TeV Strings and UHE Cosmic Rays

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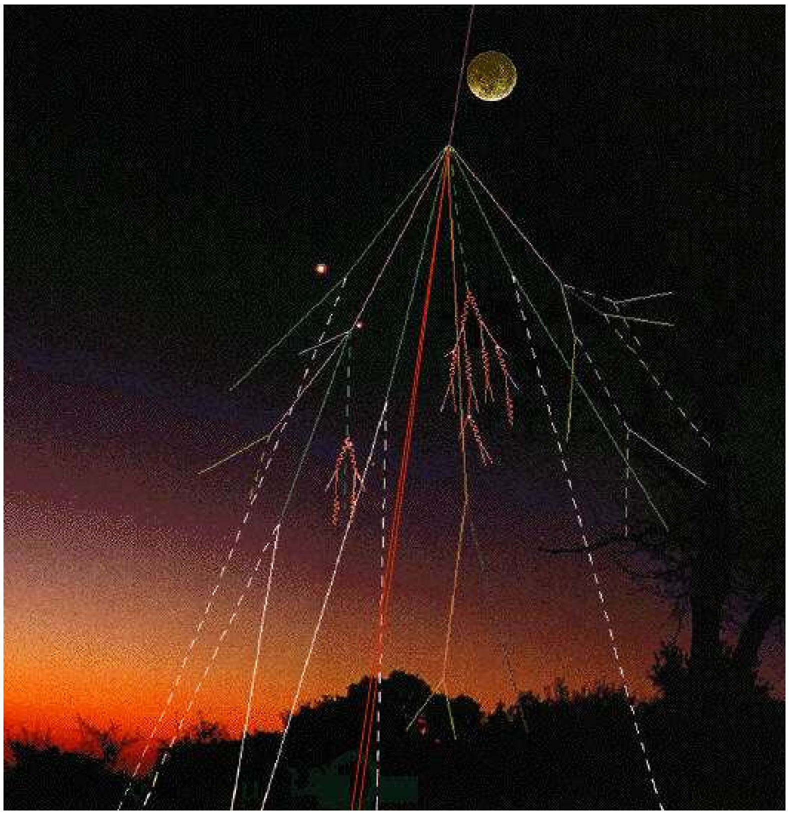
1. Mistery of UltraHigh-Energy Cosmic Rays
2. Large Compact Extra Dimensions
3. Phenomenology of TeV Strings

- *Application* to $\nu-$Nucleon Scattering
- Results and Conclusions

Cosmic Rays

Direct observation at satellite and balloon experiments becomes impractical at energies where EAS become detectable at ground

Extensive Air Showers (EAS)

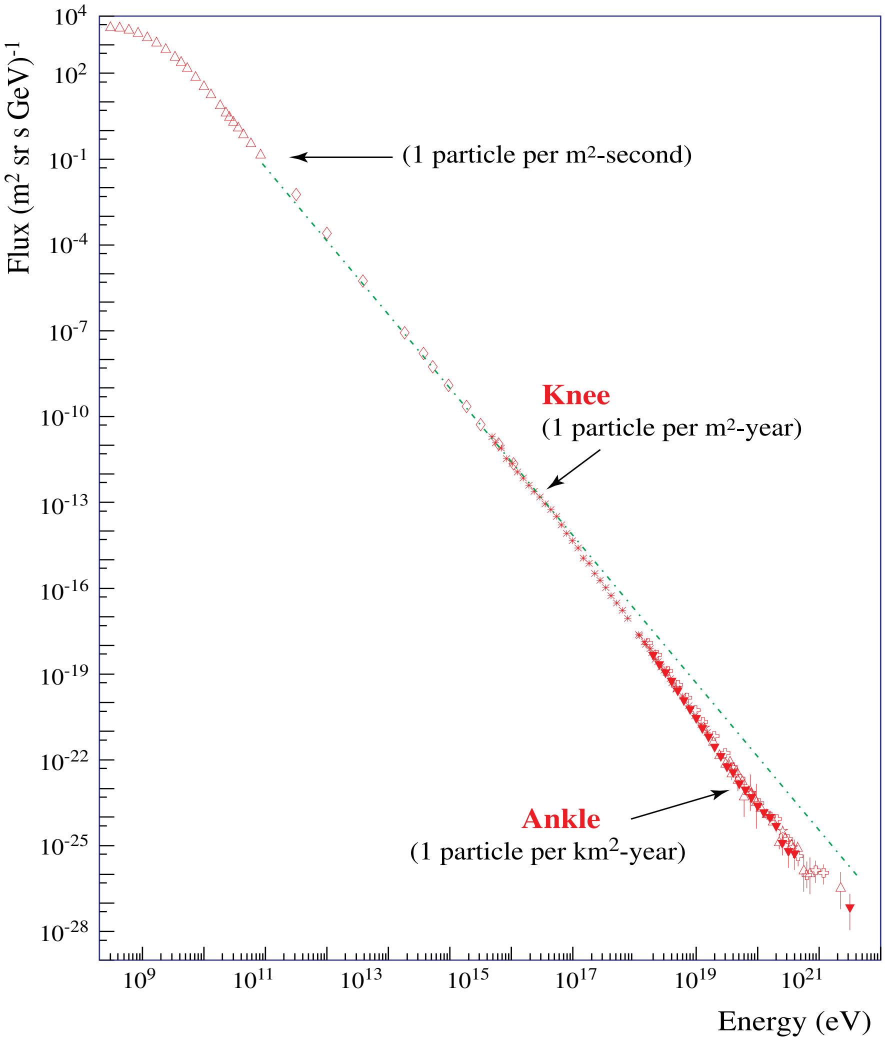


A CR hits an atmospheric $N \rightsquigarrow$ cascade of secondary particles: disk of relativistic particles covering at ground an area with a diameter of tens of metres at 10^{14} eV to several km at 10^{20} eV

EAS parameters ($\#$ electrons/muons/hadrons, shapes of lateral density distributions, reconstructed height of shower maximum...) relate to the properties of **primary** particle (mass and energy)

Some CR interactions are beyond the largest energies available at man-made accelerators

Spectrum of Cosmic Rays



- $10^9 - 10^{15}$ eV: $[\propto E^{-2.7}]$

Knee: maximum energy of some galactic accelerators reached (e.g. supernova remnants in the Sedov phase)

- 1 PeV$= 10^{15}$ eV-10^{18-19} eV: $[\propto E^{-3.2}]$

Ankle: hint that a new higher energy extragalactic component starts to dominate

UHECR [1 EeV$= 10^{18}$ eV ... 1 ZeV$= 10^{21}$ eV ...]

- $1 - 3$ EeV: excess from galactic center $[\propto E^{-2.8}]$
- $\gtrsim 10$ EeV: apparently extragalactic $\Rightarrow$ PROBLEM

GZK cutoff energy: $E_{\rm GZK} \sim 5 \times 10^{19}$ eV exceeded!!

World Record: 3.2×10^{20} eV!! *[Fly's Eye]*

Ultrahigh-Energy Cosmic Rays

Puzzles

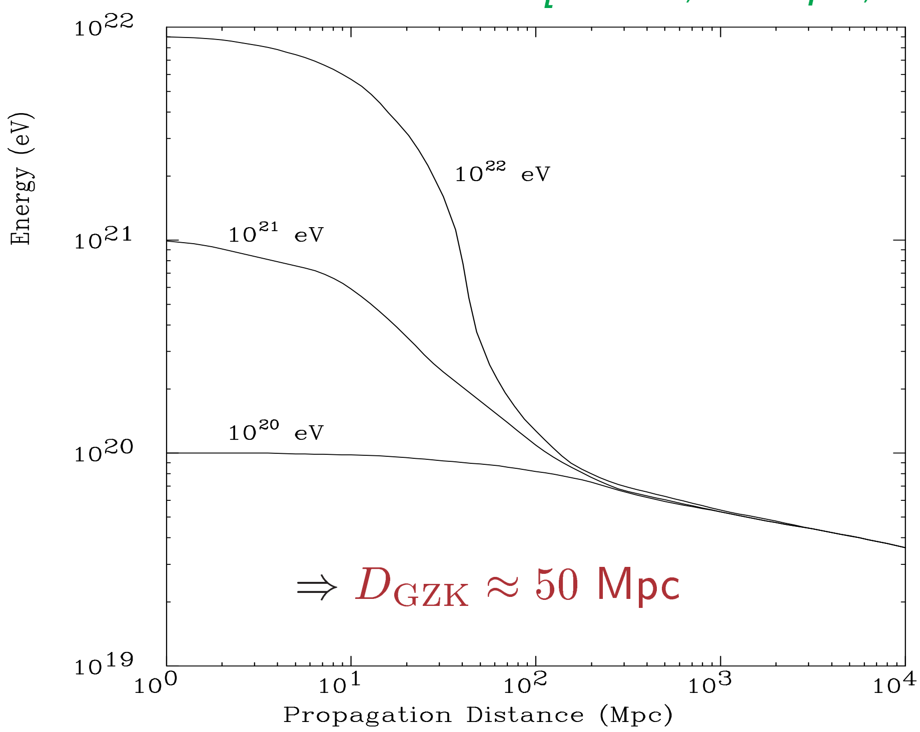
- **What is the primary particle?**

Protons lose 20% of their energy scattering with CMB photons:

$$p + \gamma_{2.7\mathrm{K}} \to \Delta^+ \to p + \pi^0 \;\; (n + \pi^+)$$

per $D \approx 6$ Mpc above the cutoff $E_{\mathrm{GZK}} \approx 5 \times 10^{19}$ eV

[Greisen; Zatsepin, Kuzmin '66]



⇒ "pile-up" structure (not yet confirmed)

Nuclei undergo photodisintegration in CMB and IR radiations losing 3 to 4 nucleons per Mpc for $E \gtrsim 2 \times 10^{19-20}$ eV

