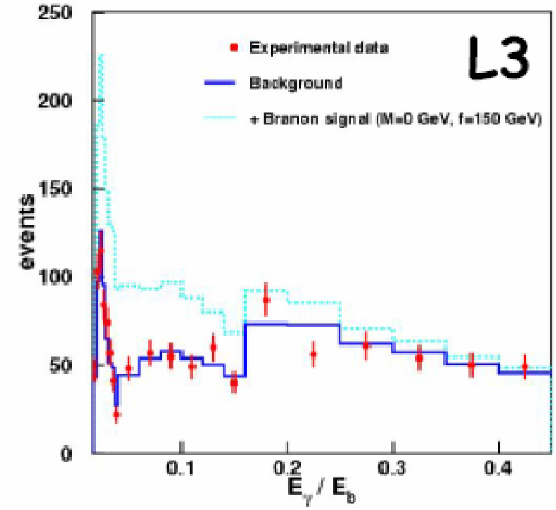
Stringy Models

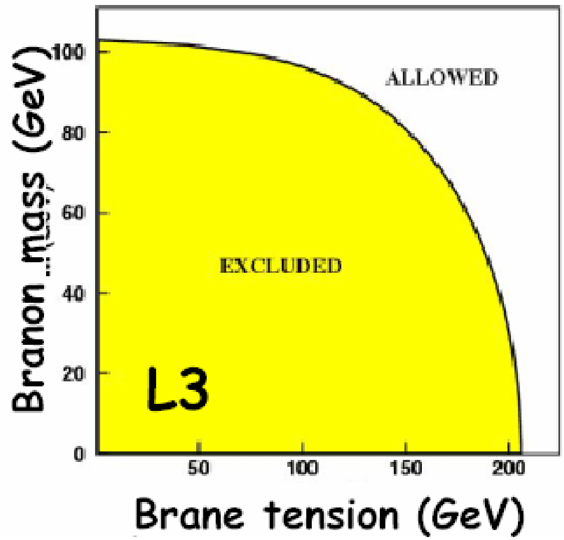
- Recent attempts to embed the idea of large extra dimensions in stringy models:
  - Shiu/Shrock/Tye
    [Phys. Lett. B **458**, 274 (1999)]
    - Type I string theory on a Z_n orbifold
    - Consider resulting twisted moduli fields which sit on the fixed points of the orbifolds and their effects on gg $\to$ gg scattering
    - These fields acquire mass ~1 TeV due to SUSY breaking, and their coupling with the bulk fields is suppressed by the volume factor
    - Since they couple to gravitons, these fields can produce bulk KK modes of the latter
    - Current sensitivity to the string scale, M_S, from CDF/DØ dijet data is ~1 TeV
- Cullen/Perelstein/Peskin,
  [Phys. Rev. D **62**, 055012 (2000)]
  - Embed QED into Type IIB string theory with n=6
  - Calculate corrections to $e^+e^- \to \gamma\gamma$ and Bhabha scattering due to string Regge excitations
  - L3 has set limit M_S > 0.57 TeV @ 95% CL
  - Also calculate $e^+e^-, gg \to \gamma G$ cross section
  - Another observable effect is a resonance in $q\bar{q} \to g^*$ at M_S



Branons

- Another possibility is to produce brane excitations, i.e. brane "wobbling" in extra dimensions
- These degrees of freedom exhibit themselves as new particles, *branons*, from the point of view of a 4-dimensional observer
- Look for pair production (to respect Lorentz invarianc) of branons in $e^+e^-/q\bar{q}' \rightarrow B+B+ME_T$
- If the brane tension $f \ll M_S$, these excitation are dominating at low energies where direct and virtual graviton emission is suppressed

