HIGHLY-IONIZING PARTICLES @ THE LHC Non-SUSY Scenarios

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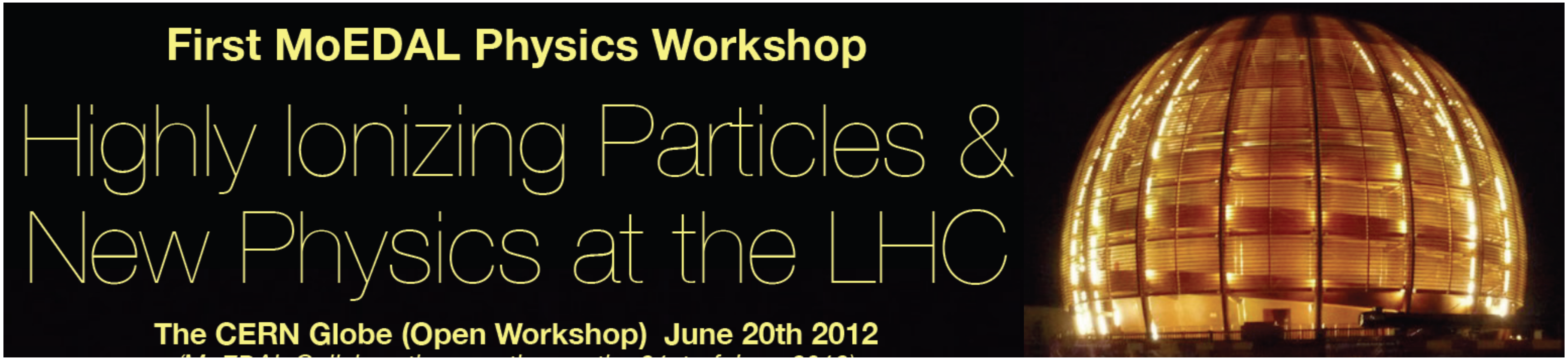


First MoEDAL Physics Workshop

Highly Ionizing Particles & New Physics at the LHC

The CERN Globe (Open Workshop) June 20th 2012

OUTLINE

- MOTIVATION: Several theories BSM predict extra highly-ionising matter…
- Focus on Non-SUSY scenarios & some unconventional SUSY ones
- DOUBLY-CHARGED HIGGS MODELS
- QUIRKS
- Q-BALLS
- D-matter
- CHAMPS
- Charged TeV Black Hole remnants…

RELEVANCE TO MoEDAL
IF: MASSIVE, LONG-LIVED &
HIGHLY IONISING

MOEDAL

The 7th LHC Experiment

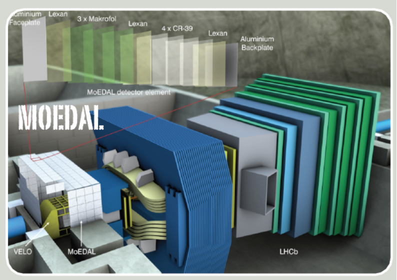
DESIGNED TO SEARCH FOR HIGHLY-IONIZING PARTICLES PRODUCED IN P-P COLLISONS AT THE LHC. SUCH PARTICLES ARE HARBINGERS OF REVOLUTIONARY NEW PHYSICS

THE INTERNATIONAL MOEDAL COLLABORATION

UNIVERSITY OF ALBERTA (CDN); INFN BOLOGNA (IT); CERN (CH), DESY (DE); UNIVERSITY OF CINCINATTI, (USA); GENEVA UNIVERSITY (CH); KING'S COLLEGE LONDON (UK); INSTITUTE OF SPACE SCIENCES BUCHAREST (RO); NORTHEASTERN UNIVERSITY, BOSTON (USA); CZECH TECHNICAL UNIVERSITY IN PRAGUE (CZ),

The Pirnciples of MoEDAL Searches

Particle must be *massive*, *long-lived* & *highly ionizing* to be detected at *MoEDAL*



- *To get high ionization we need:*
  - *Magnetic charge or multiple electric charge (Monopoles, Dyons, SMPs…)*
  - *Very low velocity & electric charge (Stable Massive Particles - SMPs)*
  - *Any combination of the above*
- *MoEDAL has a threshold of Z/β ~ 5*

VELOCITY: $\beta = V/C$

$$-\frac{dE}{dx} = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2} \right]$$

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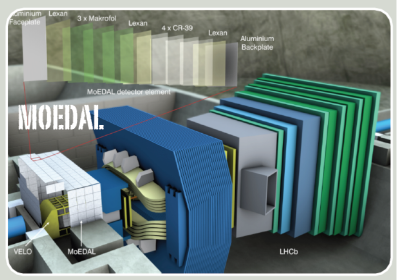

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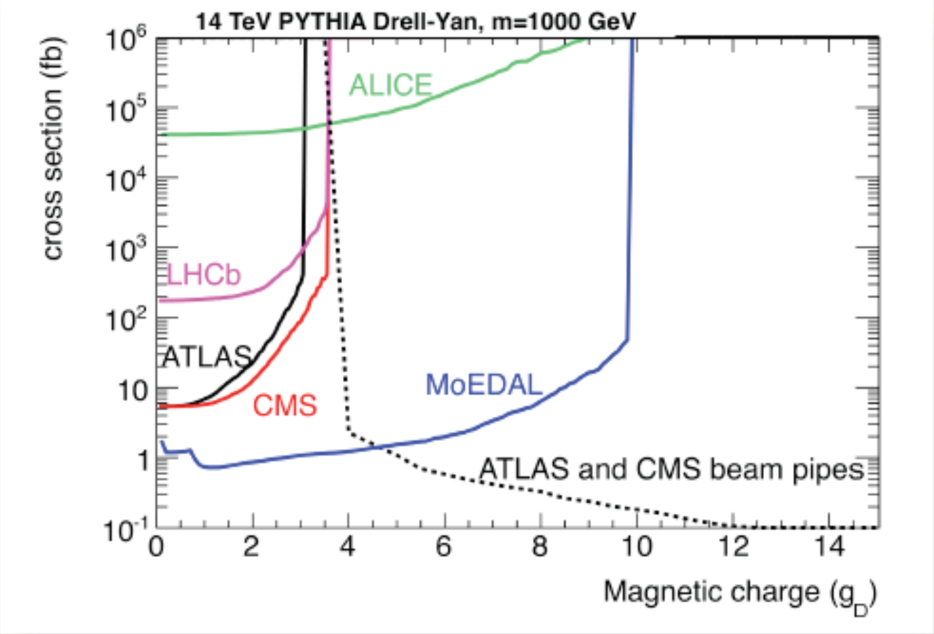
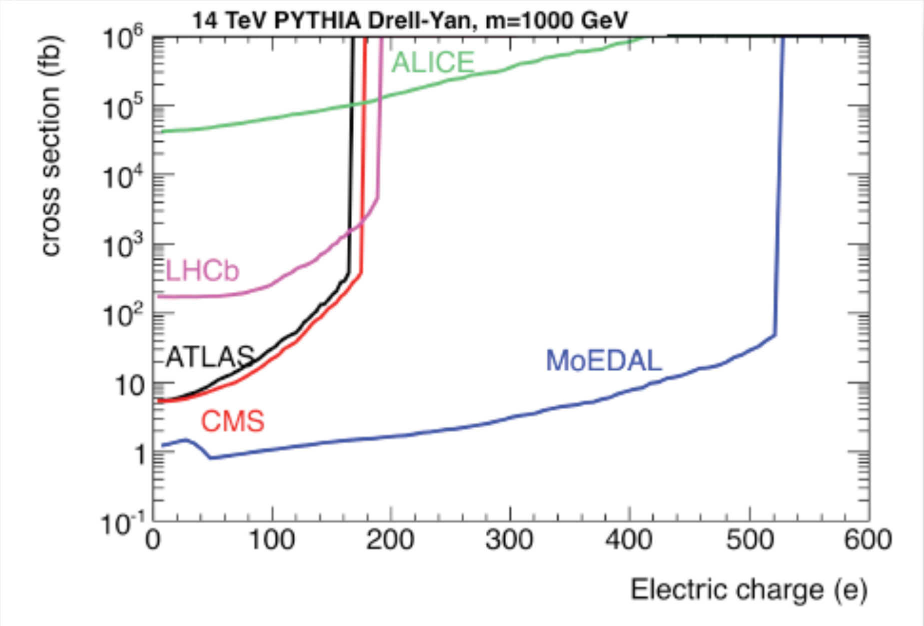
MOEDAL SENSITIVITY





@ 20 fb^{-1} (assumed)

ArXive:1112.2999v2

DOUBLY
CHARGED
HIGGS

DOUBLY-CHARGED HIGGS

- Extended Higgs sector in BSM models: $SU_L(2) \times SU_R(2) \times U_{B-L}(1)$ P-violating model
- Higgs triplet model with massive left-handed neutrinos but not right-handed ones
- COMMON FEATURE: *doubly charged* Higgs bosons $H^{\pm\pm}$ as parts of a Higgs triplet
- **$H_L^{\pm\pm}$: couple to Higgs, EW gauge bosons & left-handed charged leptons**
- **$H_R^{\pm\pm}$: couple to Higgs EW gauge bosons & right-handed charged leptons**

Higgs Triplet Model (HTM) - details

- Yukawa couplings

$$\mathcal{L} \ni h_{ij} \psi_{iL}^T C i \sigma_2 \Delta \psi_{jL} + \mathrm{h.c.} \qquad i, j = e, \mu, \tau$$

- Higgs triplet $(\delta^{++}, \delta^{+}, \delta^{0})$ $\boxed{\langle \delta^0 \rangle = v_\Delta/\sqrt{2}}$

Realistic neutrino masses & $\rho_{EW} = \dfrac{M_W^2}{M_Z^2 \cos^2\theta_W} \simeq 1$

for $1\,\mathrm{eV} \leq v_\Delta \leq 1\,\mathrm{GeV}$

Triplet in 2 x 2 rep: $\Delta = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+/\sqrt{2} \end{pmatrix}$

COLLIDER PRODUCTION OF $H_{L,R}^{\pm\pm}$

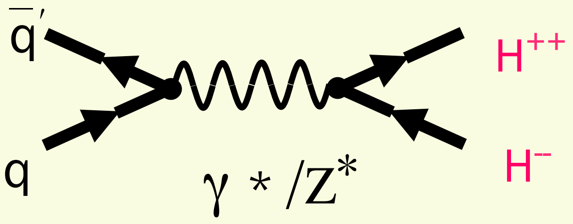
$$q\,\overline{q}\;\rightarrow \gamma^*/Z \rightarrow\; H^{++}\,H^{--}$$

$$q\,\overline{q}'\;\rightarrow W^*\;\rightarrow H^{\pm\pm}\,H^{\mp}$$

Comparable
Cross sections
if $m(H^{\pm\pm}) \approx m\,(H^{\pm})$

Collider Production of $H^{\pm\pm}$

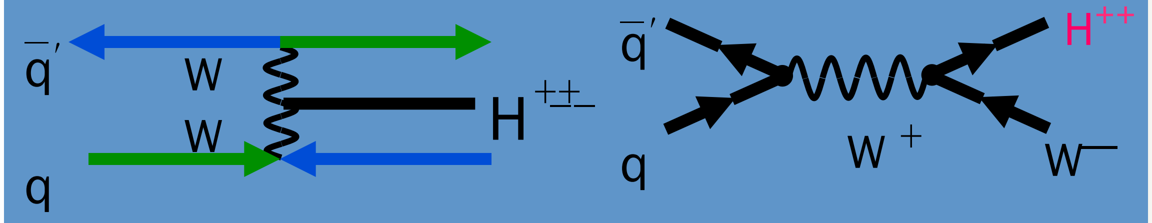
Pair Production :



Dominant Production mode

Cross section independent of Fermionic coupling

W-W Fusion :

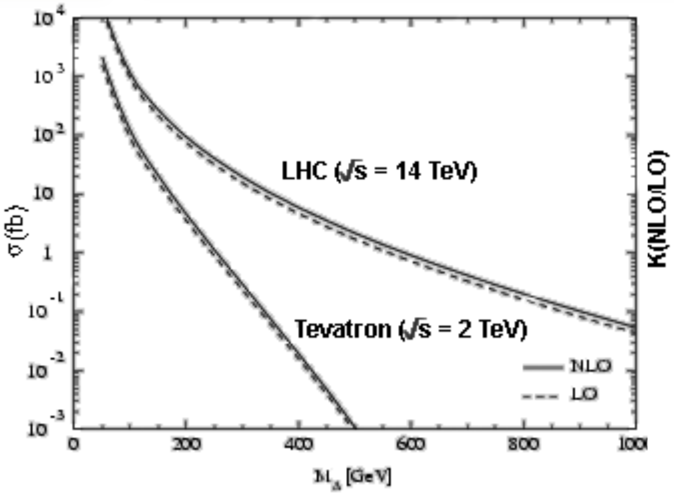


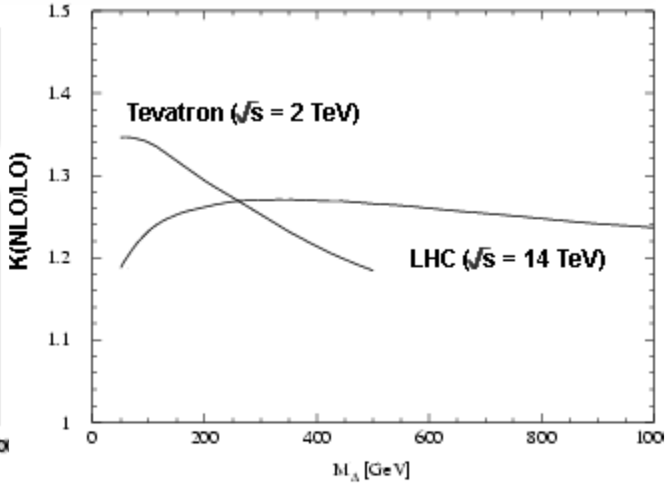
Small probability

$|\rho_{EW} - 1|$ Is small, experimentally observed

Doubly-charged Higgs production cross section is enhanced substantially (~35%) due to NLO corrections.

R-handed H++ cross section is smaller by a factor of ~2 due to different value of coupling of these particles to Z bosons.