Electrons lose energy very rapidly via synchrotron radiation

Photons have a short absorption length (~ 10 Mpc) since they produce e^+e^- pairs with CRB, CMB and IR radiations, but ... ~ 100 Mpc if $E \gg 10^{21}$ eV (possible!), recreating secondary photons reaching us with the observed UHE *[Kuzmin et al 6.7.01]*

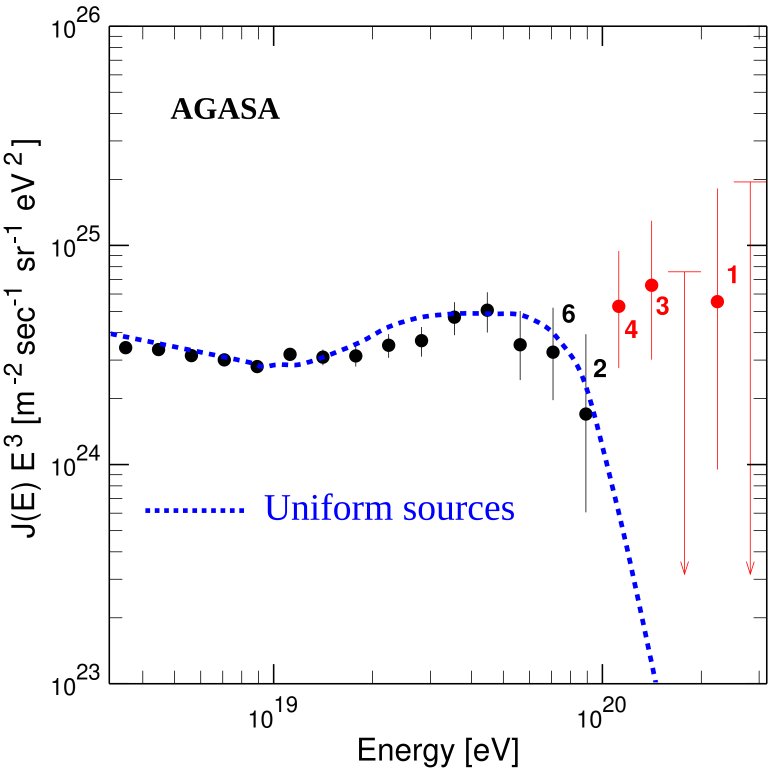
??? ...

Ultrahigh-Energy Cosmic Rays

$\gtrsim$ **20 supra-GZK events oberved by five different expts**
[AGASA, Fly's Eye, HiRes, Havery Park, Yakutsk]

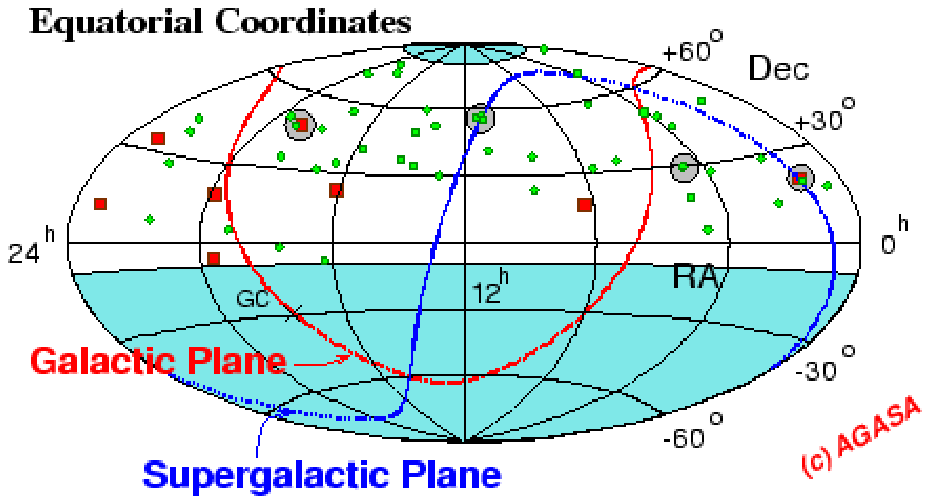
The UHE cosmic ray spectrum ($\times E^3$) observed by AGASA:

[dashed: for extragalactic sources uniformly distributed $\rightsquigarrow E_{\mathrm{GZK}}$]



Isotropy?: $E \geq 10^{20}$ eV, $(4-9)\times 10^{19}$ eV

[Pairing!: 3 doublets and 1 triplet ($P < 1\%$)]



Ultrahigh-Energy Cosmic Rays

• **What are the acceleration mechanisms?**

Conventional: "Bottom-Up" scenarios

– Direct: one-shot acceleration by very high electric fields, within or near very compact objects. No power-law spectrum

– "**Fermi mechanism**": stochastic schock-wave acceleration in magnetized clouds. It predicts a power-law spectrum but seems too slow and too inefficient to account for the observed UHECRs

Gamma Ray Bursts accelerate p to 10^{20} eV, but they cannot be, since GRBs are cosmological according to their red-shift

Exotic:

– "Top-Down" scenarios: decay or annihilation of super-heavy particles or cosmological relics: topological defects, relic magnetic monopoles... almost impossible pairing and flatter spectrum

– New Physics? Breakdown of Lorentz invariance or General Relativity (10^{20} eV$/M_{\rm Pl} \sim 10^{-8}$... too speculative?)

• **Where are the sources?**

Candidates [Hillas plot] according to conventional scenarios: Pulsars, AGN cores, radio-loud quasars, catastrophic events ...

No visible source within the GZK distance (~ 50 Mpc), maybe M87 (AGN at ~ 20 Mpc) and NGC5128 (radio galaxy at 3.4 Mpc) $\Rightarrow$ how to justify the large-scale isotropy of the events with a just a couple of nearby sources?

▷ Directional/temporal decorrelation with source by $\vec{B}$ of μG? *[Farrar and Piran '00]*

▷ Further sources not ruled (BL Lacertae) if photons are primaries *[Kuzmin et al 6.7.01]*

Hillas plot

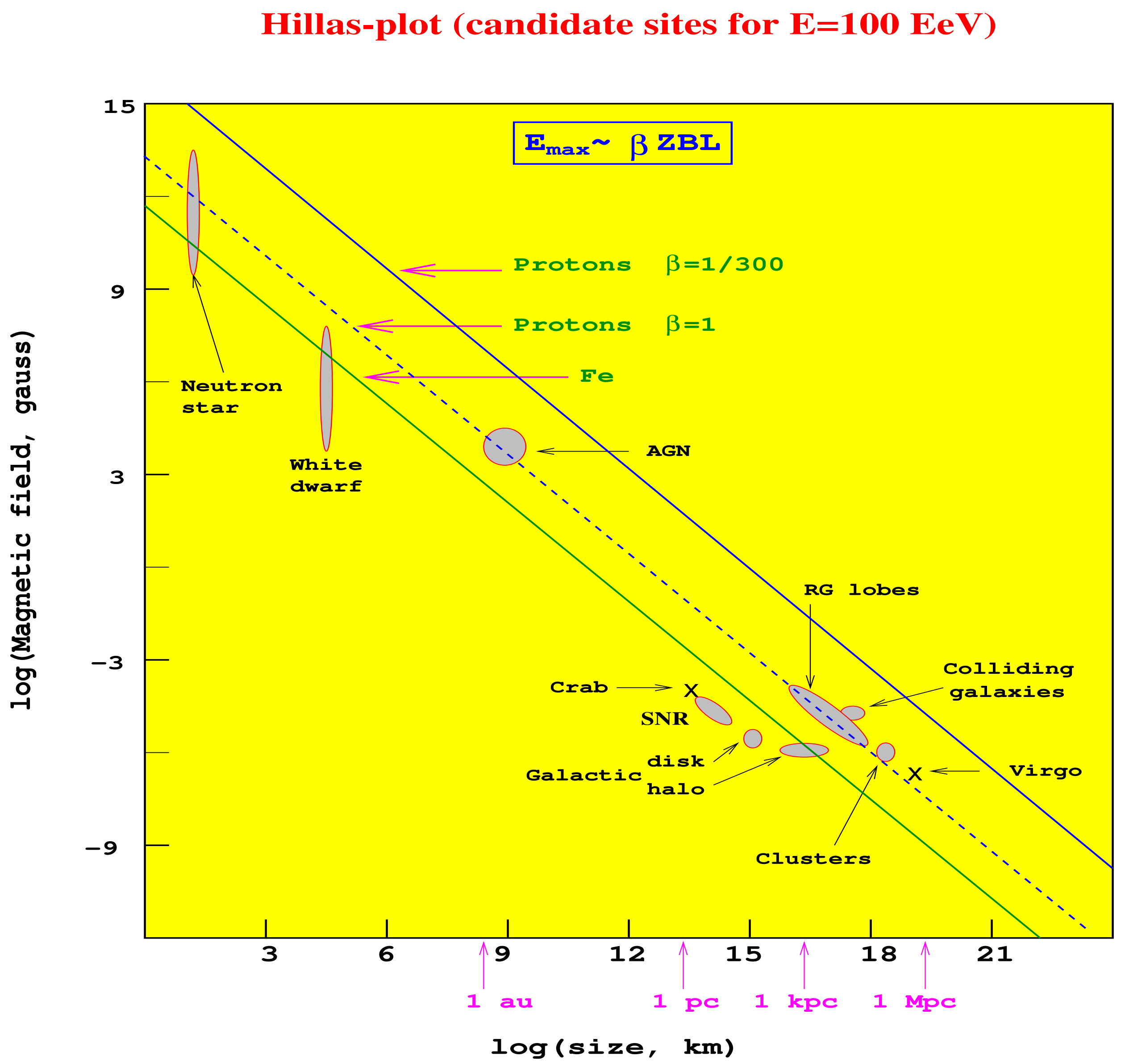
Irrespective of details of the acceleration mechanism, the maximum energy of a particle of charge Ze within a site of size L is

$$E_{\rm max} \approx \beta Z \left(\frac{B}{1\ \mu{\rm G}}\right)\left(\frac{L}{1\ \text{kpc}}\right) 10^{18}\ \text{eV}$$

where

B is the magnetic field inside the acceleration volume,

β is the velocity of the shock wave



Ultrahigh-Energy Cosmic Rays

Possible solutions

What do we need?