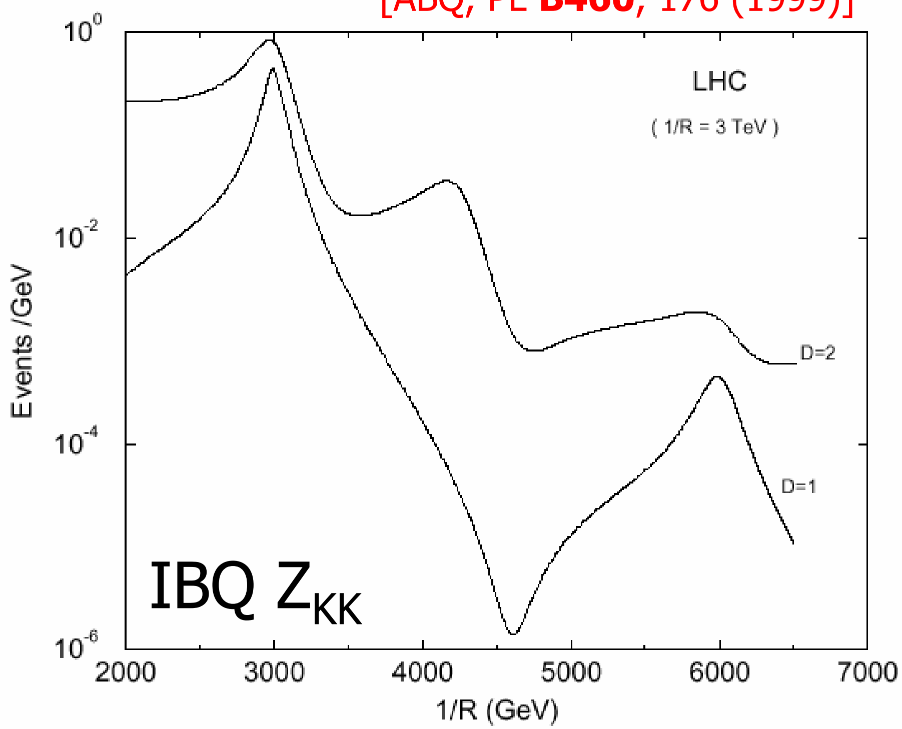




TeV^{-1} Extra Dimensions

- Intermediate-size extra dimensions with ~TeV^{-1} radius
- Introduced by Antoniadis [PL **B246**, 377 (1990)] in the string theory context; used by Dienes/Dudas/Ghergheta [PL **B436**, 55 (1998)] to allow for low-energy unification
  - SM gauge bosons can propagate in these extra dimensions
  - Expect Z_{KK}, W_{KK}, g_{KK} resonances
  - Effects of the virtual exchange of the Kaluza-Klein modes of vector bosons at lower energies
- Gravity is not included in this model

[ABQ, PL **B460**, 176 (1999)]



- Antoniadis/Benaklis/Quiros [PL **B460**, 176 (1999)] – direct excitations; require LHC energies

Current Limits on TeV^{-1} ED

From Cheung/GL [PRD **65**, 076003 (2002)]

	η (TeV^{-2})	η_{95} (TeV^{-2})	M_C^{95} (TeV)
LEP 2:			
hadronic cross section, ang. dist., $R_{b,c}$	$-0.33\ ^{+0.13}_{-0.13}$	0.12	5.3
μ, τ cross section & ang. dist.	$0.09\ ^{+0.18}_{-0.18}$	0.42	2.8
ee cross section & ang. dist.	$-0.62\ ^{+0.20}_{-0.20}$	0.16	4.5
LEP combined	$-0.28\ ^{+0.092}_{-0.092}$	0.076	6.6
HERA:			
NC	$-2.74\ ^{+1.49}_{-1.51}$	1.59	1.4
CC	$-0.057\ ^{+1.28}_{-1.31}$	2.45	1.2
HERA combined	$-1.23\ ^{+0.98}_{-0.99}$	1.25	1.6
TEVATRON:			
Drell-yan	$-0.87\ ^{+1.12}_{-1.03}$	1.96	1.3
Tevatron dijet	$0.46\ ^{+0.37}_{-0.58}$	1.0	1.8
Tevatron top production	$-0.53\ ^{+0.51}_{-0.49}$	9.2	0.60
Tevatron combined	$-0.38\ ^{+0.52}_{-0.48}$	0.65	2.3
All combined	$-0.29\ ^{+0.090}_{-0.090}$	0.071	6.8