M. Spira & M. Mühlleitner, hep-ph/0305288

DECAYS OF $H_{L,R}^{\pm\pm}$

DECAYS TO WW

$$H^{\pm\pm} \to W^{\pm} W^{\pm}$$

LEPTONIC DECAY MODES :

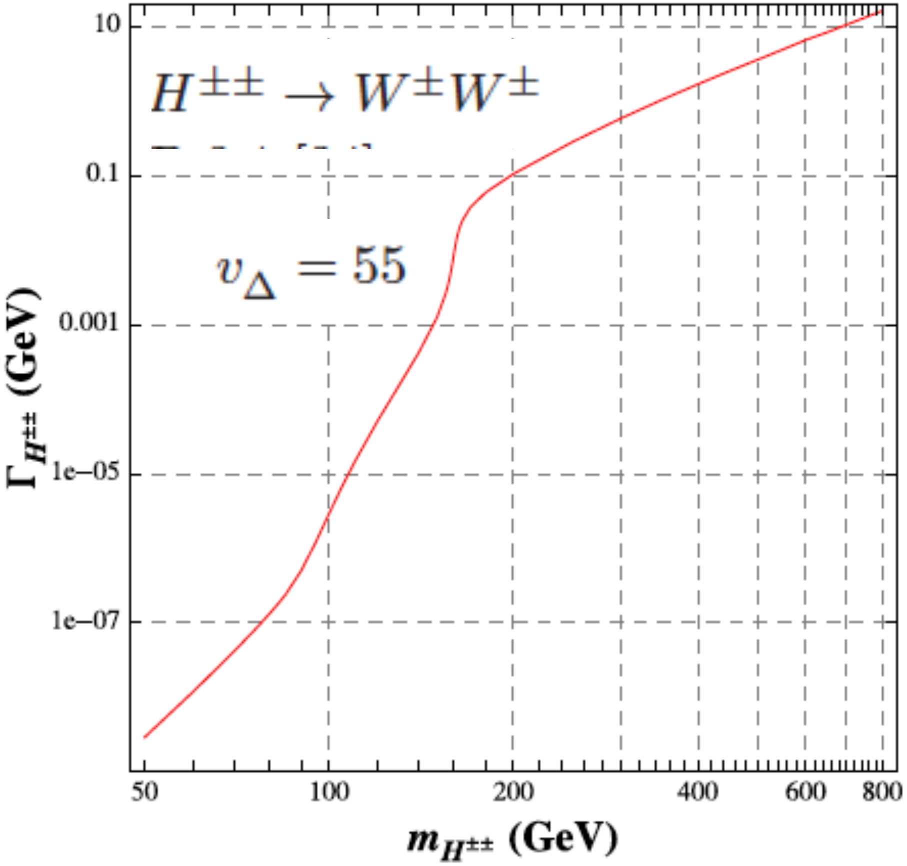
$$H^{\pm\pm} \to \ell^{\pm} \ell^{\pm}$$

DOMINANT FOR MASS RANGE:

$$m(H^{\pm\pm}) < m(W^{\pm}) + m(H^{\pm})$$

LEPTON-FLAVOUR-VIOLATING DECAY MODES ALLOWED
-may be particular large, e.g. BR($H^{--} \to \mu\, \tau$) ≈ 1/3

Life-Time of $H^{\pm\pm}$

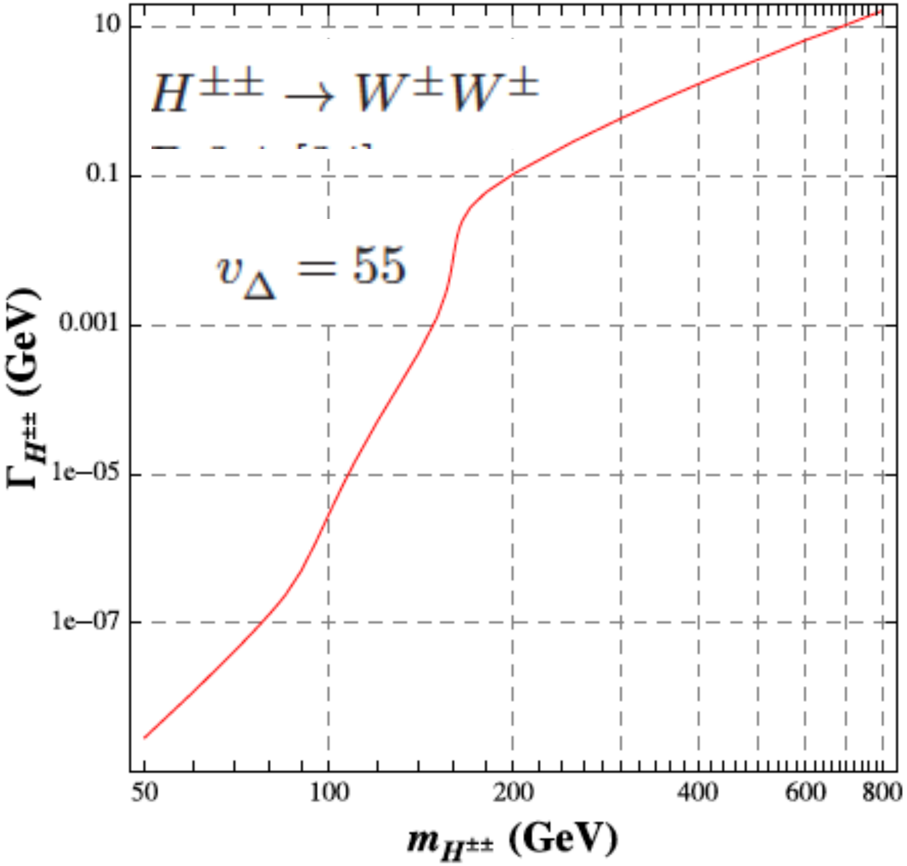


Partial decay width of $H^{\pm\pm} \to W^{\pm}W^{\pm}$

Chiang, Nomura, Tsumura, arXive 1202.2014

Depends on many parameters : Yukawa h_{ij}, mass of $H^{\pm\pm}$, , v_Δ , QCD effects....

Life-Time of $H^{\pm\pm}$



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Essentially there are no constraints on its life time …
it can be long (e.g. for $h_{ij} < 10^{-8}$)
→ RELEVANT FOR MoEDAL

Decaying $H^{\pm\pm}$ SEARCHES @ LHC

$$\boxed{\sigma_{H^{\pm\pm}} = \sigma(p\bar{p}, pp \to H^{++}H^{--}) + \sigma(p\bar{p}, pp \to H^{++}H^{-}) + \sigma(p\bar{p}, pp \to H^{--}H^{+})}$$

@ LHC: $\sigma(pp \to H^{++}\, H^{-}) > \sigma(pp \to H^{-} - H^{+})$

Several Studies @ LHC in decay channel (increased sensitivity of LHC vs Tevatron) $H^{\pm\pm} \to \ell_i^{\pm}\ell_j^{\pm}\ (i,j = e,\mu,\tau)$

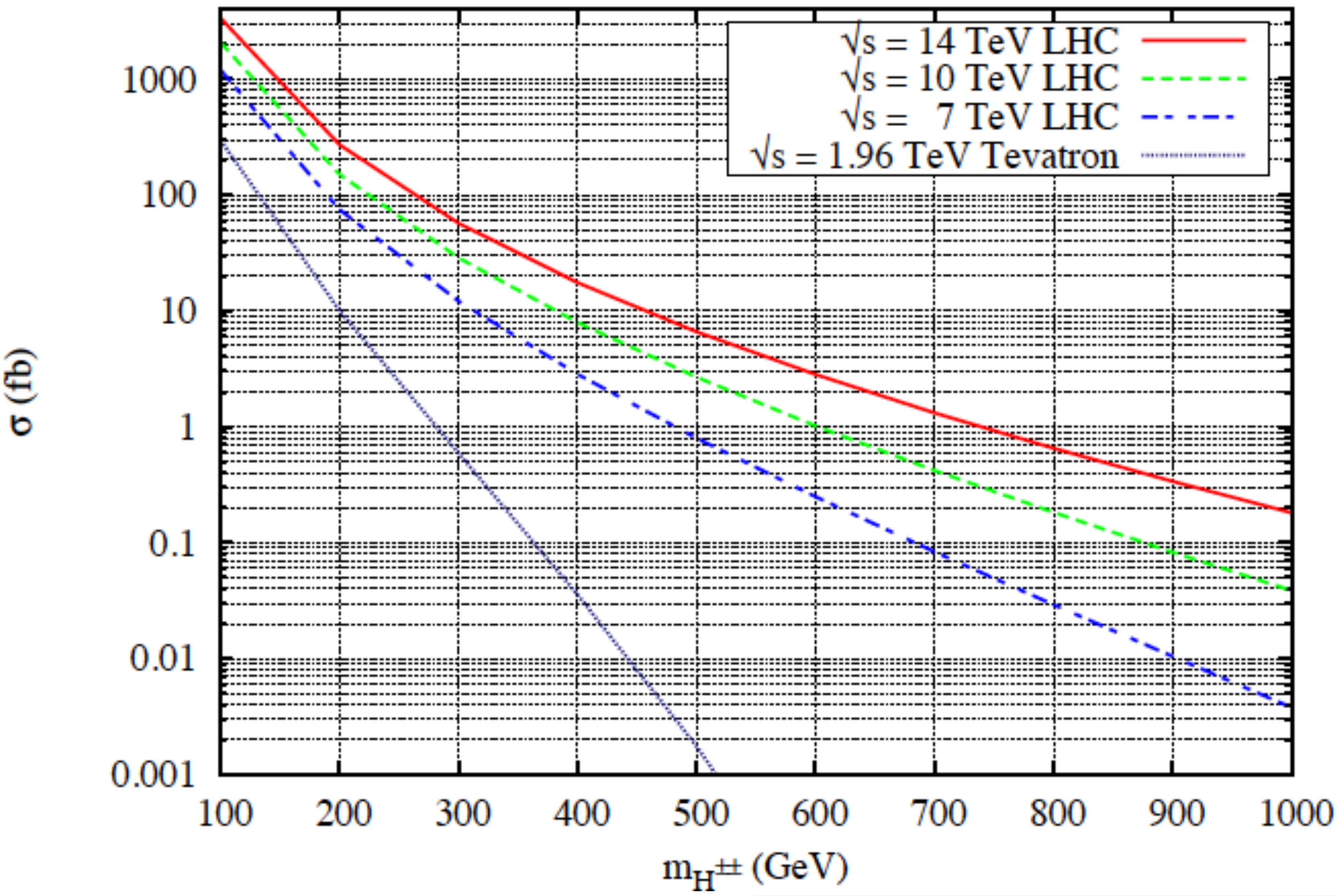
e.g. study of production $q\bar{q} \to \gamma^*, Z^* \to H^{++}H^{--}$

followed by a decay $H^{++}H^{--} \to \ell^{+}\ell^{+}\ell^{-}\ell^{-}$

Expected LHC exclusion limits assuming BR($H^{\pm\pm} \to \mu^{\pm}\mu^{\pm}$) = 100 %

$$\boxed{m_{H^{\pm\pm}} < 800 \text{ GeV and } \mathcal{L} = 50 \text{ fb}^{-1}}$$

$$\sigma_{H^{\pm\pm}} = \sigma(p\bar{p}, pp \to H^{++}H^{--}) + \sigma(p\bar{p}, pp \to H^{++}H^{-}) + \sigma(p\bar{p}, pp \to H^{--}H^{+})$$

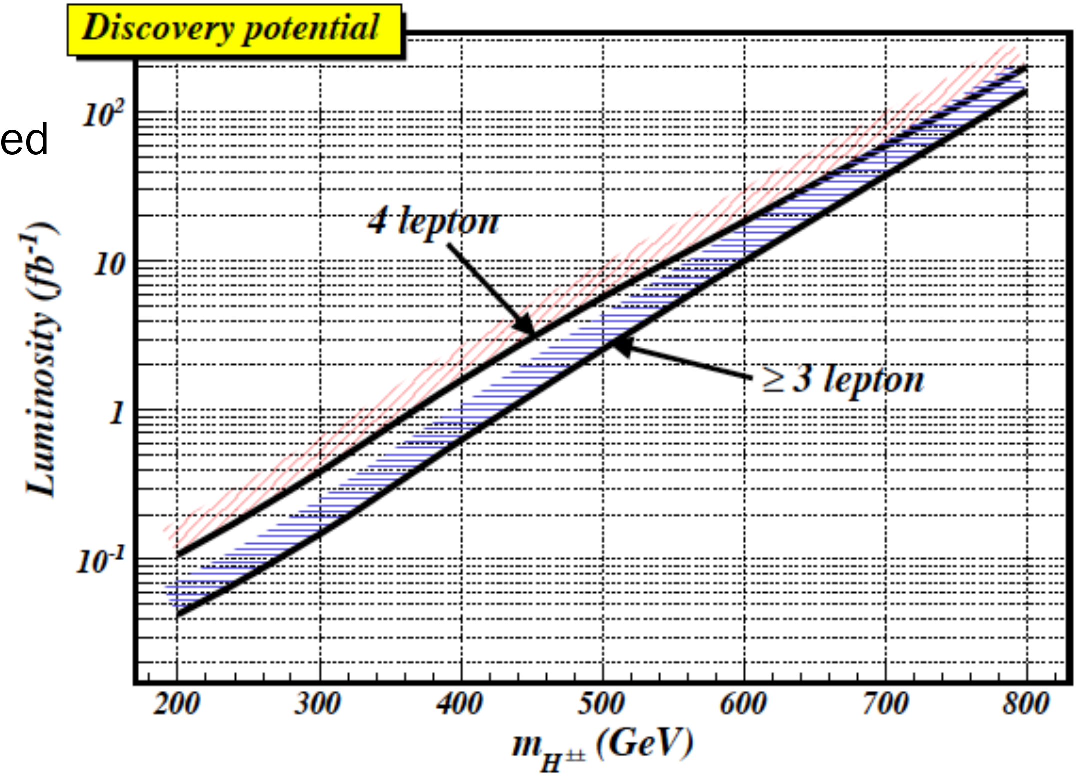


Akeroyd, Chiang, Gaur, arXive:10092780

$H^{\pm\pm}$ SEARCHES @ LHC - Higgs Triplet Model

Three-Lepton decay signatures may offer significantly greater discovery potential of $H^{\pm\pm}$ in Higgs triplet model vs four-lepton signatures

In such a case, production mechanism $pp \to W^{\pm *} \to H^{\pm\pm} H^{\mp}$ contributes to the signal and has superior sensitivity in the region of $m(H^{\pm\pm}) > 200$ GeV (i.e. high invariant mass of charged lepton pairs) for which SM background is small



$H^{\pm\pm}$ SEARCHES @ LHC –HTM

Akeroyd, Sugiyama, arXive:1105.2209

Large branching ratios of $H^{\pm} \to H^{\pm\pm}W^{*}$ in sizable regions of parameter space

From $q'\overline{q} \to W^{*} \to H^{\pm\pm}H^{\mp}$ → pair production of $H^{\pm\pm}$ with cross section comparable to standard $H^{\pm\pm}$ pair production via $q\overline{q} \to \gamma^{*}, Z^{*} \to H^{++}H^{--}$

→ enhanced detection process in four lepton channel @ LHC

Additional decays $H^0 \to H^{\pm}W^{*}$ and $A^0 \to H^{\pm}W^{*}$ from production of neutral triplet scalars, lead to additional production of $H^{\pm}$ with additional production (via $H^{\pm}$ decays) to $H^{\pm\pm}$.