– Stable particle (able to travel very long distances)

– Neutral (not bent by $\vec{B}$: large/small-scale iso/anisotropy)

– Small magnetic moment (no dipole interaction with CMBR)

$\Rightarrow$ **neutrinos** with hadronic-size cross section

[$\lambda \sim 10^2$ Gpc (intergal.) $\sim$ Mpc (gal.) only stopped by atmph]

$\surd$ The flux of cosmogenic neutrinos matches well the flux of UHECRs beyond $E_{\rm GZK}$ (produced by pions generated by energy-degraded protons)

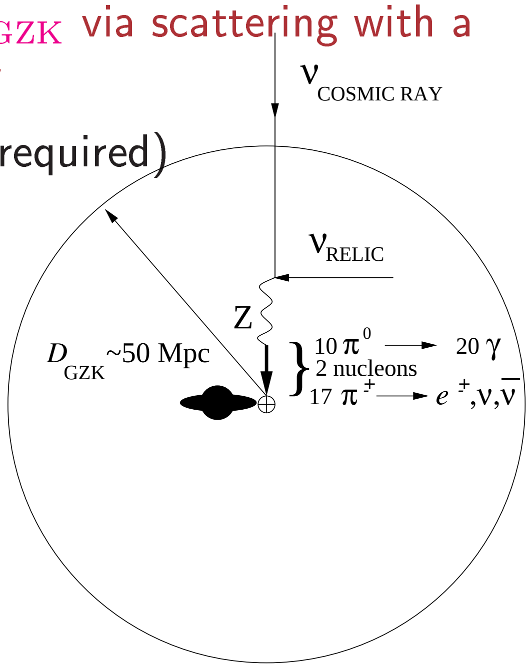
- But νN cross section is too small ($\sigma^{\rm SM}_{\nu N} \sim 10^{-6} \sigma^{\rm SM}_{pN/\gamma N}$)

  $\Rightarrow$ **Stronger νN cross section at $E \gtrsim E_{\rm GZK}$?** *[our choice]*

- ***Z*-bursts** *[T. Weiler '82 '99]*

  Cosmogenic ν are not the primaries but resonantly create a "local" flux of N and γ of $E \gtrsim E_{\rm GZK}$ via scattering with a relic neutrino (CNB) of $m_\nu \sim 1$ eV

  (fits oscillation expts!, large ν flux required)



$$E_{\nu{\rm CR}} = \frac{M_Z^2}{2m_\nu} \approx 4 \left(\frac{\rm eV}{m_\nu}\right) 10^{21}\ {\rm eV}$$

- or **Gravi-bursts** (resonant KK)

  [Goyal et al; Rizzo et al '01]

Large Compact Extra Dimensions

• *Assume* gravity can propagate in n extra spatial dims of size R.
Then (Gauss's law):

$$r \gg R: \;\; F_G = -\frac{1}{{M_{\rm Pl}}^2}\frac{m_1 m_2}{r^2}; \quad r \ll R: \;\; F_G \sim -\frac{1}{{M_\star}^{2+n}}\frac{m_1 m_2}{r^{2+n}}$$

$\Rightarrow$ Gravity becomes strong at distances shorter than

$$R \sim \frac{1}{M_\star}\left(\frac{M_{\rm Pl}}{M_\star}\right)^{\frac{2}{n}}$$

$\Rightarrow$ Planck scale not fundamental but derived: augmented $V_n \sim R^n$

$$ {M_{\rm Pl}}^2 \sim {M_\star}^{2+n} R^n$$

• $M_\star \sim 1$ TeV *[ADD '98]* $\Rightarrow$

n	R
1	$\sim$ a.u. (excluded)
2	$\sim$**mm** (possible!)
3	$\sim$ nm
...	...

$\Rightarrow$ New scenario:

– SM fields confined to a 3+1-dim spacetime *wall* (3-brane)

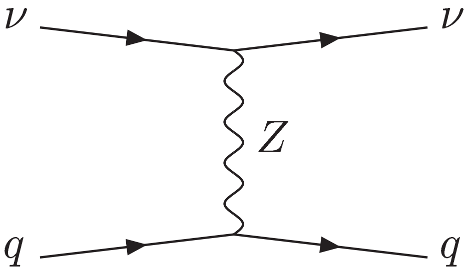
– Gravity propagates also in the *bulk*: *compact* dimensions

$\rightsquigarrow$ Tower of KK gravitons with increasing masses proportional to $M_c = 1/R \sim 1/\text{mm} \;\sim 10^{-14}$ GeV very weakly coupling to SM particles with a strength rapidly growing with the energy (spin 2)

$\rightsquigarrow$ Weakness of the interaction partially compensated by the High multiplicity of KK at the electroweak scale $M_{\rm EW}$ since still $M_c \ll M_{\rm EW} \ll M_{\rm Pl} \Rightarrow$ potentially observable effects

Quantum Field Theory

SM



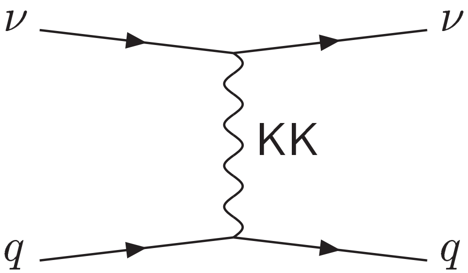
$$\mathcal{A}_{\rm SM}(s,t) \propto g^2 \frac{s}{t - M_Z^2}$$ dominated by low $-t = \frac{1}{2}(1-\cos\theta)$

$$\sigma_{\rm SM}(s) = \frac{1}{16\pi}\frac{1}{s^2}\int_{-s}^{0} \mathrm{d}t\ |\mathcal{A}|^2 \propto \frac{g^4}{M_Z^2} - \underbrace{\cancel{\frac{g^4}{s+M_Z^2}}}_{=0 \text{ for large } s}$$

Extra Dimensions

Gravity/Gauge in $(n=2)$ extra dimensions (neglecting gauge mass)

[taking massless KK below $\sqrt{-t}$ and neglecting the ones above]



spin 2: $\mathcal{A}_{\rm grav}(s,t) \sim \frac{1}{M_{\rm Pl}^2}\frac{s^2}{t} \times \underbrace{\frac{t}{M_c^2}}_{\text{multiplicity } N(t)} = \frac{\kappa^2}{M_\star^4} s^2, \quad M_c^2 < -t < \underbrace{\Lambda_{\rm grav}^2}_{\text{cutoff}}$

spin 1: $\mathcal{A}_{\rm gauge}(s,t) \sim g^2 \frac{s}{t} \times \overbrace{\frac{t}{M_c'^2}} = \frac{g^2}{M_c'^2} s, \quad M_c'^2 < -t < \overbrace{\Lambda_{\rm gauge}^2}$

$$\sigma_{\rm grav}(s) \sim \frac{\kappa^4}{M_\star^2}\frac{\Lambda_{\rm grav}^2}{M_\star^2}\frac{s^2}{M_\star^4} \text{ may take over } \sigma_{\rm gauge}(s) \sim \frac{g^4}{\Lambda_{\rm gauge}^2}\left(\frac{\Lambda_{\rm gauge}^2}{M_c'^2}\right)^2$$

BUT: How far can we trust this picture?

String Theory
The framework for a consistent theory of gravity

- Quantization $\rightsquigarrow$ tower of string vibration modes with squared masses $M^2 = nM_S^2$ and arbitrary spins

  (Regge trajectories)

  $\Rightarrow$ massless modes + String Regge (SR) excitations

  – Open strings: massless modes are gauge and matter fields

  – Closed strings: massless modes are gravitons

- Natural cutoff: string scale $M_S = \alpha'^{-1/2}$ (string tension):

$$\Lambda_{\rm grav} \sim \Lambda_{\rm gauge} \sim M_\star \sim M_S \sim \ 1 \text{ TeV (!?)}$$

  [for energies comparable to M_S string excitations appear]

- In a Weakly-coupled String Theory

$$g^2 \frac{\Lambda_{\rm gauge}{}^2}{M_c'^2} \lesssim 1 \Rightarrow M_c' \sim M_S$$

  $\Rightarrow$ At TeV scale ($s \sim M_S^2$):

  – $\sigma_{\rm grav} \sim \dfrac{\kappa^4}{M_S^2}, \quad \sigma_{\rm gauge} \sim \dfrac{g^4}{M_S^2}$

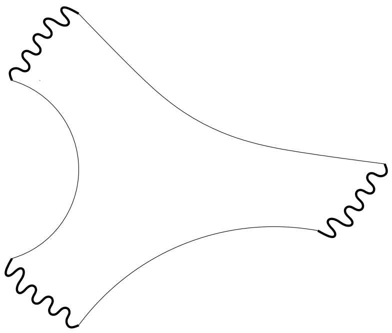
  – $\kappa^2 \sim g^4$ (topological equivalence of string diagrams)

  $\Rightarrow$ Gravity is subleading versus gauge interactions

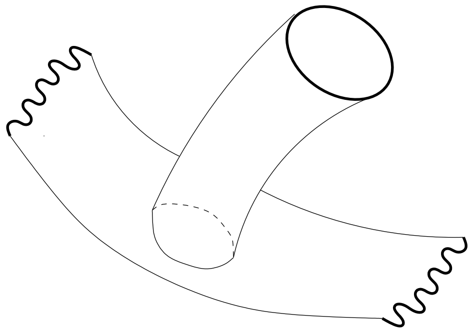
  [Accomando, Antoniadis, Benakli '00; Cullen, Perelstein, Peskin '00]