Tevatron and LHC Tests

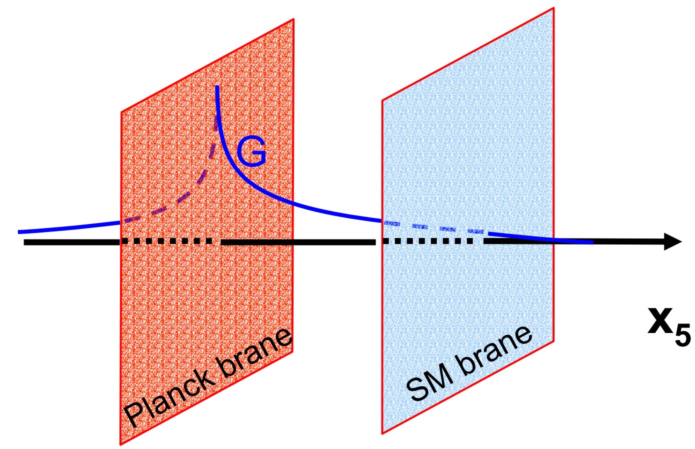
- We expect the dijet and DY production to be the most sensitive probes of TeV^{-1} extra dimensions
- The 2D-technique similar to the search for ADD effects in the virtual exchange yields the best sensitivity in the DY production [Cheung/GL, PRD **65**, 076003 (2002)]
- Similar (or slightly better) sensitivity is expected in the dijet channel; detailed cuts and NLO effects need to be studied
- Run IIb could yield sensitivity similar to the current limits from indirect searches at LEP
- These tests are complementary in nature to those via loop diagrams at LEP

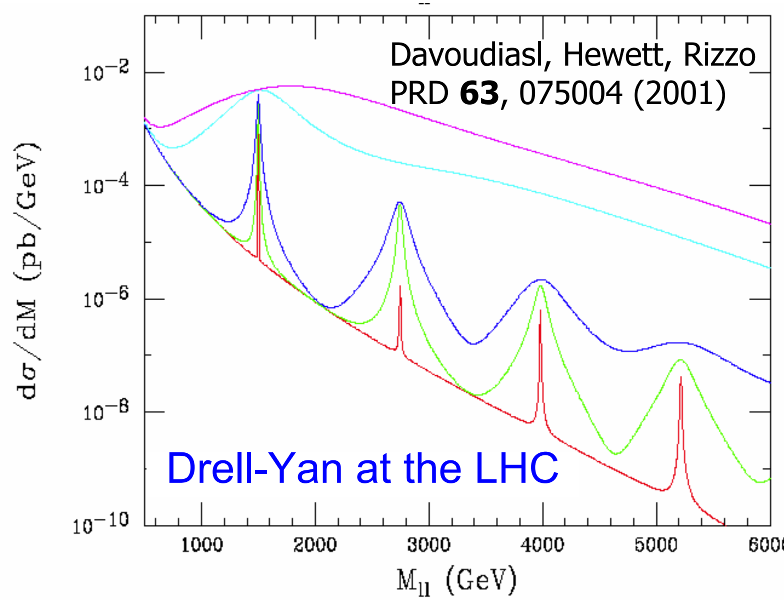
	η_{95} (TeV^{-2})	95% C.L. lower limit on M_C (TeV)
Run 1 (120 pb^{-1})	1.62	1.4
Run 2a (2 fb^{-1})	0.40	2.9
Run 2b (15 fb^{-1})	0.19	4.2
LHC (14 TeV, 100 fb^{-1}, 3% systematics)	1.81×10^{-2}	13.5
LHC (14 TeV, 100 fb^{-1}, 1% systematics)	1.37×10^{-2}	15.5

From Cheung/GL [PRD **65**, 076003 (2002)]

Randall-Sundrum Scenario

- Randall-Sundrum (RS) scenario
  [PRL **83**, 3370 (1999); PRL **83**, 4690 (1999)]
  - Gravity can be localized near a brane due to the non-factorizable geometry of a 5-dimensional space
  - + brane (RS) – no low energy effects
  - +– branes (RS) – TeV Kaluza-Klein modes of graviton
  - ++ branes (Lykken-Randall) – low energy collider phenomenology, similar to ADD with n=6
  - –+– branes (Gregory-Rubakov-Sibiryakov) – infinite volume extra dimensions, possible cosmological effects
  - +–+ branes (Kogan et al.) – very light KK state, some low energy collider phenomenology