Connection with MoEDAL

$H^{\pm\pm}$ must be *long-lived* & *highly ionizing* in order to be detected at *MoEDAL*

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Long Lived Doubly Charged Higgs

- No constraint on the lifetime of $H^{\pm\pm}$, can be long
- Search for particles with $c\tau > 3$ m, no decay within the detector
- They will behave like heavy stable particles, (muons but more ionising)
- Main process of energy loss is ionization , $dE/dx \propto (\text{charge})^2$

Measurement of ionization – dE/dx measurement along the charged particle track in tracker and calorimeter.

Background – Advantage is lack of Standard Model decays. Events expected from highly ionizing particles.

- Muons – data from cosmic rays (pure muon sample)
- Electrons – W $\rightarrow$ e υ Monte Carlo sample
- Hadronic decays for taus from Monte Carlo sample
- QCD contribution calculated from experimental data

CDF strategy:
S Banerjee ICHEP2004

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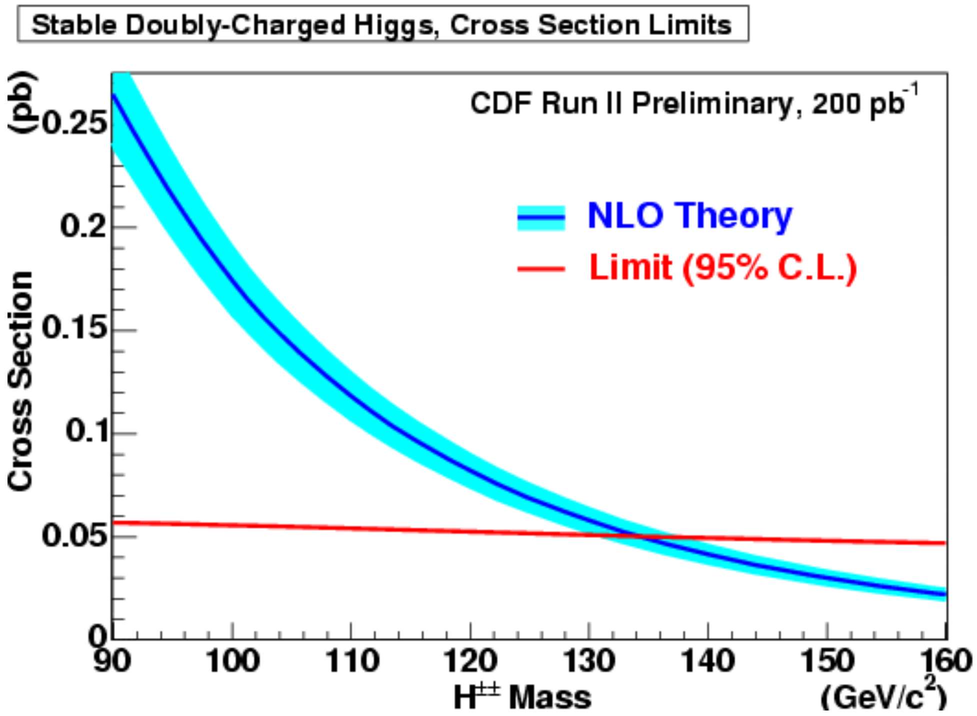
Mass Limit for Long Lived $H^{\pm\pm}$

CDF strategy:
S Banerjee ICHEP2004



Bayesian upper limit on $H^{\pm\pm}$ crosssection

$$\sigma\ H^{\pm\pm} = \frac{\text{Upper Limit on No. of Signal Events at 95\% C.L. for 0 Observed Events}}{\text{Total } H^{\pm\pm} \text{ Acceptance x Integrated Luminosity}}$$

For a $H^{\pm\pm}$ mass of 130 GeV $H^{\pm\pm}$ cross section is 0.057 ± 0.0066 ± 0.0030

Mass Limit for Quasi-Stable Doubly charged Higgs is 134 GeV

Long Lived Doubly Charged Higgs & MoEDAL

$$\mathcal{L} \ni h_{ij}\psi_{iL}^{T}Ci\sigma_2\Delta\psi_{jL} + \text{h.c.}$$

For very small Yukawa couplings $h_{ij} < 10^{-8}$ the doubly charged Higgs boson could be quasi-stable.

In this case very slow pseudo-stable Higgs could be detected in the MoEDAL NTDs. For example with **CR39**, one could detect doubly charged Higgs particles with a $Z/\beta > 5$ (15), where $\beta \leq 0.4$ (0.13).

If such slow heavy particles are produced then one could have difficulty measuring them in ATLAS and CMS as their journey through the detector to the muon system would span more than one beam crossing.

Long Lived Doubly Charged Higgs & MoEDAL

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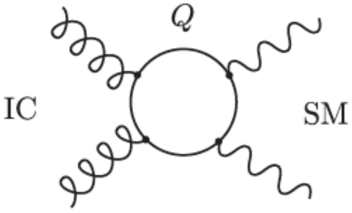
QUIRKS

EXTENSION OF THE SM WITH NEW HEAVY FERMIONS (QUIRKS) CHARGED UNDER BOTH A NEW UNBROKEN GAUGE GROUP & THE SM GUAGE GROUP

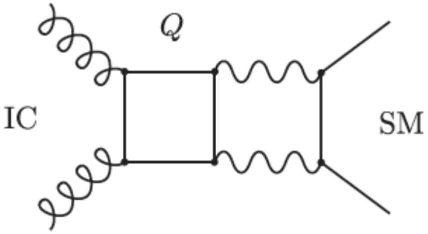
Kang, Lutty arXive: 0805.4642

NEW GAUGE GROUP (``INFRACOLOUR’’ (IC)) SU(N) WITH FERMIONS (QUIRKS) IN FUNDAMENTAL REPRESENTATION BECOMES STRONG AT A SCALE $\Lambda << m$, WHERE m IS THE QUIRK MASS ASSUMED TO BE IN THE PHENOMENOLOGIVCALLY INTERESTING RANGE 100 GeV < m < TeV

COUPLING OF FM TO INFRACOLOUR SECTOR



(a)



(b)

$$\mathcal{L}_{\rm eff} \sim \frac{g^2 g'^2}{16\pi^2 m_Q^4} F_{\mu\nu}^2 F'^2_{\rho\sigma}.$$

EFFECTIVE OPERATOR MEDIATES INFRACOLOUR GLUEBALL DECAY WITH RATE OF ORDER

$$\Gamma \sim \frac{1}{8\pi}\left(\frac{g^2 g'^2}{16\pi^2 m_Q^4}\right)^2 \Lambda^9.$$

$$c\tau \sim 10\ \mathrm{m}\ \left(\frac{\Lambda}{50\ \mathrm{GeV}}\right)^{-9}\left(\frac{m_Q}{\mathrm{TeV}}\right)^{-8}.$$

INFRACOLOUR GLUEBALLS CSAN DECAY INSIDE PARTICLE DETECTOR FOR Λ > 50 GeV

FOR Λ < 50 MeV LIFE TIME BECOMES LONGER THAN AGE OF UNIVERSE (METASTABLE STATE) → **RELEVANCE FOR MoEDAL** AS

QUIRKS CAN BE HIGHLY IONIZING

IN PARTICULAR:

BREAKING OF INFRACOLOUR STRING IS EXPONENTIALLY SUPPRESSED FOR Λ << m

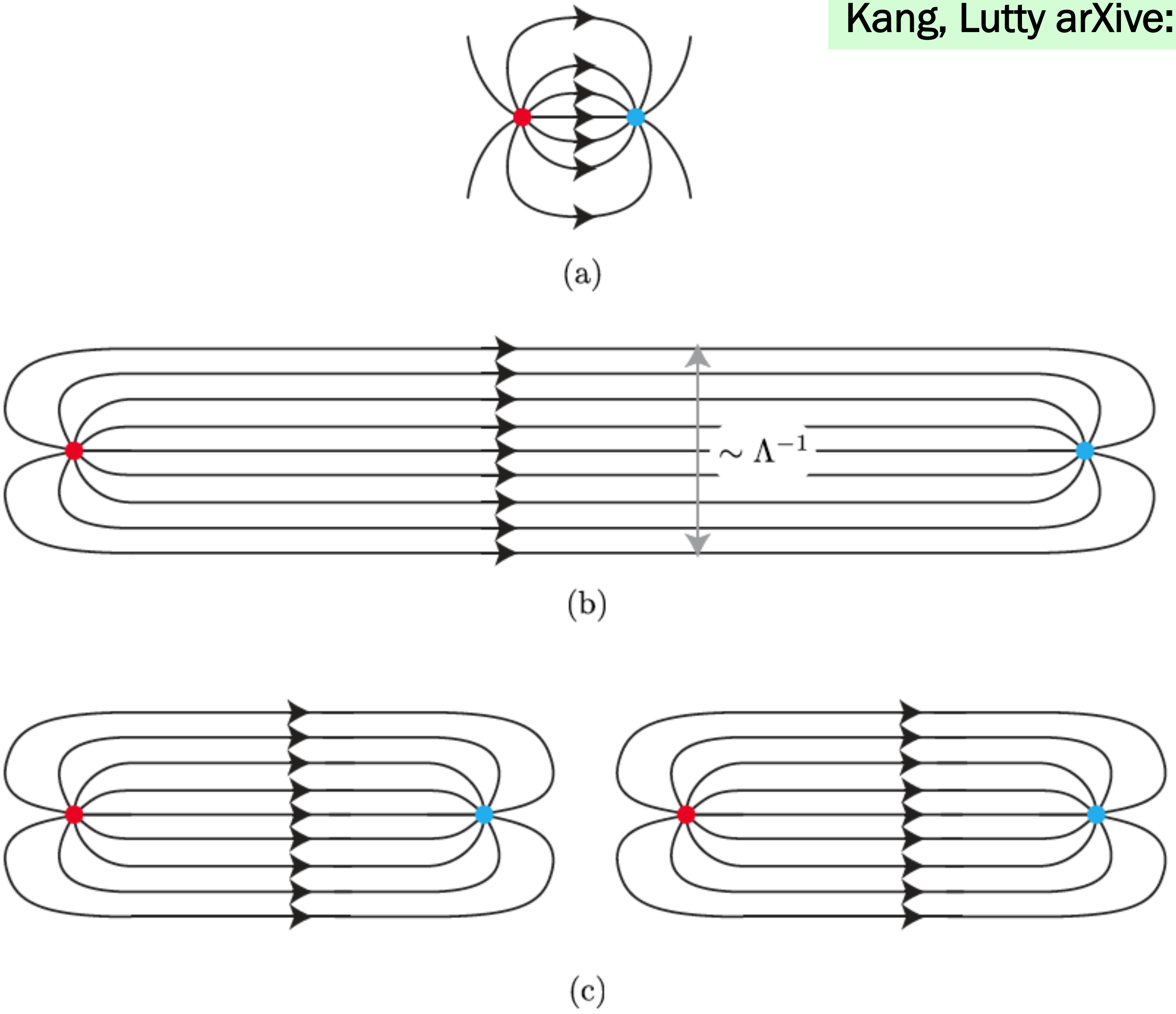
Life time :

(*cf.* Schwinger mechanism for pair creation of charged ptcles by weak Electric field)

$$\tau \sim \frac{4\pi^2}{m}\, e^{m^2/\Lambda^2}$$

Longer than Age of Universe for m > 100 GeV, Λ = 50 MeV

Kang, Lutty arXive: 0805.4642



Schematic view of color flux for quirk separation for (a) $r \ll \Lambda^{-1}$ and (b) $r \gg \Lambda^{-1}$. String breaking (c) requires a quirk-antiquirk pair to be created, which costs energy $2m_Q \gg \Lambda$.

IN PARTICULAR:

BREAKING OF INFRACOLOUR STRING IS EXPONENTIALLY SUPPRESSED FOR $\Lambda << m$

QUIRK-ANTIQUIRK PAIR STAYS CONNECTED BY THE INFRACOLOUR STRING LIKE A ``RUBBER BAND'' THAT CAN STRETCH UP TO MACROSCOPIC LENGTHS

$$L \simeq \frac{m_Q}{\Lambda^2} \simeq 1\ \mu\mathrm{m}\ \left(\frac{m_Q}{100\ \mathrm{GeV}}\right)\left(\frac{\Lambda}{100\ \mathrm{keV}}\right)^{-2}.$$

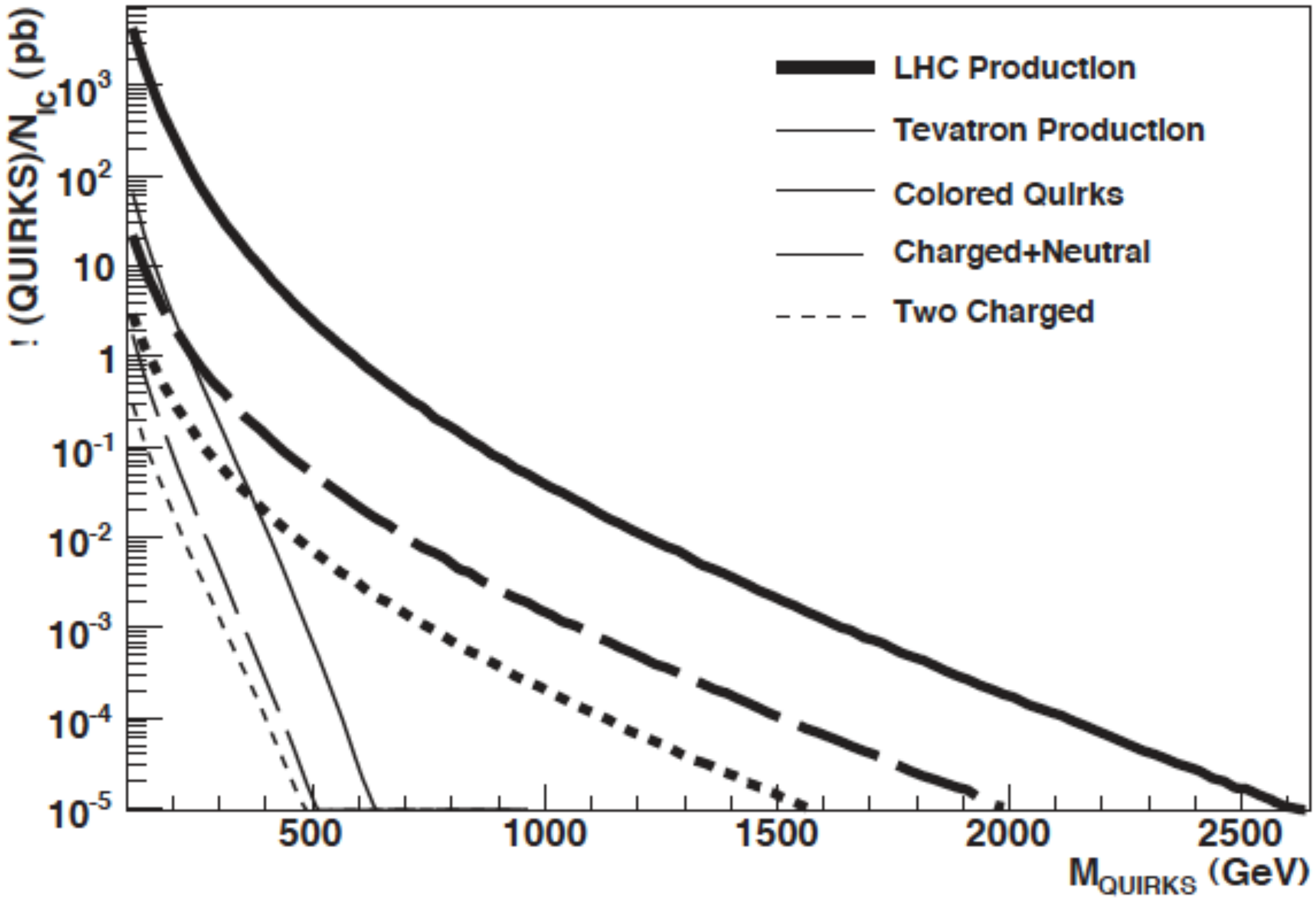
ASSUMING QUIRKS TO HAVE CHARGE e , no strong colour charge → quirk-antiquirk pair is reconstructed in the detector as a highly-ionizing track

SIGNATURE: large ionization-energy loss rate dE/dx , a jet, from initial state radiation, and missing transverse energy E_T aligned with the track

D0 Coll. arXive:1008.3547

QUIRK PRODUCTION

Kang, Lutty arXive: 0805.4642



Quirk production cross section at the Tevatron and LHC.