  $\rightsquigarrow$ Enough to consider open string (lowest order) diagrams

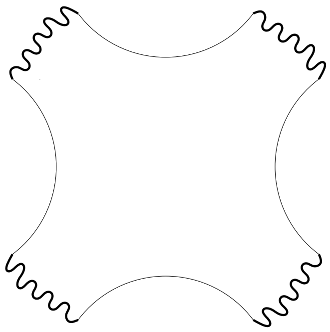
Open vs Closed Strings



$\mathcal{O}(g)$

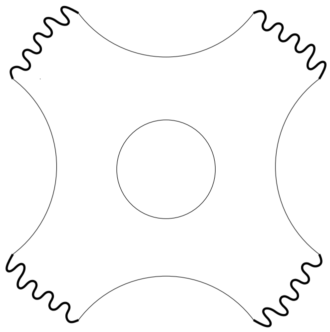


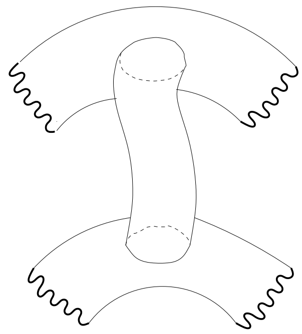
$\mathcal{O}(\kappa)$



Gauge tree level $\mathcal{O}(g^2)$

[disk diagram]



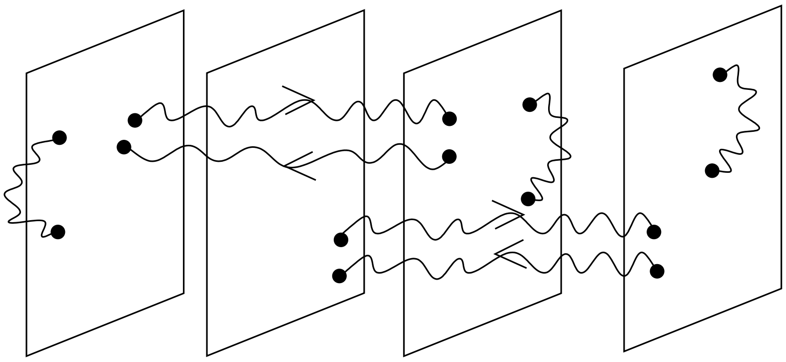


Gauge one loop $\mathcal{O}(g^4)$ $\quad\sim\quad$ Gravity tree level $\mathcal{O}(\kappa^2) = \mathcal{O}(g^4)$

[sphere diagram]

Phenomenology of TeV Strings

The model



N coincident D3-branes

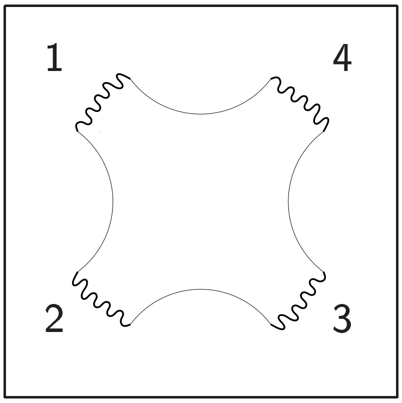
(3-d dynamical objects where open strings may end)

N=4 supersymmetry

$U(N)$ gauge symmetry $\underset{\text{orbifold projection}}{\rightsquigarrow}$ SM (gauge & matter)

Four-fermion string amplitude

[Cullen, Perelstein, Peskin '00]



$$\begin{aligned}\mathcal{A}(1,2,3,4) &= g^2\mathcal{S}(s,t)F^{1243}(s,t,u)\mathrm{Tr}[t^1t^2t^4t^3+t^3t^4t^2t^1]\\ &+ g^2\mathcal{S}(s,u)F^{1234}(s,u,t)\mathrm{Tr}[t^1t^2t^3t^4+t^4t^3t^2t^1]\\ &+ g^2\mathcal{S}(t,u)F^{1324}(t,u,s)\mathrm{Tr}[t^1t^3t^2t^4+t^4t^2t^3t^1]\end{aligned}$$

- Yang-Mills coupling constant g (unified gauge coupling)
- Veneziano factor $\mathcal{S}(s,t)=\dfrac{\Gamma(1-\alpha' s)\Gamma(1-\alpha' t)}{\Gamma(1-\alpha' s-\alpha' t)}$, $\quad\alpha'=M_S^{-2}$
- 4–point ordered tree amplitudes F^{abcd}: "Kinematics"
- Chan-Paton traces of reps. $t^i\in U(N)$: embedding of SM

Veneziano factor

$$\mathcal{S}(s,t)=\frac{\Gamma(1-\alpha' s)\Gamma(1-\alpha' t)}{\Gamma(1-\alpha' s-\alpha' t)}, \qquad \alpha'=1/M_S^2$$

poles @ $1-\alpha' s=0,-1,\ldots$ and zeroes @ $1-\alpha' s-\alpha' t=0,-1,\ldots$

$[\Gamma(\epsilon)=1/\epsilon,\ \Gamma(-1+\epsilon)=-1/\epsilon,\ \ldots]$

Duality: $\mathcal{S}(s,t)=\mathcal{S}(t,s)$

Expansion:

$$\mathcal{S}(s,t)=\sum_{n=1}^{\infty}\frac{\alpha' s+\alpha' t-1}{\alpha' s-n}\,\frac{\alpha' t(\alpha' t+1)\cdots(\alpha' t+n-2)}{(n-1)!}$$

- Low energy limit $(s,|t|\ll M_S^2)\rightsquigarrow$ contact term

$$\mathcal{S}(s,t)=1-\frac{\pi}{6}\frac{st}{M_S^4}+\ldots$$

- At poles $\rightsquigarrow$ String Resonances

$$\mathcal{S}(s,t)=\frac{t}{s-nM_S^2}\,\frac{(t/M_S^2+1)\cdots(t/M_S^2+n-1)}{(n-1)!}$$

- Away from poles $\rightsquigarrow$ interference effects
  - Regge limit:
    Large s and t fixed (small angle) $\rightsquigarrow$ power-law suppression

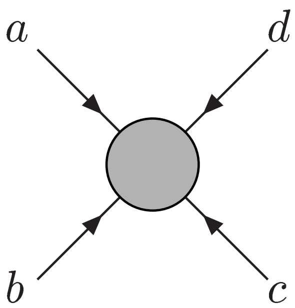
$$\mathcal{S}(s,t)\propto(1-\alpha' s-\alpha' t)\Gamma(1-\alpha' t)\ s^{\alpha' t-1} \qquad [t<0]$$

  - Hard-scattering limit:
    Large s and t/s fixed (fixed θ) $\rightsquigarrow$ exponential suppression

$$\mathcal{S}(s,t)=(1-\alpha' s-\alpha' t)\ \mathrm{e}^{-\alpha' s f(\theta)} \qquad [f(\theta)\geq 0]$$

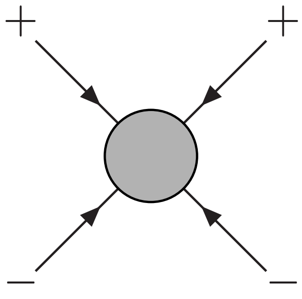
4-point ordered tree amplitudes

(Fermion legs)

$F^{abcd}(s,t,u) \equiv$ 

$$
\begin{aligned}
s &= (p_a + p_b)^2 \\
t &= (p_a + p_c)^2 \\
u &= (p_a + p_d)^2
\end{aligned}
$$

depending on the helicities only (all momenta directed inward):



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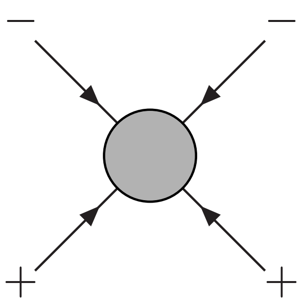
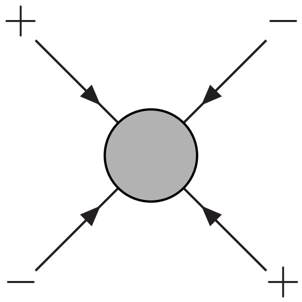


$= -4\dfrac{t}{s}$



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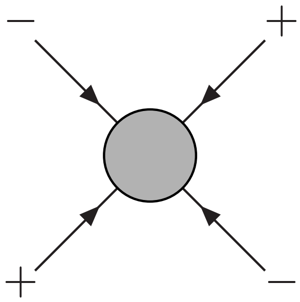
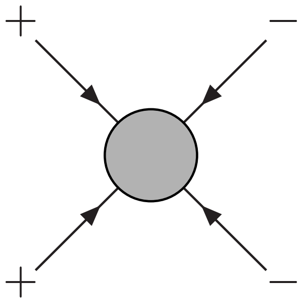


$= -4\dfrac{u^2}{st} = 4\left(\dfrac{u}{s} + \dfrac{u}{t}\right)$



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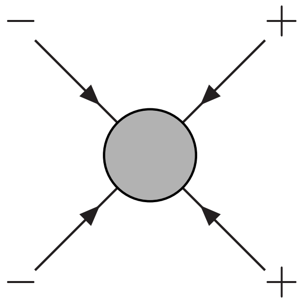