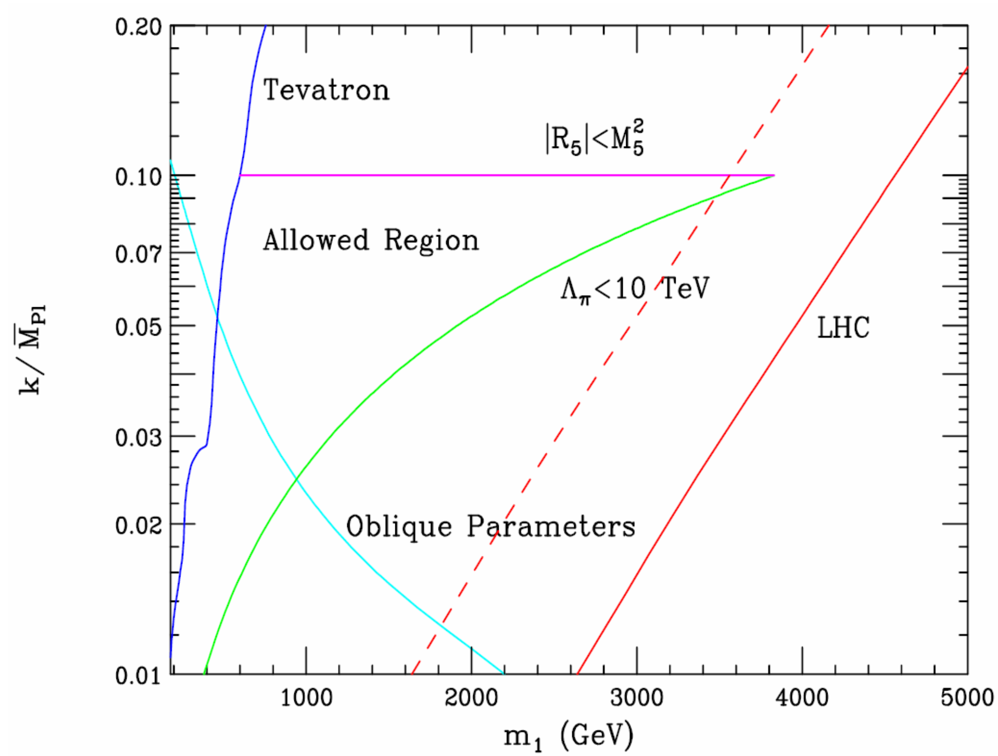




Current Constraints

- Neither gravity experiments, nor cosmology provide interesting limits on most of the RS models
- Existing limits come from collider experiments, dominated by precision electroweak measurements at LEP
- As the main effect involves direct excitation of the G_{KK} levels, energy is the key
- Given the existing constraints and the theoretically preferred parameters, there is not much the Tevatron can do to test RS models
  - Nevertheless both the CDF and DØ collaborations are testing these models; first results already available
- Extra degree of freedom due to the compact dimension results in a light scalar field – the radion
- LHC is the place to probe RS models

$$\overline{M}_{Pl}^2 = \frac{M_5^3}{k}\left(1 - e^{-2kr_c\pi}\right); \quad \Lambda_\pi = \overline{M}_{Pl} e^{-kr_c\pi}$$