D0 Coll. arXive:1008.3547

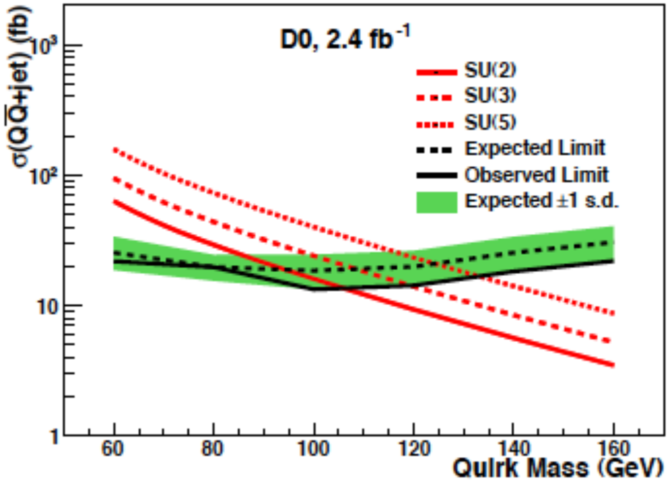
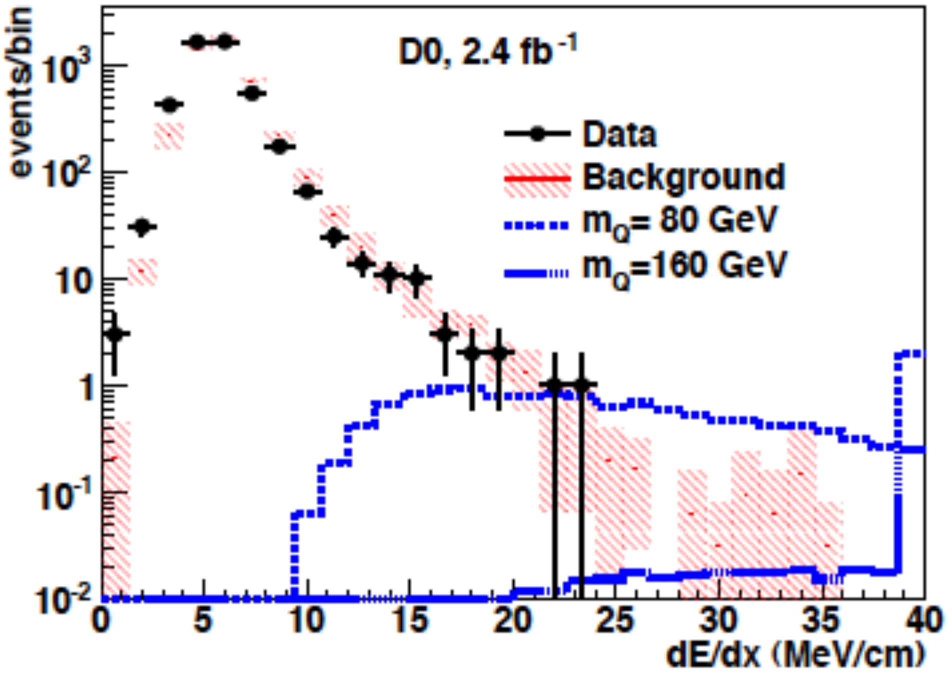


FIG. 3: (color online) Observed and expected 95% C.L. limits on $\sigma(Q\bar{Q} + jet)$ for $SU(2)$, $SU(3)$ and $SU(5)$ gauge sectors. The band shows ±1 standard deviation of the median expected limit.

QUIRK SIGNAL



QUIRK IN MoEDAL…

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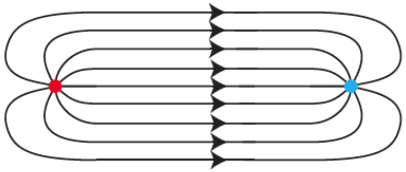
$$L \simeq \frac{m_Q}{\Lambda^2} \simeq 1\ \mu\mathrm{m}\ \left(\frac{m_Q}{100\ \mathrm{GeV}}\right)\left(\frac{\Lambda}{100\ \mathrm{keV}}\right)^{-2}.$$

STRONG IONIZATION EFFECTS – MOST RELEVANT for MoEDAL detector for Λ < 10 keV



Two scenarios for quirk-antiquirk pair:

(i) Move away from the LHCb detector towards the plastic film as a slowly moving pair (decelerated by flux tube)

(i) if produced close to threshold: One end moves towards LHCb detector & gets stuck, the other towards the plastic film

Quirks May be undetected if moving slowly although stuck in the detector.
LHCb much less dense medium for quirk motion → good candidates for MoeDAL

Q-BALLS

Q-balls

Non-topological soliton field configurations with a global charge Q

$$L = \frac{1}{2}(\partial_\mu \phi)^2 - V(\phi) + (\partial_\mu \chi)^*(\partial_\mu \chi) - h\phi^2 \chi^* \chi$$

Coleman

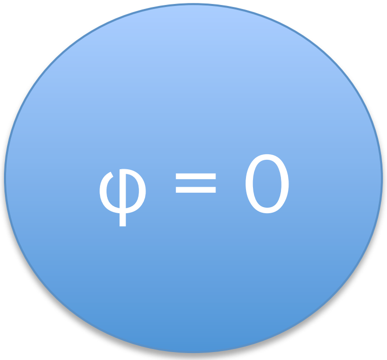
$$\phi = (\phi_1, \ \phi_2)$$

Global U(1) (phase) symmetry

Friedberg-Lee-Sirlin (multiple scalars)

$$\chi \rightarrow e^{i\alpha} \chi$$

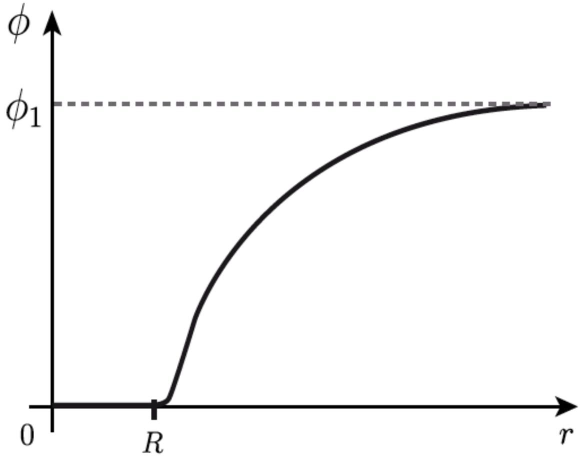
Spherical Q-ball



$\varphi = \varphi_1 \neq 0$

$$\frac{\delta V}{\delta \phi}\Big|_{\phi=\phi_1} = 0$$

(Potential Minimization)



Size R → Minimize: $E(R) = \frac{\pi Q}{R} + \frac{4\pi}{3} R^3 V_0$

$$V_0 = V(0) - V(\phi_1)$$

Single scalar field Q-balls of size R

φ rotates around the internal symmetry space SO(2) with frequency ω

Conserved charge:
$$Q = \int d^3x \left[\phi_1\partial_0\phi_2 - \phi_2\partial_0\phi_1\right] = \frac{4\pi}{3}R^3\omega\phi^2$$

Energy $E = \frac{4\pi}{3}R^3\left(\frac{1}{2}\omega^2\phi^2 + V\right)$ is minimised @ radius R, with energy

per unit charge at minimum
$$E/Q = \sqrt{2V/\phi^2}$$

Stable Q-ball if $m > \sqrt{2V/\phi^2}$

Many SUSY models have logarithmic one-loop corrections which allow such a condition to be satisfied, but in most models Q-ball masses are much higher than electroweak scale ... so unlikely to be produced at LHV energies....

Q-balls may be important for **Cosmology**: can be produced abundantly in early Universe & play a role in ***Baryon asymmetry*** and **Dark Matter**

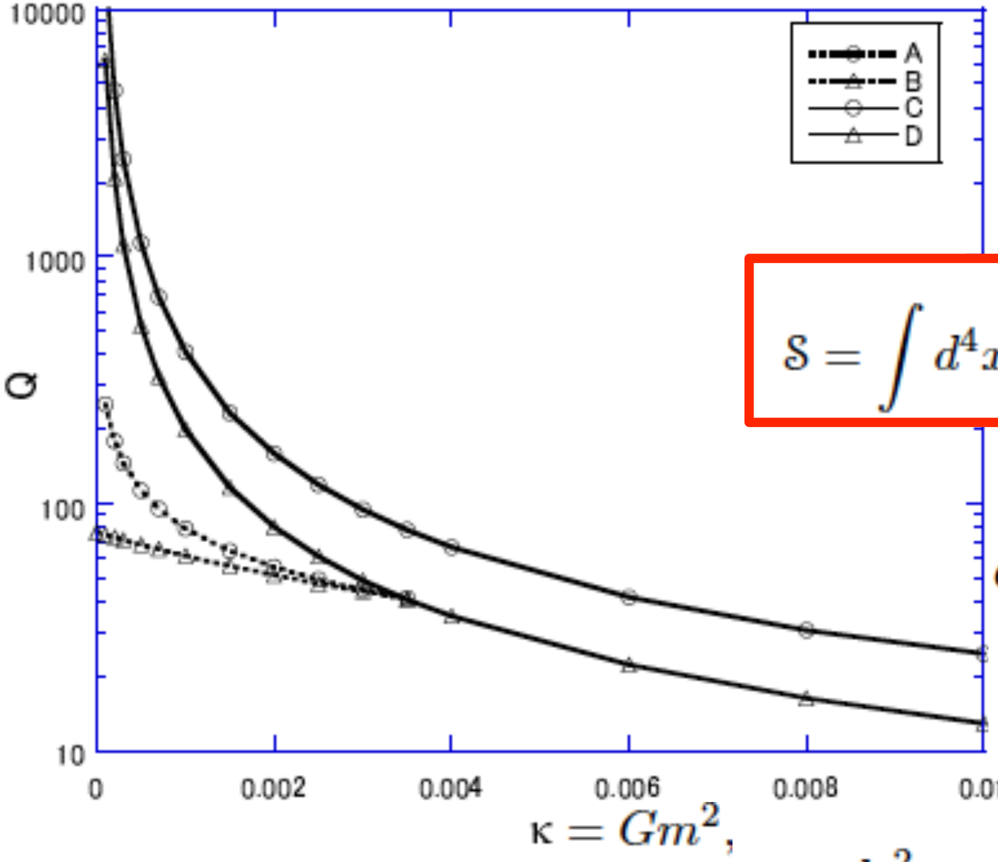
Kusenko, Shaposhnikov, Tinyakov

…BUT ABOVE RESULTS FOR FLAT SPACE TIMES ---

Gravity affects Q-ball stability

Tamaki, Sakai arXive:1108.3902

Stable Q-balls with arbitrarily small charge exist in non-flat space-times in contrast to Minkowski space-time cases for Affleck-Dine potentials …



$$V_{\mathrm{gauge}}(\phi) := m^4 \ln\left(1 + \frac{\phi^2}{m^2}\right)$$

$$\mathcal{S} = \int d^4x\sqrt{-g}\left\{\frac{\mathfrak{R}}{16\pi G} - \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\cdot\partial_\nu\phi - V(\phi)\right\}$$

$$\phi = (\phi_1,\ \phi_2)$$

$$Q := \int d^3x\sqrt{-g}g^{0\nu}(\phi_1\partial_\nu\phi_2 - \phi_2\partial_\nu\phi_1) = \omega I,$$

$$\text{where} \quad I := 4\pi\int\frac{Ar^2\phi^2}{\alpha}dr.$$

…no matter how weak gravity is

$$ds^2 = -\alpha^2(r)dt^2 + A^2(r)dr^2 + r^2(d\theta^2 + \sin^2\theta d\varphi^2)$$

Q-balls in MoEDAL

HENCE ….

Self-gravitating stable charged Q-balls with relatively low masses may EXIST → relevant for LHC energies,
can be highly ionizing
(mass is not relevant for ionization)
so relevant for MoEDAL

CHAMPS

Charged
massive
Particles

de Rujula, Glashow, Sarid (1990)
Dimopoulos, Eichler, Esmailzadeh, Starkman (1990)
Starkman, Gould, Esmailzadeh, Dimopoulos (1990)

WHAT ARE SIMPS?