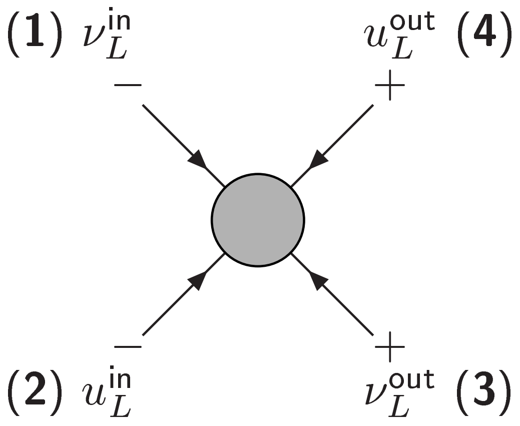
$= -4\dfrac{s}{t}$

otherwise $= 0$

Elastic process $\nu q \to \nu q$

$$[\nu \equiv \nu_L,\ q = u_L, u_R, d_L, d_R, \bar{u}_L, \bar{u}_R, \bar{d}_L, \bar{d}_R]$$

$$\boxed{\nu_L\ u_L \to \nu_L\ u_L}$$



$$\mathcal{A}(\nu_L, u_L, \nu_L, u_L) =$$

$$g^2 \mathcal{S}(s,t)\, \underbrace{F^{--++}(s,t,u)}_{-4\frac{s}{t}}\ T_{1243} + g^2 \mathcal{S}(s,u)\, \underbrace{F^{--++}(s,u,t)}_{-4\frac{s}{u}}\ T_{1234} + g^2 \mathcal{S}(t,u)\, \underbrace{F^{-+-+}(t,u,s)}_{4\left(\frac{s}{t}+\frac{s}{u}\right)}\ T_{1324}$$

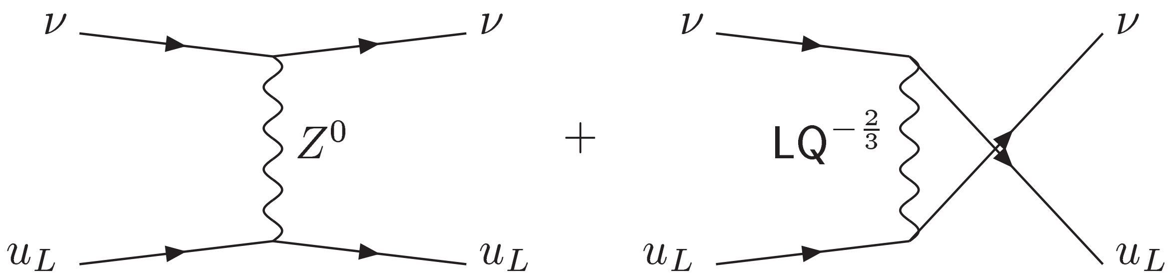
SM and String Excitations

$\mathcal{A}(1,2,3,4)$ as exchange of vibration modes of open strings

• The "massless" zero-modes ($n=0$) are SM fields
$[s,t\to 0 \Rightarrow \mathcal{S}(s,t)\to 1]$

$$\mathcal{A}_0(\nu_L,u_L,\nu_L,u_L) = -4g^2\left[\frac{s}{t}(T_{1243}-T_{1324}) + \frac{s}{u}(T_{1234}-T_{1324})\right]$$

[$t-$ and $u-$channel exchange of spin 1]



In SM [no LQ, massless Z^0 boson and unified couplings: $s_W^2=\frac{3}{8}$]

$$\mathcal{A}_0^{\mathrm{SM}} \approx \frac{2}{5}g^2\frac{s}{t}$$

$\Rightarrow$ **Constraint on the Chan-Paton factors**

$$T_{1243}-T_{1324} = -\frac{1}{10}, \quad T_{1234}=T_{1324}\equiv -\frac{a}{10}$$

• The string corrections provided by the Veneziano factors

$$\mathcal{A} = \frac{2}{5}g^2\left[\frac{s}{t}[(1+a)\mathcal{S}(s,t)-a\mathcal{S}(t,u)] + a\frac{s}{u}[\mathcal{S}(s,u)-\mathcal{S}(t,u)]\right]$$

relevant when s approaches M_S^2

String Resonances

At $s \approx nM_S^2$ string amplitudes have physical poles

[$a = 0$ to simplify]

$$\mathcal{A}_n = \frac{2}{5}\frac{g^2}{s - nM_S^2}\frac{nM_S^4}{t}\frac{(t/M_S^2)(t/M_S^2+1)\cdots(t/M_S^2+n-1)}{(n-1)!}$$

Resonant $s-$channel exchange of a tower of SR (X_n^J) with $M = \sqrt{n}M_S$ and spin $J = 0, \ldots, n-1$

$\boxed{\nu_L\ u_L \to X_n^J \to \nu_L\ u_L}$ $\quad X_n^J = \{\text{LQ}^{\frac{2}{3}}\} \in (\mathbf{3},\mathbf{3})$ of $SU(3)_c \times SU(2)_L$

$$\mathcal{A}_n = \frac{2}{5}g^2\frac{nM_S^2}{s - nM_S^2}\sum_{J=0}^{n-1}\alpha_n^J\ d_{00}^J(\theta), \qquad t = -\frac{nM_S^2}{2}(1-\cos\theta)$$

$\boxed{\alpha_n^J}$ $(a = 0)$

J \ $n = M^2/M_S^2$	1	2	3	4	5	
4					125/336	
3				8/15	0	
2			3/4	0	125/252	
1		1	0	7/15	0	
0	1	0	1/4	0	19/144	$\ldots$

$\Rightarrow$ Partial width $\Gamma(X_n^J \to \nu_L u_L) \equiv \Gamma_n^J = \dfrac{2}{5}\dfrac{g^2|\alpha_n^J|}{16\pi}\dfrac{\sqrt{n}M_S}{2J+1}$

$\Rightarrow$ Sum Rule: $\displaystyle\sum_{j=0}^{n-1}\alpha_n^J = 1$ $(a = 0)$ independent of n (in general)

– Strength of LQ interaction with fixed J: $\alpha_n^J \sim \dfrac{1}{n} \propto \dfrac{1}{M^2}$

– Number of LQ's of different J with fixed mass $\sim n \propto M^2$

$\nu-$Nucleon Total Cross Section

Resonant partonic cross-sections and $\nu q \to$ anything

Narrow Width Approximation: $\dfrac{M\Gamma}{|\hat{s}-M^2+i\Gamma M|^2} \to \pi\delta(\hat{s}-M^2)$

$$\sigma(\nu_L u_L \to X_n^J \to \text{all}) \equiv \sigma_n^J(\nu_L u_L) = \frac{4\pi^2\Gamma_n^J}{\sqrt{n}M_S}(2J+1)\delta(\hat{s}-nM_S^2)$$

$\Rightarrow$ At level n: Sum Rule $\Rightarrow$ same cross section for any mass level!

$$\sigma_n(\nu_L u_L) = \sum_{J=0}^{n-1}\sigma_n^J = \frac{\pi g^2}{4}\delta(\hat{s}-nM_S^2)\begin{cases}\frac{2}{5}|1+2a| & \text{for } n \text{ odd}\\ \frac{2}{5} & \text{for } n \text{ even}\end{cases}$$

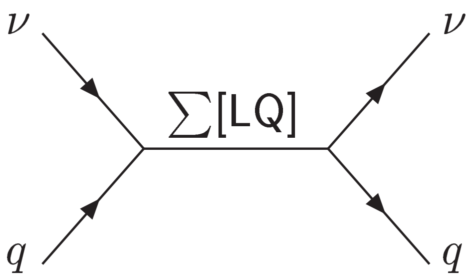
In general, $\sigma_n(\nu_L q) = \dfrac{\pi g^2}{4}\zeta_q\delta(\hat{s}-nM_S^2)$ where

ζ_q	n odd	n even
u_L	$\frac{2}{5}\|1+2a\|$	$\frac{2}{5}$
u_R	$\frac{4}{5}\|b\|$	0
d_L	$\frac{3}{5}\|1+2a'\|$	$\frac{3}{5}$
d_R	$\frac{2}{5}\|b'\|$	0

$s \leftrightarrow u$ crossing

ζ_q	n odd	n even
$\bar{u}_L$	$\frac{2}{5}\|1+2b\|$	$\frac{2}{5}$
$\bar{u}_R$	$\frac{4}{5}\|a\|$	0
$\bar{d}_L$	$\frac{1}{5}\|1+2b'\|$	$\frac{1}{5}$
$\bar{d}_R$	$\frac{6}{5}\|a'\|$	0

Free parameters: M_S and the Chan-Paton "traces" a, a', b, b'



$\to$ Equivalent to *one* LQ of mass $\sqrt{n}M_S$ and coupling $g\sqrt{\zeta}$

[Doncheski, Robinett '97]

String Amplitudes and $s \leftrightarrow u = 1 \leftrightarrow 4$ Crossing

$\mathcal{A}(1234)$	Strings	SM $[s_W^2 = \frac{3}{8};\ M_Z = 0]$	
$\mathcal{A}(\nu_L q_L \to \nu_L q_L)$	$-4g^2 \left[\frac{s}{t} \mathcal{S}(s,t) T^a_{1243} + \frac{s}{u} \mathcal{S}(s,u) T^a_{1234} + \frac{s^2}{tu} \mathcal{S}(t,u) T^a_{1324} \right]$	$\left.\begin{matrix} u_L: & \frac{2}{5} \\ d_L: & -\frac{3}{5} \end{matrix}\right\}$	$\times\, g^2 \frac{s}{t}$
$\mathcal{A}(\nu_L q_R \to \nu_L q_R)$	$-4g^2 \left[\frac{u^2}{st} \mathcal{S}(s,t) T^b_{1243} + \frac{u}{s} \mathcal{S}(s,u) T^b_{1234} + \frac{u}{t} \mathcal{S}(t,u) T^b_{1324} \right]$	$\left.\begin{matrix} u_R: & \frac{2}{5} \\ d_R: & -\frac{1}{5} \end{matrix}\right\}$	$\times\, g^2 \frac{u}{t}$
$\mathcal{A}(\nu_L \bar{q}_R \to \nu_L \bar{q}_R)$	$-4g^2 \left[\frac{u}{t} \mathcal{S}(t,u) T^a_{1243} + \frac{u}{s} \mathcal{S}(s,u) T^a_{1324} + \frac{u^2}{st} \mathcal{S}(s,t) T^a_{1234} \right]$	$\left.\begin{matrix} \bar{u}_R: & \frac{2}{5} \\ \bar{d}_R: & -\frac{3}{5} \end{matrix}\right\}$	$\times\, g^2 \frac{u}{t}$
$\mathcal{A}(\nu_L \bar{q}_L \to \nu_L \bar{q}_L)$	$-4g^2 \left[\frac{s^2}{tu} \mathcal{S}(t,u) T^b_{1243} + \frac{s}{u} \mathcal{S}(s,u) T^b_{1324} + \frac{s}{t} \mathcal{S}(s,t) T^b_{1234} \right]$	$\left.\begin{matrix} \bar{u}_L: & \frac{2}{5} \\ \bar{d}_L: & -\frac{1}{5} \end{matrix}\right\}$	$\times\, g^2 \frac{s}{t}$