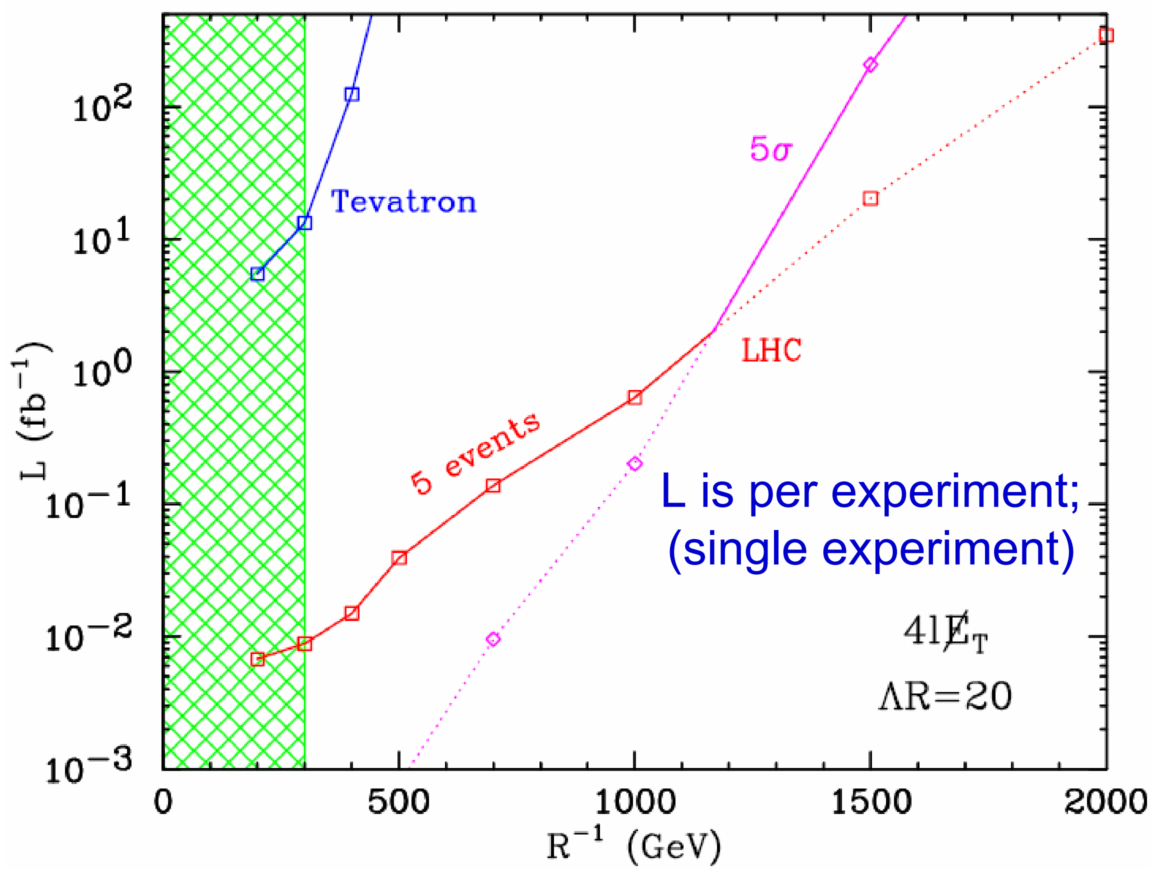
Universal Extra Dimensions

- The most "democratic" ED model: *all* the SM fields are free to propagate in extra dimension(s) with the size $R_c = 1/M_c \sim 1\ \text{TeV}^{-1}$ [Appelquist, Cheng, Dobrescu, PRD **64**, 035002 (2001)]
  - Instead of chiral doublets and singlets, model contains vector-like quarks and leptons
  - Gravitational force is not included in this model
- The number of universal extra dimensions is not fixed:
  - it's feasible that there is just one (MUED)
  - the case of two extra dimensions is theoretically attractive, as it breaks down to the chiral Standard Model and has additional nice features, such as guaranteed proton stability, etc.
- Every particle acquires KK modes with the masses $M_n^2 = M_0^2 + M_c^2$, n = 0, 1, 2, …
- Kaluza-Klein number (n) is conserved at the tree level, i.e. $n_1 \pm n_2 \pm n_3 \pm \ldots = 0$; consequently, the lightest KK mode cold be stable (and is an excellent dark matter candidate [Cheng, Feng, Matchev, PRL **89**, 211301 (2002)])
- Hence, KK-excitations are produced in pairs, similar to SUSY particles
- Consequently, current limits (dominated by precision electroweak measurements, particularly T-parameter) are sufficiently low ($M_c \sim 300$ GeV for one ED and of the same order, albeit more model-dependent for >1 ED)

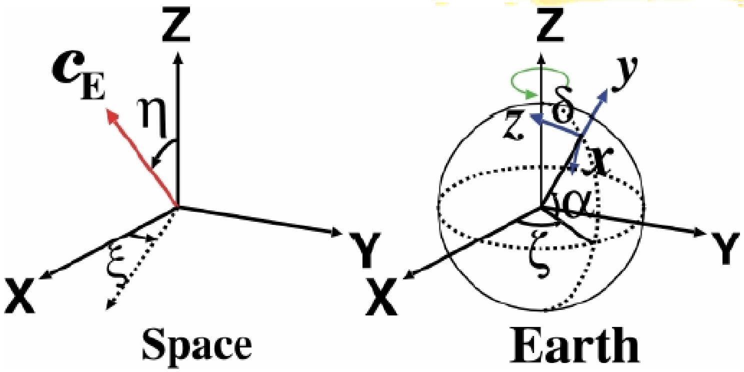
Sensitivity in the Four-Lepton Mode

- Only the gold-plated 4-leptons + ME_T mode has been considered in the original paper
- Sensitivity in Run IIb can exceed current limits
- Much more promising channels:
  - dileptons + jets + ME_T + X (x9 cross section)
  - trileptons + jets + ME_T + X (x5 cross section)
- Detailed simulations is required: would love to see this in a MC
- One could use SUSY production with adjusted masses and branching fractions as a quick fix