(I) Charged Massive Particles (CHAMP) : if the whole of DM, as originally assumed → cosmological compatibilities require them to be heavy (20 teV < M_{Ch} < 1000 TeV) if charge + 1: Superheavy remnants of H isotopes in the Universe, particle-antiparticle symmetric → anti-CHAMP may bind with ^{4}He nuclei after BBN but mostly bind to protons to behave like superheavy stable neutrons

But, may be CHAMPS are a ***(small) part*** of DM: if neutral DM decays (at late eras) to CHAMPs stringent bounds may be re-evaluated,

e.g. fraction of CHAMP in galactic halo
< 0.4 – 1.4 x 10^{-2} (**Sanchez-Salcedo *et al*. 1002.3145**)

Also Galactic magnetic fields || disc, prevent CHAMPS from entering the disc (***non detection on Earth***) if their charge q_X & mass are in the range:

$$10^2\,(\frac{q_X}{e})^2 \leq m_X \leq 10^8\,(\frac{q_X}{e})^2$$

Chuzhoy & Kolb 0809.0436

CHAMPS - REVISITED

Chuzhoy & Kolb 0809.0436

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***DM density profiles*:**
these CHAMPS interact with ordinary matter via magnetic field mediation → affect visible Universe → their density profiles depend on the Galaxy
→ : moderate effects in large elliptical galaxies and Milky way,
expulsion of CHAMPS with moderate charge (Coulomb Interactions not important) from spherical Dwarf Galaxies → agreement with observations ?

DM Annihilation different from Cold Dark Matter (CDM) model:
attractive Coulomb potential between X^+ , X^-
→ increased annihilation cross section (relative to CDM models)
→ by a factor c/v (Sommerfield-Sakharov effect)
→ after CHAMP becomes non relativistic the annihilation rate
→ falls off slower than in CDM → kinetic energies scale as (1 + z) with redshift
→ present annihilation rate depends on fraction of X^- bound to baryons

CHAMPS - REVISITED

Langacker, Steigman
arXive:11073131

(II) Fractionally Charged Massive Particles (FCHAMP): Leptons with electroweak interactions (charge $U_Y(1)$) but no strong interactions of mass m_L and charge Q_L e that could be fractional.

Constraints from primordial nucleosynthesis & Cosmic Microwave Background & invisible width of Z boson → Q_L-m_L relation:
Surviving FCHAMP abundance on Earth several orders of magnitude higher than limits from terrestrial searches for fractionally charged particles → close window for FCHAMP $Q_L \geq 0.01$.

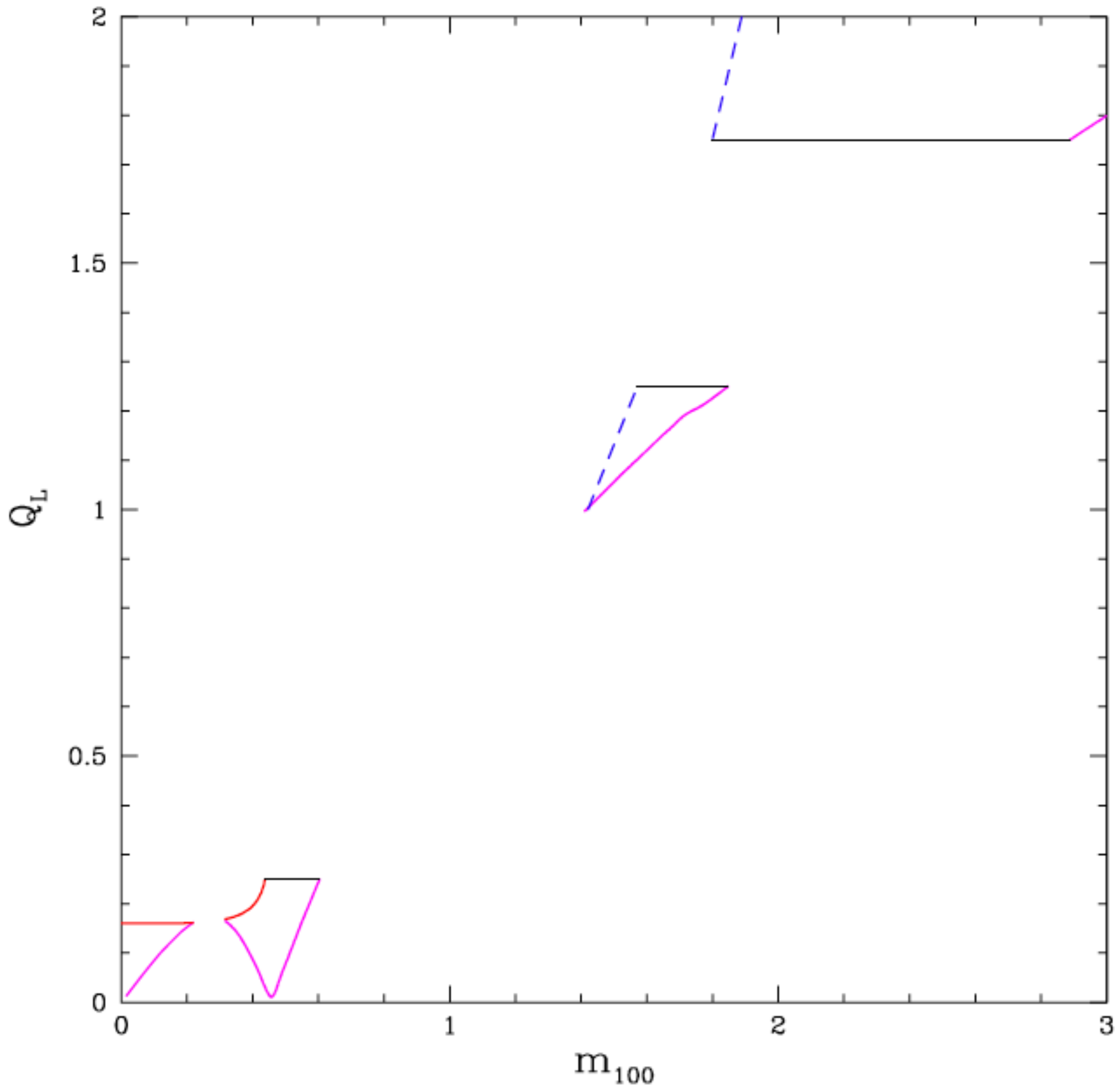
BUT… as Q approaches an integer $|Q_L - n| \leq 0.25$ these searches are increasingly insensitive → ``unconstrained islands '' in Q_L-m_L planes to be explored by searching for FCHAMPS in Cosmic Rays

& in MoEDAL detector via tracks in the plastics…

…If we can produce FCHAMPS @ LHC….

FCHAMPS ``ISLANDS''

Langacker, Steigman
arXive:11073131



$$m_L = 100\, m_{100}\ \text{GeV}$$

de Rujula, Glashow, Sarid (1990)
Dimopoulos, Eichler, Esmailzadeh, Starkman (1990)
Starkman, Gould, Esmailzadeh, Dimopoulos (1990)

WHAT ARE SIMPS?

(III) SIMP could be neutral (fermion)

Wandelt *et al.*, astro-ph/0006344

Bai, Rajaraman, 1109.6009

e.g. behave like a neutron
so most of astrophysical & terrestrial
constraints can be avoided, especially
if light ....

CONSTRAINTS ON SIMPS/CHAMPS

Bai, Rajaraman, 1109.6009

(i) Direct Detection Searches:

ground exps (CDMS, XENON) → stringent bounds **on low cross sections**

High Cross sections : SIMP stopped in the atmosphere do not reach ground or underground detectors -→ ***high-altitude expts*** (Baloon, satellite… X-ray Quantum Calorimeters (XQC)) reach interactions above the atmosphere & **eliminate large portion** of SIMP parameter space

(ii) Earth Heating:

SIMP captured gravitationally by Earth, accumulate at core,
→ **self-annihilate** into SM ptcles → thermalize/**modify Earth's heat flow**,

(iii) Neutron Star core collection of scalar SIMP → ***collapse to black hole***

(iv) Cosmic Rays:

protons-SIMP scattering → π^0 → γγ (assume SIMP near Galaxy Center, **uncertain**)

(v) CMB, Large Scale Structure modified by strong SIMP - baryon interactions

(vi) Bound States SIMP-Nucleons: if formed -→ constraints exclude models → avoid such bound states → repulsive forces between SIMPS and nucleons

CONSTRAINTS ON CHAMPS FROM PLASTIC COSMIC RAY DETECTOPS

Scattering of SIMPs off molecules in plastic causes sufficient damage by molecular bond breaking provided energy deposition is such that:

$$\frac{dE}{\rho\, dx} \geq 400\,\mathrm{MeV\,cm^2/g}$$

This corresponds to cross sections

$$\sigma_{\mathrm{pl}} \geq 7 \times 10^{-19}\,\mathrm{cm}^2$$

Minimum length of tracks required for tracks to be seen (e.g. 2.5 mm)

Wandelt *et al.*, astro-ph/0006344

Bai, Rajaraman, 1109.6009

Bound States SIMP-Nucleons:

Avoid such bound states → repulsive forces between SIMPS and nucleons
→ *fermion SIMP* and *scalar φ* attractive mediator (for charge neutrality of the Universe), *scalar force < two pion exchange*
→ nucleon bound states *do not form* due to φ :

Toy (Instructive) Models

Extend SM by one massive particle m_x
Important information: nucleon-X cross section σ_{xp}

$$L_{\rm int} = -g_X \varphi \overline{X} X - g_N \varphi \overline{N} N$$

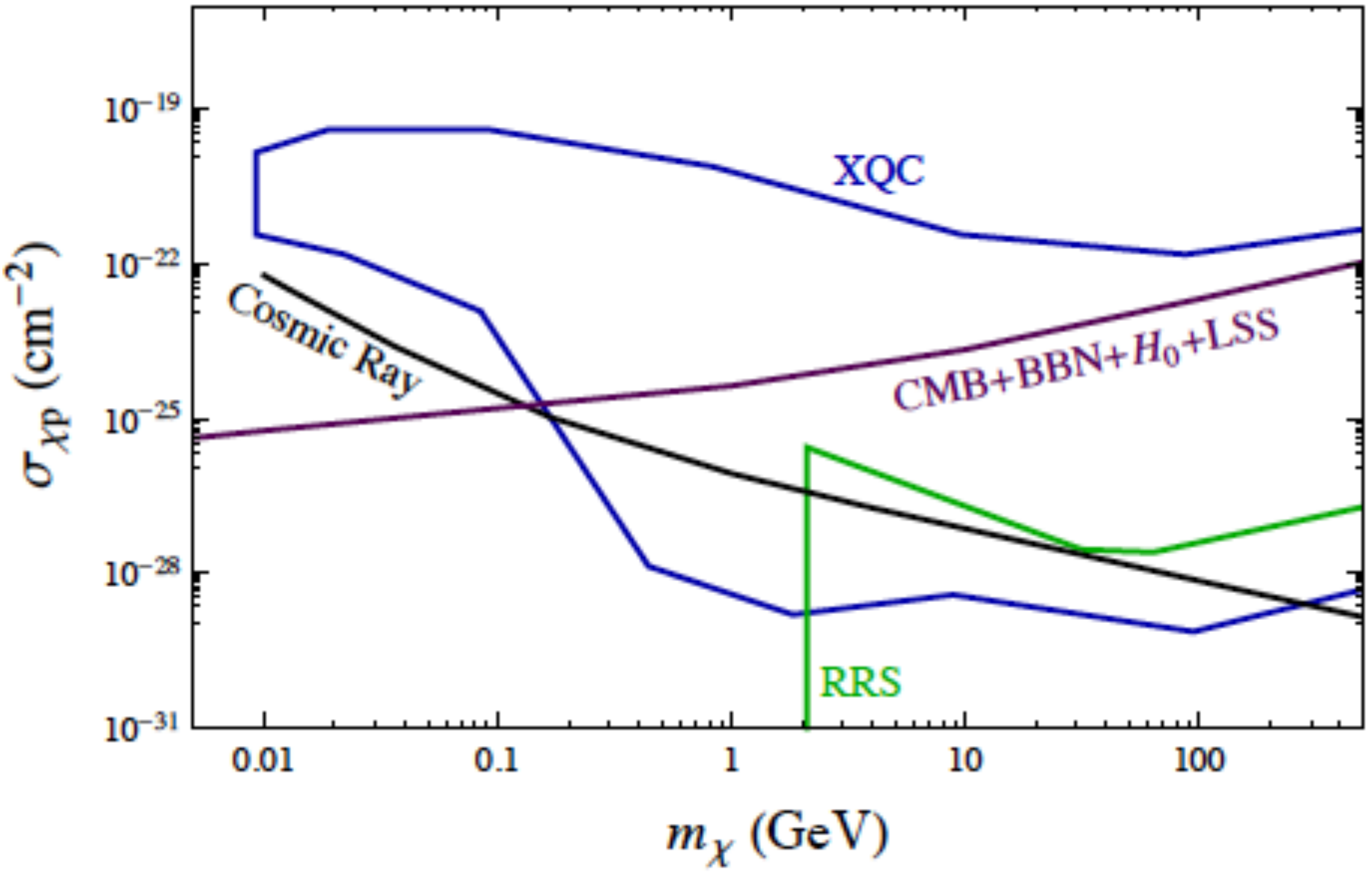
$$g_N g_X < 0, \quad m_X, m_\varphi > 0$$

Not modification of Galactic halo shape (e.g. Bullet Cluster) → $\frac{\sigma_{XX}}{m_X} \lesssim 3\ \mathrm{GeV}^{-3}$