$\Rightarrow$

	T_{1234}	T_{1243}	T_{1324}
$u_L,\ \bar{u}_R$	$-\frac{1}{10}a$	$-\frac{1}{10}(1+a)$	$-\frac{1}{10}a$
$d_L,\ \bar{d}_R$	$\frac{3}{20}a'$	$\frac{3}{20}(1+a')$	$\frac{3}{20}a'$
$u_R,\ \bar{u}_L$	$-\frac{1}{10}b$	$-\frac{1}{10}b$	$-\frac{1}{10}(1+b)$
$d_R,\ \bar{d}_L$	$\frac{1}{20}b'$	$\frac{1}{20}b'$	$\frac{1}{20}(1+b)$

Resonant part of the String Amplitudes in NWA

	Part with $s-$channel Resonances
$\nu_L q_L \to \nu_L q_L$	$\left.\begin{array}{ll} u_L: & \frac{2}{5} \\ d_L: & -\frac{3}{5} \end{array}\right\} \times g^2 \left[(1+a)\frac{s}{t}\mathcal{S}(s,t) + a\frac{s}{u}\mathcal{S}(s,u)\right]$
$\nu_L q_R \to \nu_L q_R$	$\left.\begin{array}{ll} u_R: & \frac{2}{5} \\ d_R: & -\frac{1}{5} \end{array}\right\} \times g^2 \left[b\frac{u^2}{st}\mathcal{S}(s,t) + b\frac{u}{s}\mathcal{S}(s,u)\right]$
$\nu_L \bar{q}_R \to \nu_R \bar{q}_R$	$\left.\begin{array}{ll} \bar{u}_R: & \frac{2}{5} \\ \bar{d}_R: & -\frac{3}{5} \end{array}\right\} \times g^2 \left[a\frac{u^2}{st}\mathcal{S}(s,t) + a\frac{u}{s}\mathcal{S}(s,u)\right]$
$\nu_L \bar{q}_L \to \nu_L \bar{q}_L$	$\left.\begin{array}{ll} \bar{u}_L: & \frac{2}{5} \\ \bar{d}_L: & -\frac{1}{5} \end{array}\right\} \times g^2 \left[b\frac{s}{t}\mathcal{S}(s,t) + (1+b)\frac{s}{u}\mathcal{S}(s,u)\right]$

- Expanding $\mathcal{S}(s,t)$ and $\mathcal{S}(s,u)$, the generic resonant amplitudes:

$$g^2 \left[(1+c)\frac{s}{t}\mathcal{S}(s,t) + c\frac{s}{u}\mathcal{S}(s,u)\right] \to g^2 \frac{nM_S^2}{s-nM_S^2} \sum_{J=0}^{n-1} \alpha_n^J[L]\; d_{00}^J(\theta)$$

$$g^2 \left[c\frac{s}{t}\mathcal{S}(s,t) + (1+c)\frac{s}{u}\mathcal{S}(s,u)\right] \to g^2 \frac{nM_S^2}{s-nM_S^2} \sum_{J=0}^{n-1} (-)^{n+1}\alpha_n^J[L]\; d_{00}^J(\theta)$$

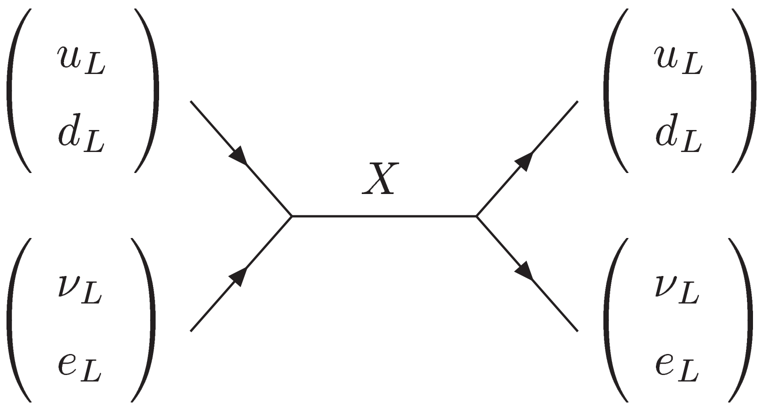
$$g^2 \left[c\frac{u^2}{st}\mathcal{S}(s,t) + c\frac{u}{s}\mathcal{S}(s,u)\right] \to g^2 \frac{nM_S^2}{s-nM_S^2} \sum_{J=1}^{n+1} \alpha_n^J[R]\; d_{00}^J(\theta)$$

- $\sigma(\nu_L q) = \sum_J \frac{4\pi^2 \Gamma_n^J}{\sqrt{n}M_S}(2J+1)\delta(\hat{s}-nM_S^2), \quad \Gamma_n^J \propto \frac{g^2}{16\pi}|\alpha_n^J|\frac{\sqrt{n}M_S}{2J+1}$

$\sum_J \lvert\alpha_n^J\rvert$	n odd	n even
L	$\lvert 1+2c\rvert$	1
R	$2c$	0

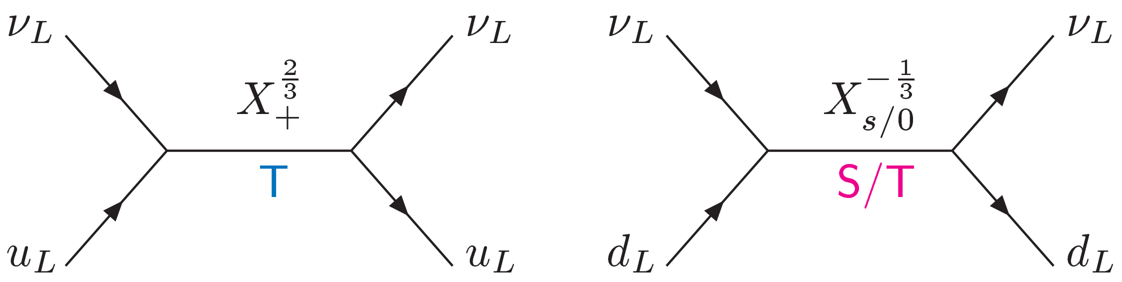
Lepto-Quarks: singlets or triplets of SU(2)

$SU(3)_c \times SU(2)_L \times U(1)_Y$ gauge invariance:



	$SU(3)_c \times SU(2)_L$	Q
$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$(\mathbf{1}, \mathbf{2})$	$\begin{matrix} 0 \\ -1 \end{matrix}$
$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$(\mathbf{3}, \mathbf{2})$	$\begin{matrix} \frac{2}{3} \\ -\frac{1}{3} \end{matrix}$
$X_s^{-\frac{1}{3}}$	$(\mathbf{3}, \mathbf{1})$	$-\frac{1}{3}$
$\begin{pmatrix} X_+^{\frac{2}{3}} \\ X_0^{-\frac{1}{3}} \\ X_-^{\frac{4}{3}} \end{pmatrix}$	$(\mathbf{3}, \mathbf{3})$	$\begin{matrix} \frac{2}{3} \\ -\frac{1}{3} \\ \frac{4}{3} \end{matrix}$

$\Rightarrow$



Gauge invariance: $\mathcal{A}(\mathsf{T}) = \frac{1}{3}\mathcal{A}$, $\mathcal{A}(\mathsf{T}) = \frac{1}{6}\mathcal{A} \Rightarrow \mathcal{A}(\mathsf{T}) = 2\mathcal{A}(\mathsf{T})$

$\Rightarrow$ Mixing of S and T for gauge inv of $n-$odd and $n-$even levels

$\nu-$Nucleon Total Cross Section

Validity of the NWA

Level n: $M_n = \sqrt{n} M_S$ and $\Gamma_n = \sum_J (2J+1)\Gamma_n^J = \frac{2}{5}\frac{g^2}{16\pi} M_n$

(total width grows with $\sqrt{n}$)

- The NWA is poor when $\Gamma_n \sim (M_{n+1} - M_n)/2$, namely

$$\frac{2}{5}\frac{g^2}{16\pi}\sqrt{n} M_S \sim \frac{1}{2}(M_{n+1} - M_n) \approx \frac{M_S}{4\sqrt{n}} \Rightarrow \frac{2}{5}\frac{g^2}{4\pi} n \sim 1$$

$$\left[\frac{g^2}{4\pi} = \frac{\sqrt{2} M_W^2 G_F}{\pi} \approx \frac{1}{20}\right]$$

- For $n \gtrsim n_{cut} \sim 50$ interference effects become important
  They form a cotinuum and cross sections go to zero:
  - as a power law at small angles (large s, t fixed)
  - exponentially at fixed angles (large s, t/s fixed)

Therefore: consider only resonant contributions available below cut

Given $s = 2m_N E_\nu$ above M_S scale, $\hat{s} = xs$ picks n resonances

$$n \in [1, \min\{n_{cut}, n_{max}\}], \quad n_{max} = \mathrm{INT}\frac{s}{M_S^2}$$