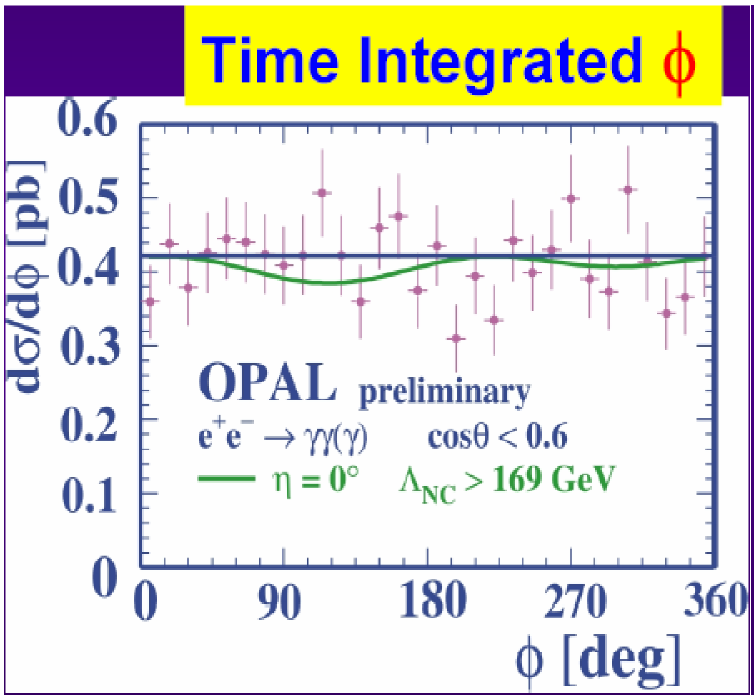
[Cheng, Matchev, Schmaltz, PRD **66**, 056006 (2002)]

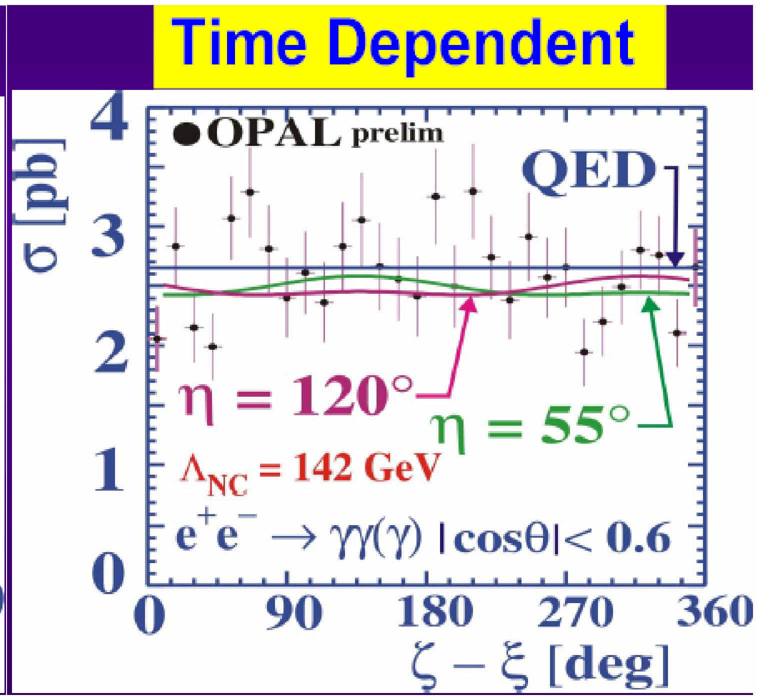


Non-Commutative Geometry



- Non-commutative QED in the $e^+e^- \to \gamma\gamma$ production at LEP
- Laws of physics depend on the position in space; use the siderial reference frame
- $\Lambda < 142$ GeV has been excluded by OPAL





Conclusions

- String theory entered a new realm: the realm of string phenomenology
- While not guaranteed, there are rich possibilities for quantum gravity to exhibit itself below the Planck scale, perhaps significantly below
- These possibilities would result in rich phenomenology, which could be tested in the lab as soon as in the next decade
- Some of the scenarios offer no less than "ultimate unification" – the unification of particle physics, astrophysics, and astronomy
- If any of the above would be confirmed, we might be witnessing the greatest revolution in our field ever, and we could be a part of it