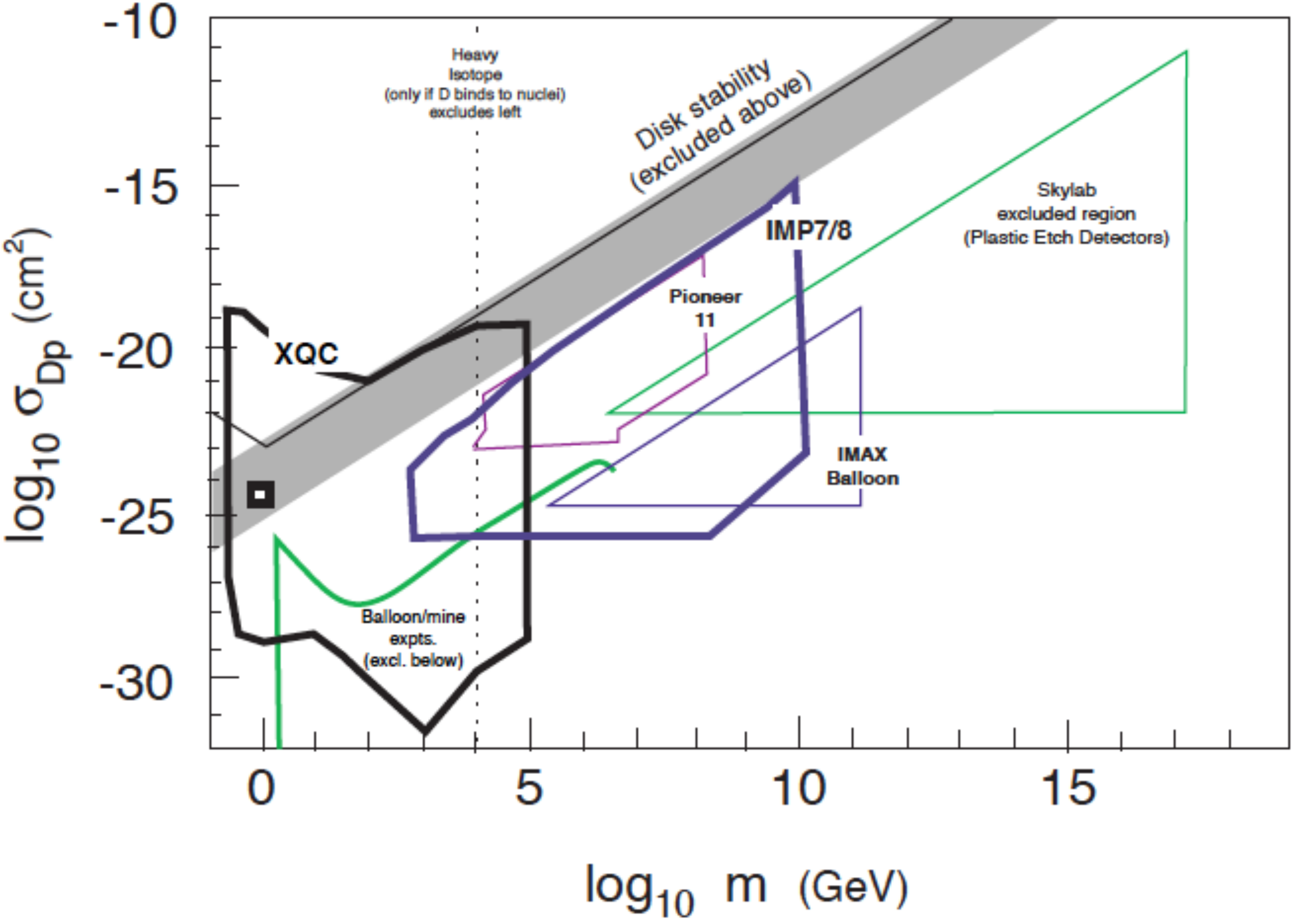
$$\boxed{\sigma_{Xp} \lesssim \frac{4\, g_N^2}{g_X^2} \frac{m_X}{1\ \mathrm{GeV}} \times 10^{-27}\ \mathrm{cm}^2}$$

CONSTRAINTS ON SIMPS/CHAMPS

Bai, Rajaraman, 1109.6009



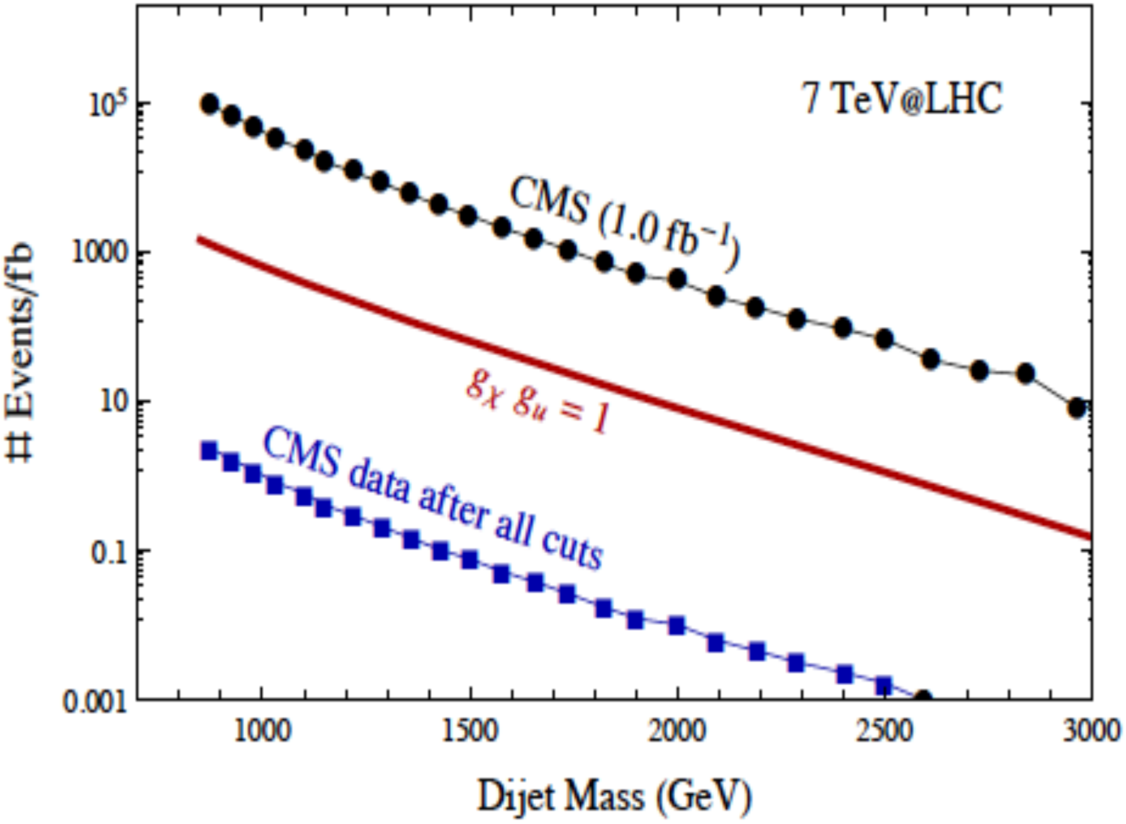
$m_\chi < 1$ GeV , $\sigma_{xp} < 10^{-25}$ cm^{-2} ALLOWED !!



Wandelt *et al.*, astro-ph/0006344

DARK MATTER di-JETS FROM ALLOWED *Neutral* SIMPs

Bai, Rajaraman, 1109.6009



scattering Length

$$L_\chi = L_n \frac{\sigma_{\chi p}^{\text{inela}}}{\sigma_{np}^{\text{inela}}} .$$

can be smaller than calorimeter size → deposit energy in the form of Jets → if DM ***neutral***, ***no track***
→ difference from QCD jets

Such phenomena for $m_\chi < 1$ GeV are interesting but not relevant to MoEDAL…

Relevant to MoEDAL possibly if …

sufficient damage in plastics requires

$$\sigma_{\rm pl} \geq 7 \times 10^{-19}\ {\rm cm}^2$$

Cosmology constraints

$$\boxed{\sigma_{\chi p} \lesssim \frac{4\, g_N^2}{g_\chi^2}\, \frac{m_\chi}{1\ {\rm GeV}} \times 10^{-27}\ {\rm cm}^2}$$

So we need unnatural large factors if relevance to MoEDAL is attained

$$\frac{g_N^2}{g_\chi^2}\, \frac{m_\chi}{1\, {\rm GeV}} > 10^8$$

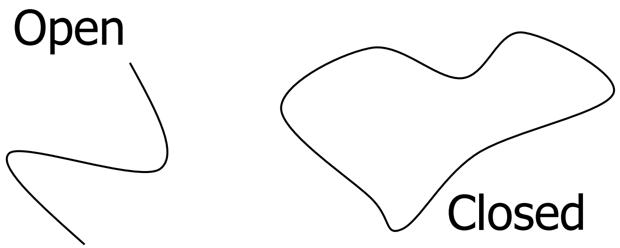
e.g. for m_χ = 1 TeV
must have $\frac{g_N}{g_\chi} > 10^3,$

Rather unlikely , taking into account other constraints – see above … BUT not quite impossible

D-MATTER

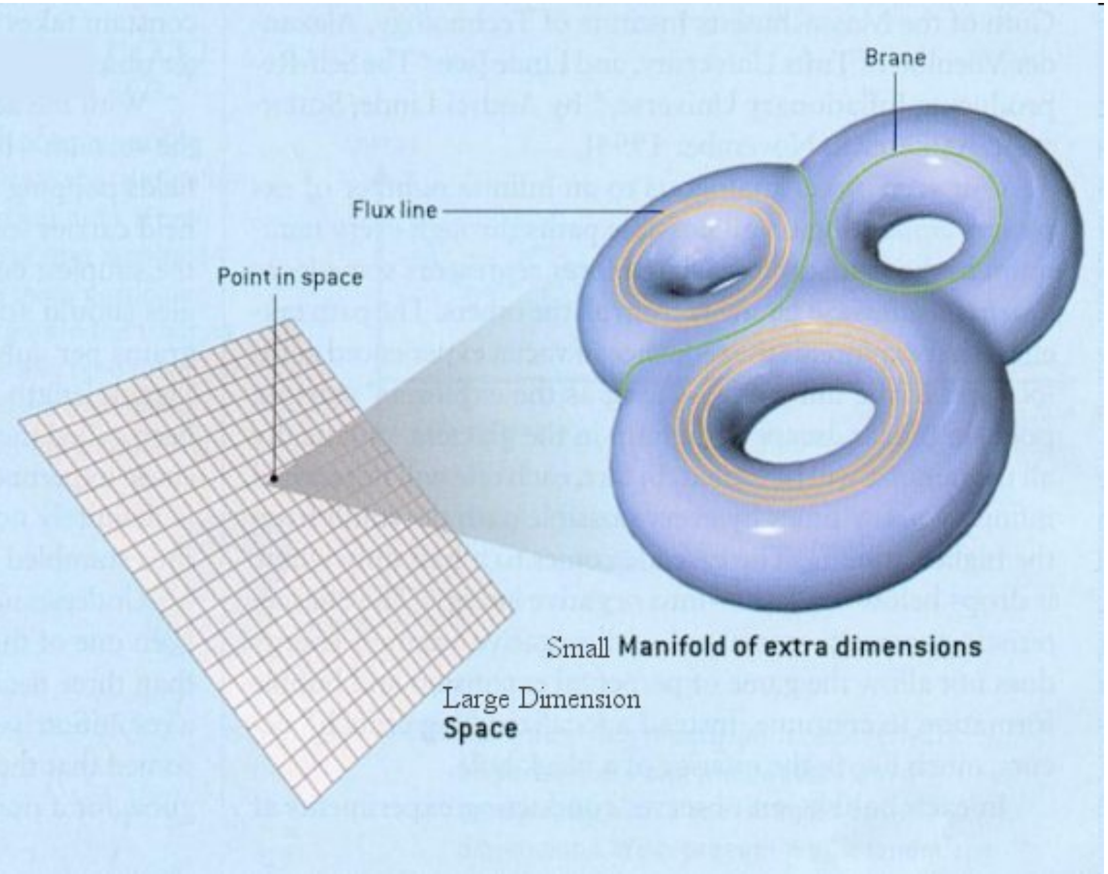
What is String Theory?

Fundamental Excitations are not point-like but one-dimensional (strings)



ONE VERSION :

Strings live in Large Four space-time dimensions but have extra dimensions ``Curled-up'' in small-size but of complicated Geometry spaces



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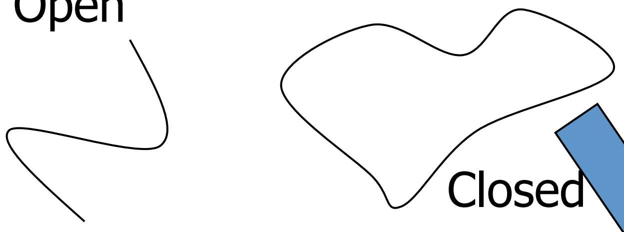

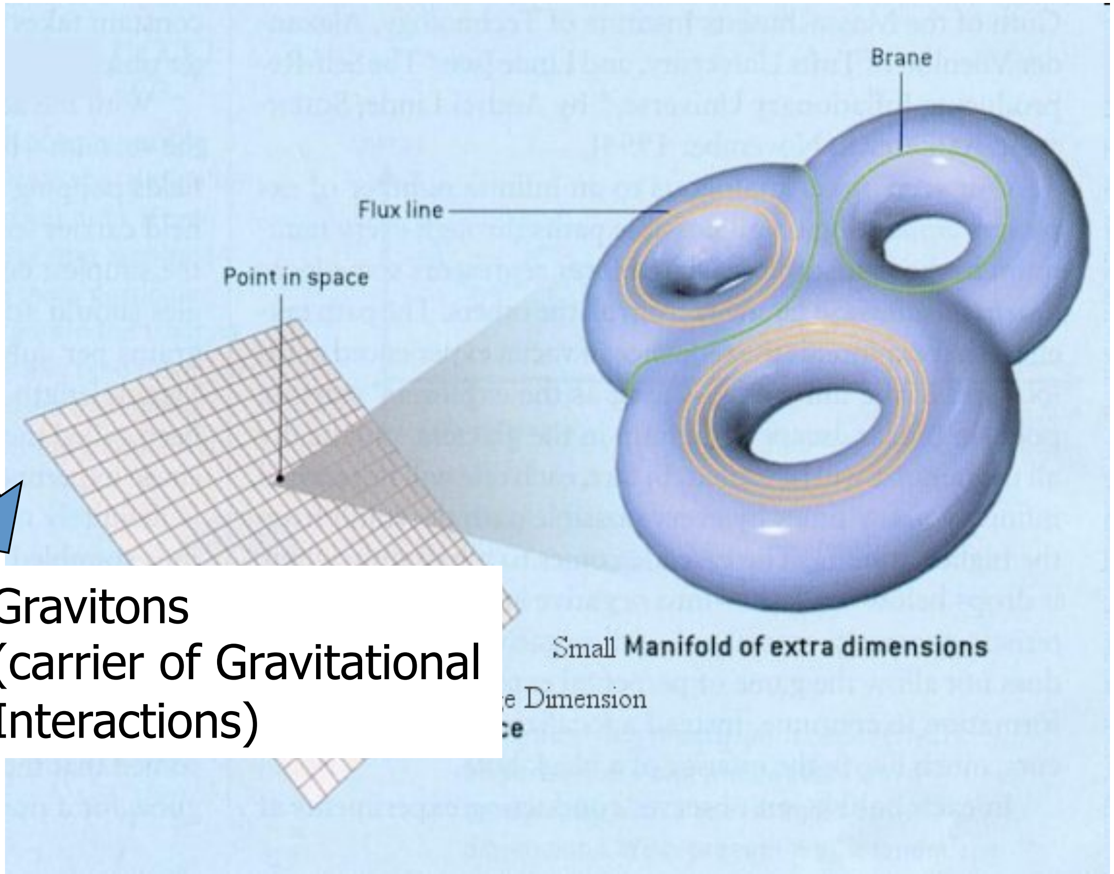

Gravitons
(carrier of Gravitational Interactions)