$\nu-$Nucleon Total Cross Section

Convolution with Parton Distribution Functions

$$\text{Isoscalar Nucleon } N = \frac{p+n}{2}$$

$$s = 2m_N E_\nu, \quad \hat{s} = xs, \quad \hat{t} = -xys \equiv -Q^2$$

- **SM**

$$\sigma_{\nu N}^{\rm SM} = \sigma_{\nu N}^{\rm NC} + \sigma_{\nu N}^{\rm CC}$$

$$\frac{\mathrm{d}^2\sigma_{\nu N}^{\rm NC/CC}}{\mathrm{d}x\mathrm{d}y}(s) = \frac{G_F^2 s}{\pi}\left(\frac{M_{\rm V}^2}{Q^2+M_{\rm V}^2}\right)^2 \left[xq^{\rm V}(x,Q^2) + x(1-y)^2\bar{q}^{\rm V}(x,Q^2)\right]$$

$\mathrm{V} = Z^0,\ W^\pm$ and $q^{\rm V}(x,Q^2) =$ pdf's $\times$ appropriate couplings

- **String-SM**

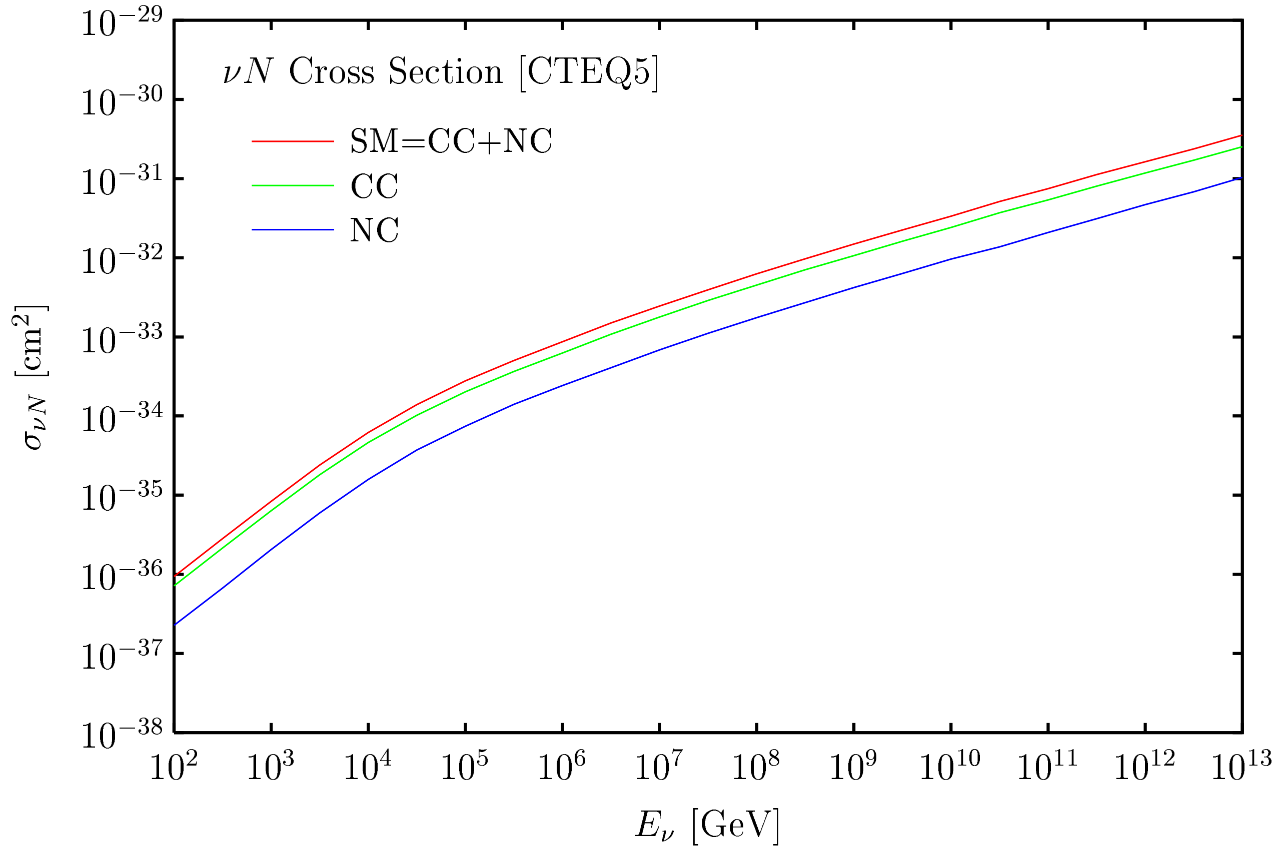
$$\begin{aligned}\sigma_{\nu N}(s) &\approx \int \mathrm{d}x \frac{\pi g^2}{4}\sum_{n=1}^{n_{\rm cut}}\sum_q \zeta_q \delta(xs - nM_S^2) q(x,Q^2) \\ &= \frac{\pi g^2}{4}\sum_{n=1}^{n_{\rm cut}}\sum_q \zeta_q \frac{x_n q(x_n,Q_n^2)}{nM_S^2}\end{aligned}$$

with $x_n = \dfrac{nM_S^2}{s}$, $Q_n^2 = nM_S^2$

$$x_{\rm min} \approx 0.5\times 10^6 \left(\frac{M_S}{\text{TeV}}\right)^2 \left(\frac{E_\nu}{\text{GeV}}\right)^{-1} \Rightarrow 0.5\times10^{-5} \text{ for } E_\nu = 10^{11} \text{ GeV}$$

if $M_S = 1$ TeV

$\nu-$Nucleon Total Cross Section in SM



Parton distribution functions

– CTEQ5 in the DIS scheme *[Lai et al '00]*

$$[x_{\rm min}^{\rm HERA} \sim 10^{-4} \Rightarrow E_\nu \lesssim 10^6 \text{ GeV probes HERA values}]$$

extrapolated for $x < 10^{-5}$: *[Quigg et al '98]*

$$xq_s(x) \propto x^{-\lambda}, \quad \lambda > 0$$

$\rightsquigarrow$ Low x and the unitarity problem (saturation?):

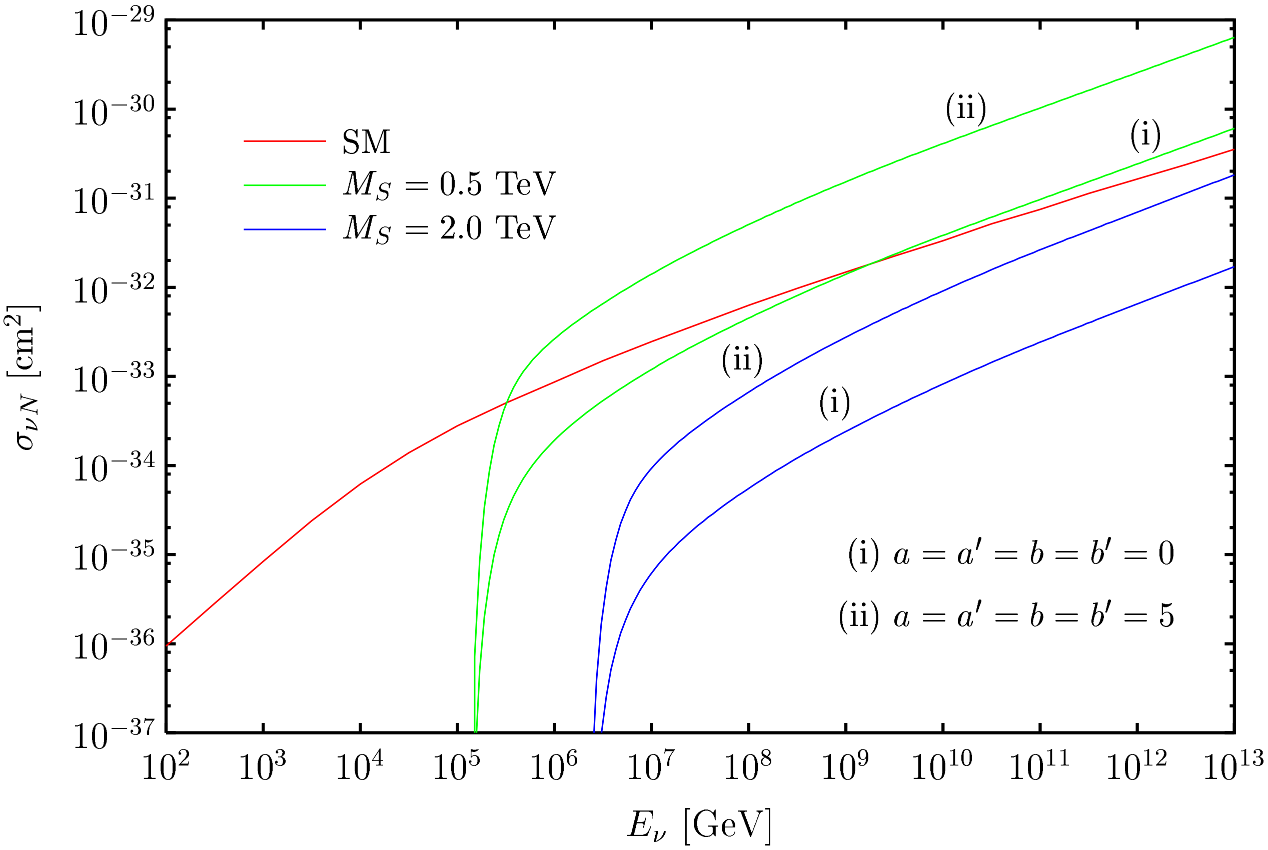
Recent unitarity bound: $\sigma_{\nu N} \leq 9.3 \times 10^{-33}$ cm^2 *[Dicus et al '01]*