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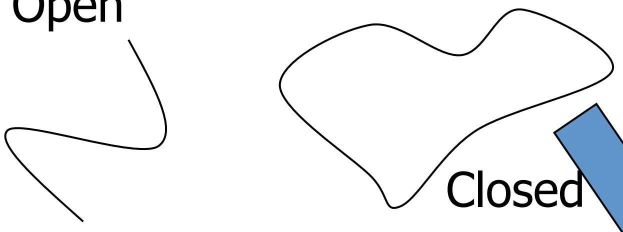

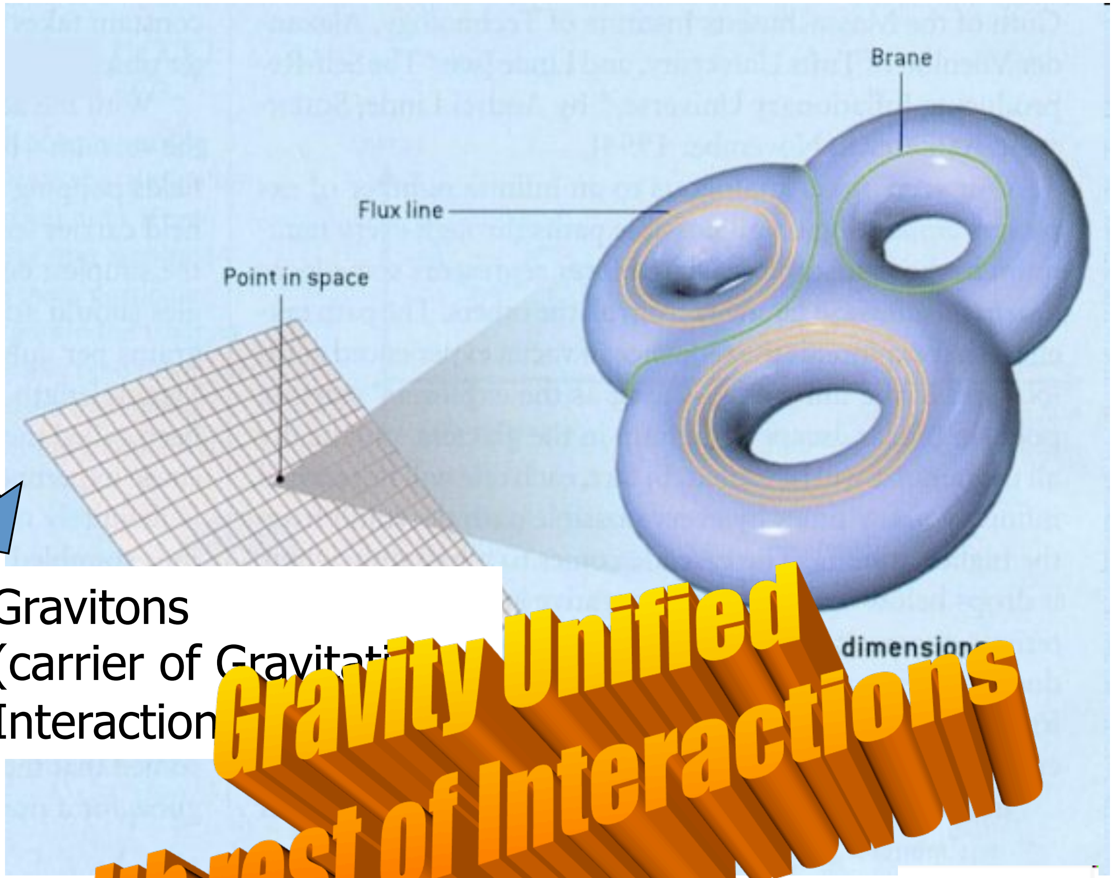

Gravitons
(carrier of Gravitati
Interaction

Gravity Unified with rest of Interactions

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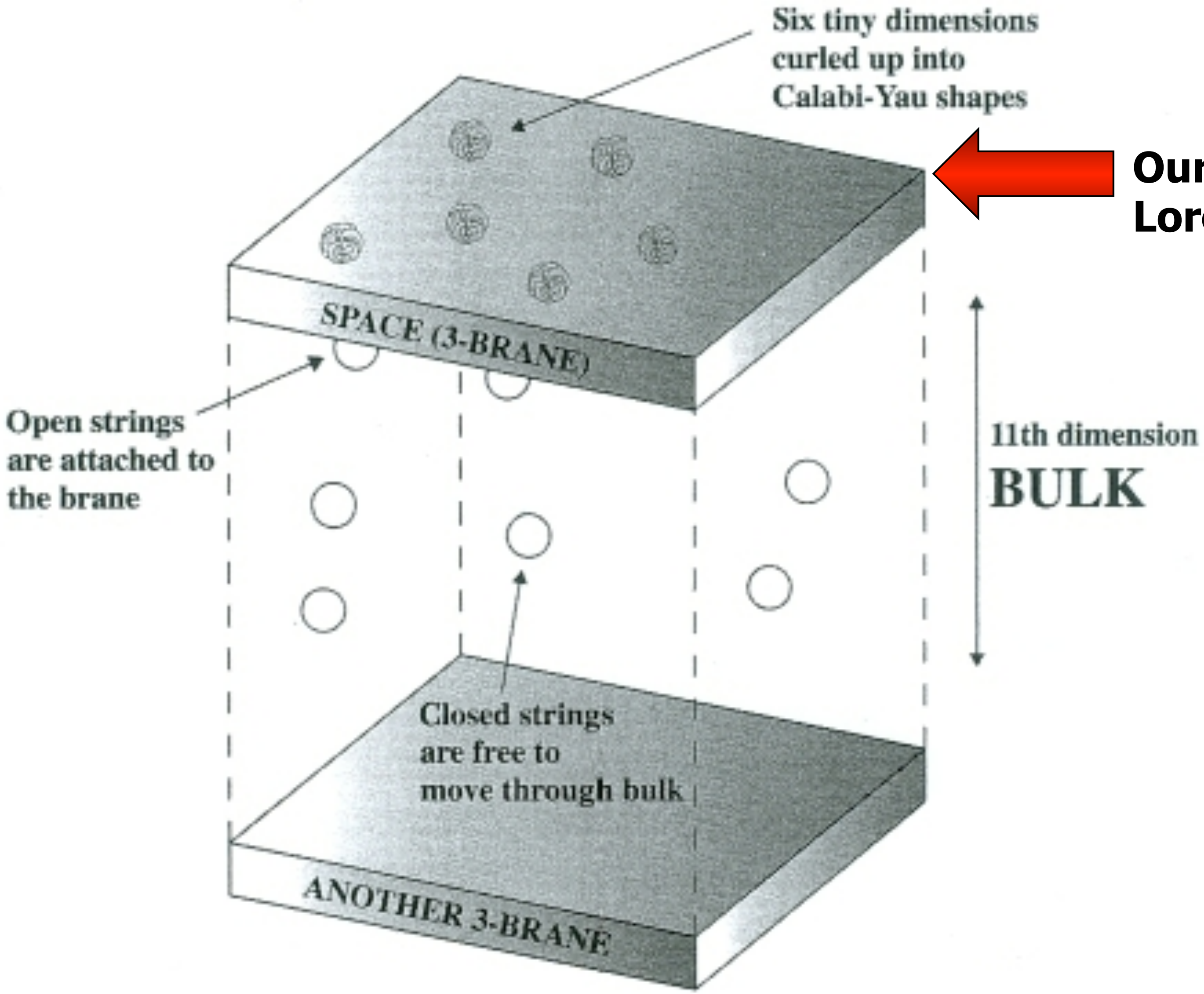
SECOND VERSION OF STRING THEORY (BRANE-THEORY):



Our Universe
Lorentz Invariant

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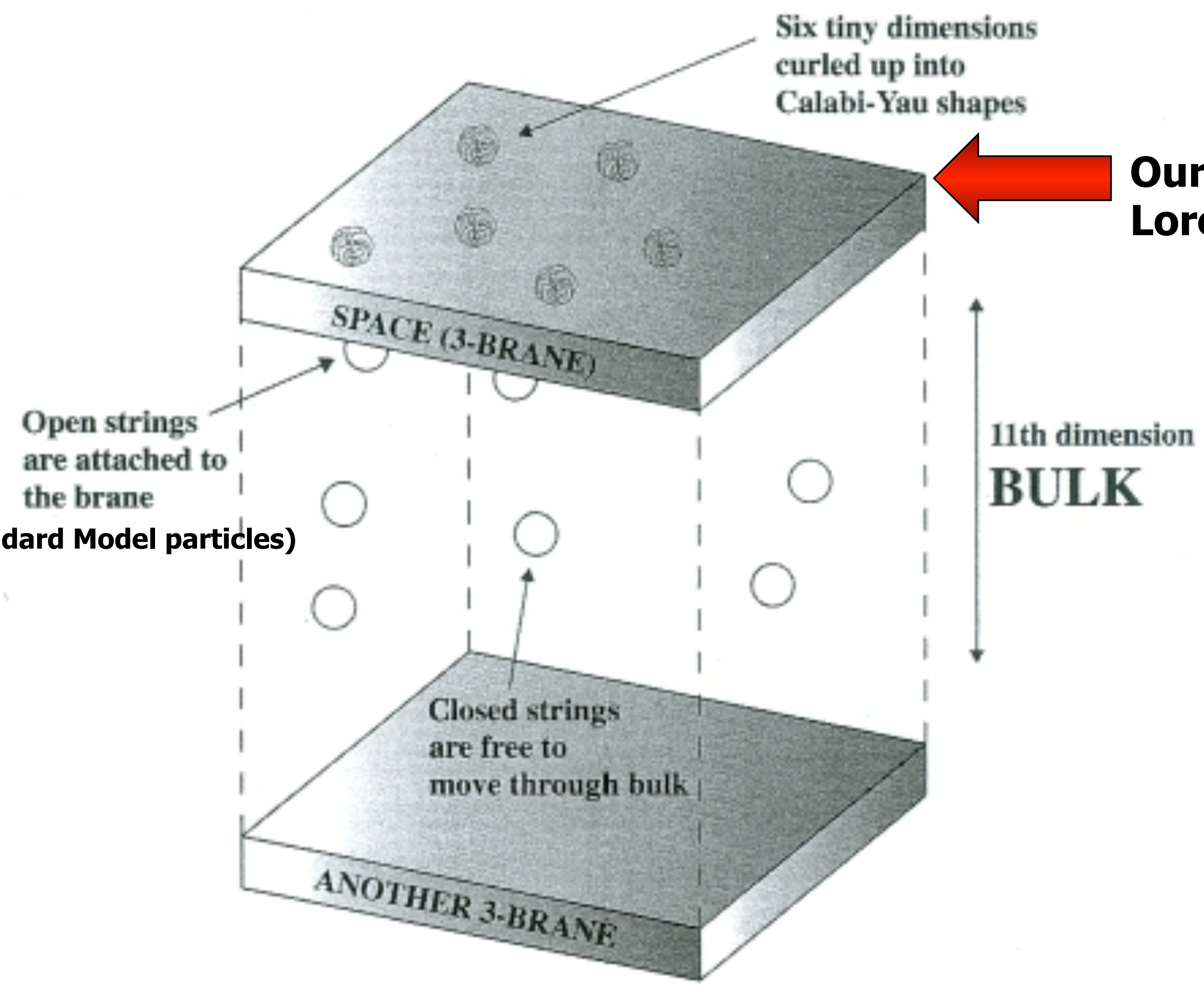

Our Universe
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(Standard Model particles)

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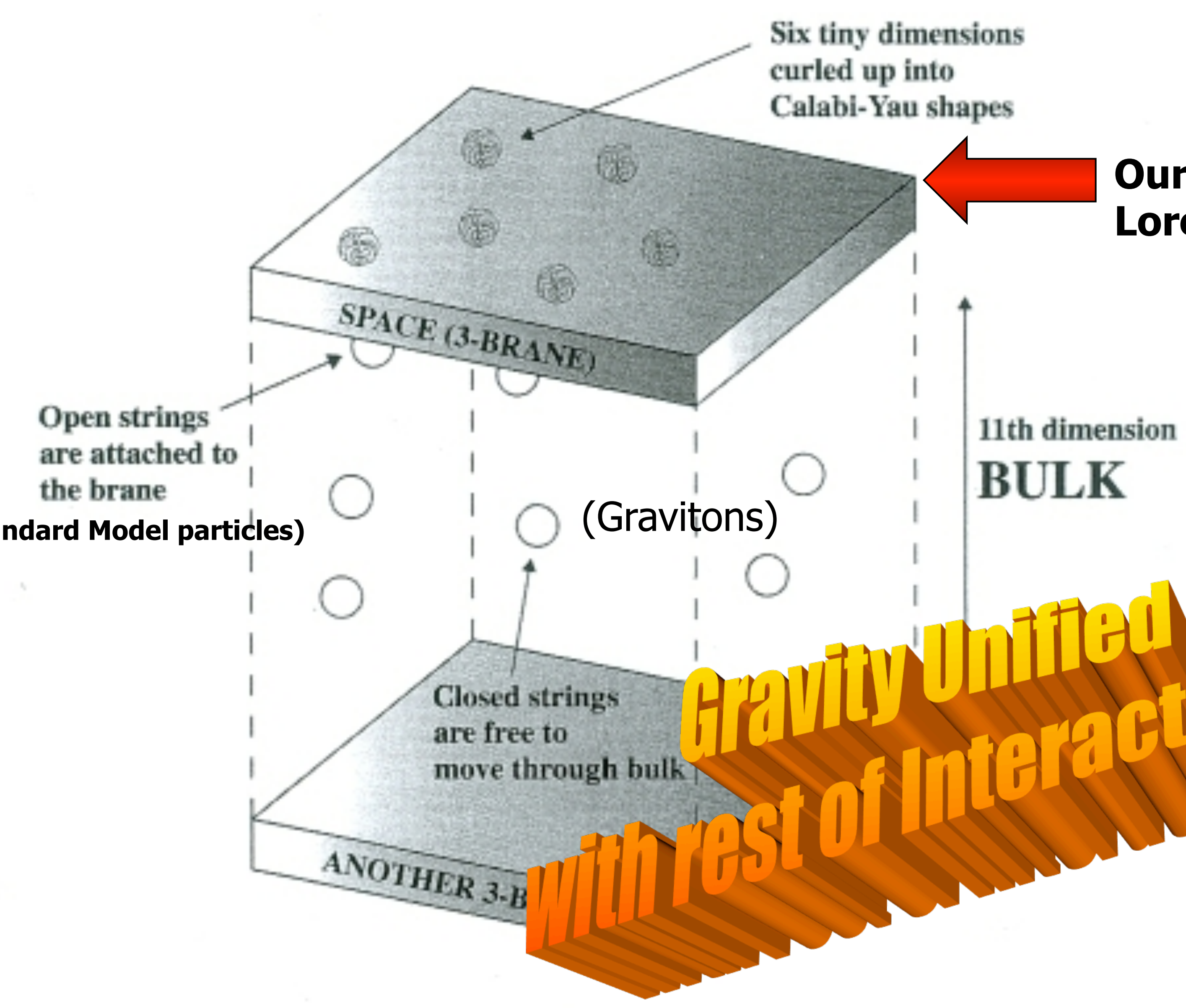