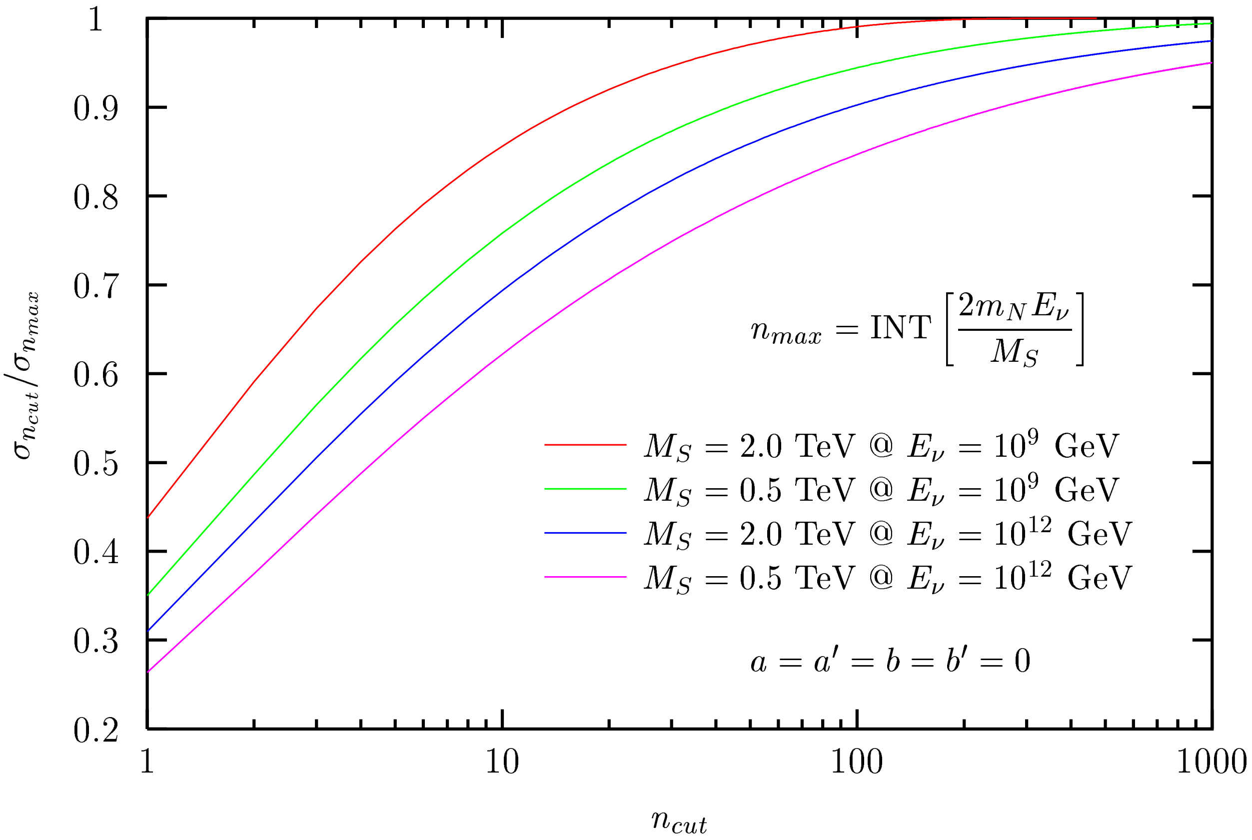
$\Rightarrow E_\nu \gtrsim 2 \times 10^8$ GeV probes *potentially overestimated* pdf's in SM

$$\langle x \rangle \approx \frac{1}{\sigma}\frac{G_F^2 M_W^2}{16\pi}\frac{M_W}{\sqrt{s}} \approx 10 \left(\frac{E_\nu}{\text{GeV}}\right)^{-0.8} \Rightarrow 10^{-8} \text{ for } E_\nu = 10^{11} \text{ GeV}$$

ν−Nucleon Total Cross Section in the String-SM

We would like $\sigma_{\nu N} \sim \sigma_{pp} \sim 10^{-25}$ cm^2, but ...





Conclusions

- νN cross section in extra dimensions $\rightsquigarrow$ enhancement
  Large multiplicity of states consistent in string theory context

- Weakly-interacting string theory $\rightsquigarrow$ gravity subleading

$$\frac{\text{gravity (closed)}}{\text{gauge (open)}} \sim \mathcal{O}(g^2)$$

- s, t, u dualities: massless vector bosons in $t-$channel
  $\Rightarrow$ tower of massive leptoquarks as string excitations
  $\Rightarrow$ dominance of resonant $s-$channel LQ's for $s \gtrsim M_S^2$

▷ Insufficient to explain supra-GZK events

▷ Deviation perhaps detectable if *horizontal air showers* observed in next experiments; or in *neutrino telescopes*:

[Tyler, Olinto, Sigl '00]

[OWL (space); AMANDA (under ice), Baikal (under water) ...]

now: $\underbrace{2 \times 10^{-30}}_{\times 10^{-2} \text{ in future}} \lesssim \sigma \lesssim \underbrace{10^{-27}\ \text{cm}^2}_{\text{to penetrate atmph}}$ excluded

or in *second-generation neutrino telescopes* [Icecube]
measuring neutrino energies until 10^7 GeV over 4π solid angle

[F. Halzen et al '01]

○ Gravity dominates in the forward region $-t \ll M_S^2 \ll s$:

Regge behavior of Virasoro (closed) versus Veneziano (open) string amplitudes $\rightsquigarrow$ dominance of massless spin 2 (graviton) over spin 1 (gauge) fields for large s and small t (forward)

$\Rightarrow$ no impact on UHECR's: no air shower development
(only nucleon could initiate shower but E transfer too small)

[Kachelriess, Plümacher '00]

Development of Air Showers

A. Total Cross Section

The atmosphere is ≈ 36 times deeper horizontally than vertically

Vertical depth: $x_V = 1033\ \mathrm{g/cm}^2$

Horizontal depth: $x_H \approx 36\ x_V$

In terms of the mean free path λ of a particle with cross section σ:

$$\frac{x_V}{\lambda} = \frac{\sigma}{1.6\ \mathrm{mb}} \qquad \frac{x_H}{\lambda} = \frac{\sigma}{44\ \mu\mathrm{b}}$$

Namely:

- $\sigma \lesssim \frac{1}{2}40\ \mu$b: chance for a horizontal air shower deep enough to be detected at ground (with present experiments)
- $\sigma \gtrsim 1$ mb: primary cannot penetrate the atmosphere or shower too high to be detected

Conclusions:

$$2 \times 10^{-30} \lesssim \sigma \lesssim 10^{-27}\ \mathrm{cm}^2 \text{ excluded}$$

⋆ Smaller than the lower bound cannot produce the UHECRs but above the upper limit it is possible $(10^{-25}$ cm^2 needed)

Neutrinos:

⋆ UHE primary cannot be a neutrino even in presence of SR

⋆ Nevertheless, effects of SR on horizontal air showers possible:

– below present exclusion limit of 2×10^{-30} cm^2 and

– above SM predictions of 10^{-31} cm^2

Development of Air Showers

B. Energy Transfer

$$y = \frac{E_\nu - E'_\nu}{E_\nu}, \quad Q^2 = y\hat{s}$$

- NN interactions:

  $y \approx 0.6$ and both nucleons initiate a hadronic shower

  $\Rightarrow$ But where do the supra-GZK nucleons come from?

- νN interactions in the SM or via KK-exchange:

  $y \approx 0.1$ (at very high energy)

  - Charged-Current scattering [SM]:
    the charged lepton initiates an electromagnetic shower
    (practically undistinguishable from a hadronic shower)
    but the cross section is not high enough!
  - Neutral-Current scattering [SM or KK-gravitons]:
    neither the hit nucleon (small energy) nor the scattered
    neutrino can initiate an air shower

    [Kachelriess, Plümacher '00]

  $\Rightarrow$ Neutrinos cannot be the primaries in this framework

- νN scattering in Weakly-coupled String Theory:

  - Resonant region:
    Open strings dominant & their SR exchanged in $s-$channel
    $\Rightarrow$ SR$\to$anything $\rightsquigarrow$ air showers if σ was high enough
  - Forward region [Regge limit]:
    Massless modes dominant $\rightsquigarrow$ $t-$channel graviton dominant
    $\Rightarrow$ Cross section probably high but small $y \rightsquigarrow$ no air shower

Collider Probes of TeV Strings

[Cullen, Perelstein, Peskin '00]

If Quantum Gravity represented by a Weakly-coupled String Theory
$\Rightarrow$ up-to-now signatures of large extra dimensions overshadowed by genuine string effects (string resonances in two-body scattering)

- Probes on extra dimensions rely on:

– graviton emission (missing energy):

	R / $M_\star$ $(n=2)$	R / $M_\star$ $(n=4)$	R / $M_\star$ $(n=6)$
SN1987A	3×10^{-5} / 50000	1×10^{-9} / 1000	6×10^{-11} / 100
LEP 2	4.8×10^{-2} / 1200	1.9×10^{-9} / 730	6.8×10^{-12} / 530
Tevatron	5.5×10^{-2} / 1140	1.4×10^{-9} / 860	4.1×10^{-12} / 780
LC	1.2×10^{-3} / 7700	1.2×10^{-10} / 4500	6.5×10^{-13} / 3100
LHC	4.5×10^{-4} / 12500	5.6×10^{-11} / 7500	2.7×10^{-13} / 6000

R [cm] $M_\star$ [GeV]

– graviton exchange $\Rightarrow$ disregard
[model-dependent and may not be of purely gravitational origin]

- There is a model-dependent relation of $M_\star$ to M_S:

$$M_\star/M_S \approx 1.6 - 3.0$$

- Limits:

– Since string resonances have not yet been observed:

$M_S \gtrsim 1$ TeV $\Rightarrow M_\star \gtrsim 1.6$ TeV [strongest limit except for SN1987A]

– In the future:

$$M_\star \gtrsim 8\ \text{TeV} \Rightarrow M_S \gtrsim 5\ \text{TeV}\ [\text{LC}]$$

and somewhat better in LHC applying a very hard E_T cut