Our Universe
Lorentz Invariant

(Standard Model particles)

(Gravitons)

Gravity Unified with rest of Interactions

STRING/D-BRANE BASICS

p-branes:

have **p** longitudinal dimensions over which strings have their ends attached

String theory	p-brane types allowed
type-IIA	$p = 0, 2, 4, 6, 8$
type-IIB	$p = -1, 1, 3, 5, 7, (9)$
type-I	$p = 1, 5, 9$

Heterotic Strings admit no p-branes

STRING/D-BRANE BASICS

Phenomenologically relevant

String theory	p-brane types allowed
type-IIA	$p = 0, 2, 4, 6, 8$
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Heterotic Strings admit no p-branes

Wrap 3-branes around 3 cycles

Effective ``point-like'' localised on higher dimensional brane worlds

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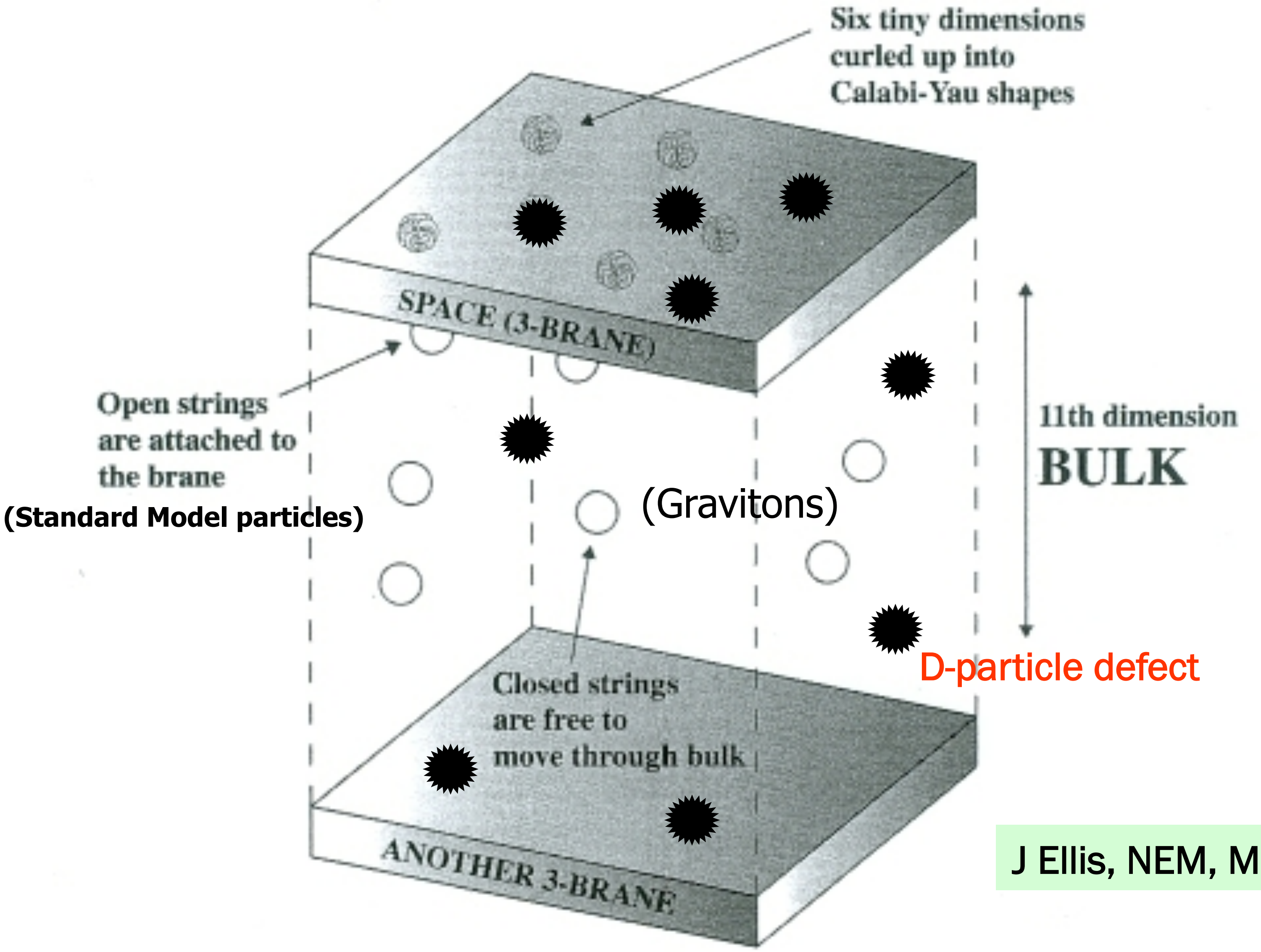
Heterotic Strings admit no p-branes

Wrap 3-branes around 3 cycles

Effective ``point-like'' localised on higher dimensional brane worlds e.g. 5,7-branes

ANTOHER VERSION of BRANE WORLDS with D-PARTICLE (POINT-LIKE BRANE) DEFECTS :



J Ellis, NEM, M Westmuckett

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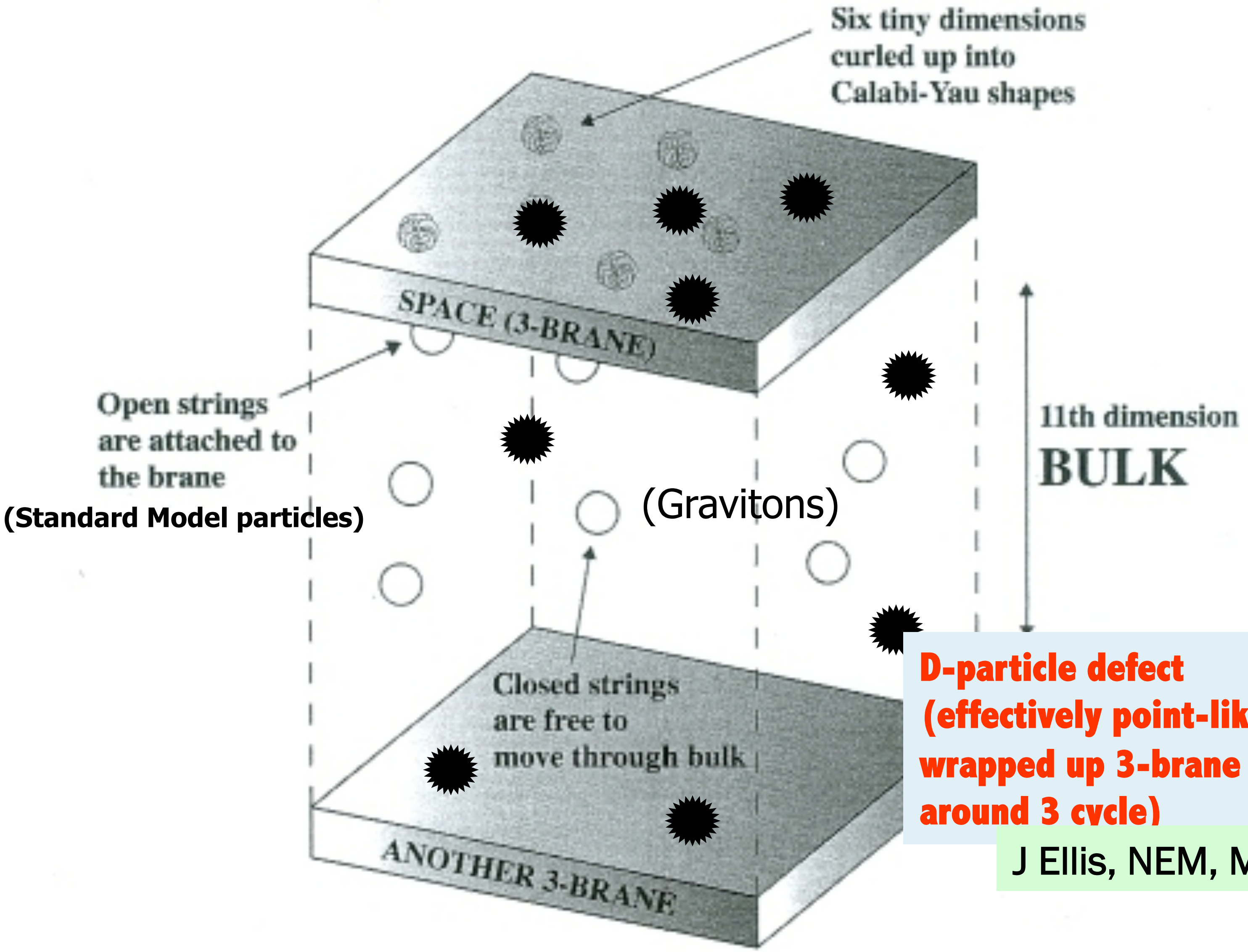
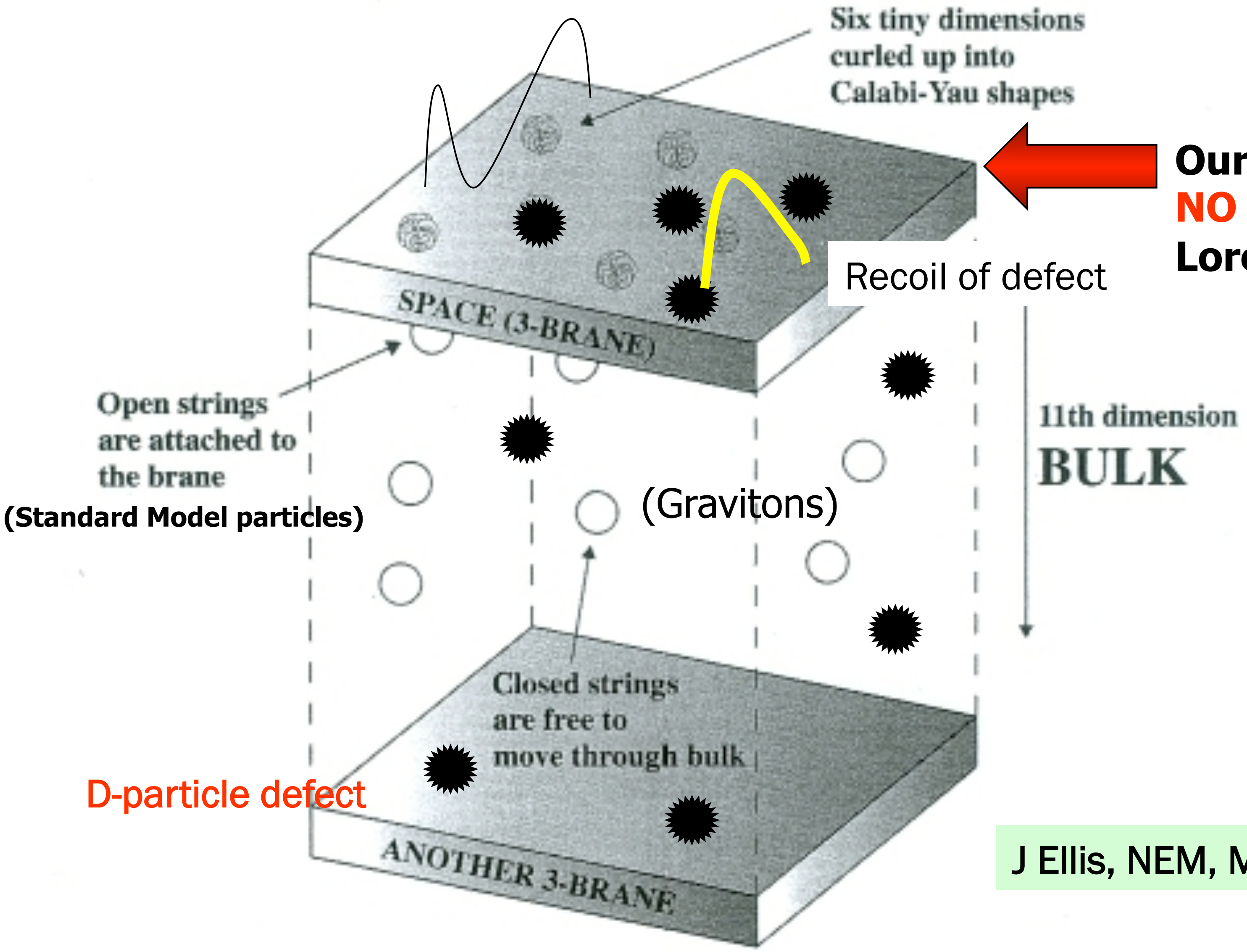


D-particle defect (effectively point-like, wrapped up 3-brane around 3 cycle)

J Ellis, NEM, M Westmuckett

ANTOHER VERSION of BRANE WORLDS with D-PARTICLE (POINT-LIKE BRANE) DEFECTS :

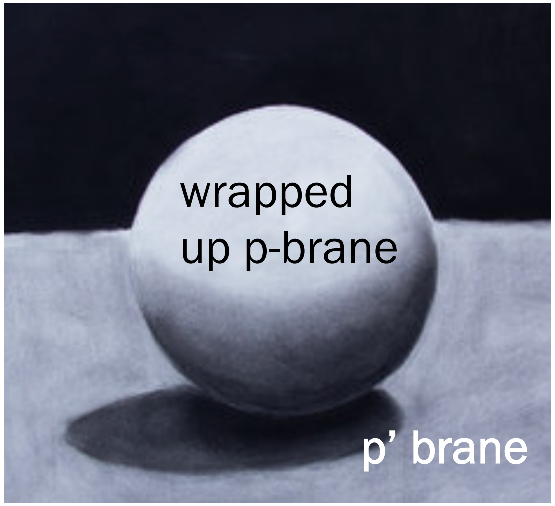


Our Universe
NO LONGER
Lorentz Invariant

J Ellis, NEM, M Westmuckett

D-matter

- Such wrapped up p-branes branes around p-cycles appear as localised objects when embedded in higher-dimensional p’ brane worlds (p’ > p)



- Have small (string scale) compactification radii

- Can be considered as effectively point-like ``localised’’ excitations from string vacuum

- TERMED D-PARTICLES → form of D(efect)-matter

- They have masses $M_D = M_s/g_s$

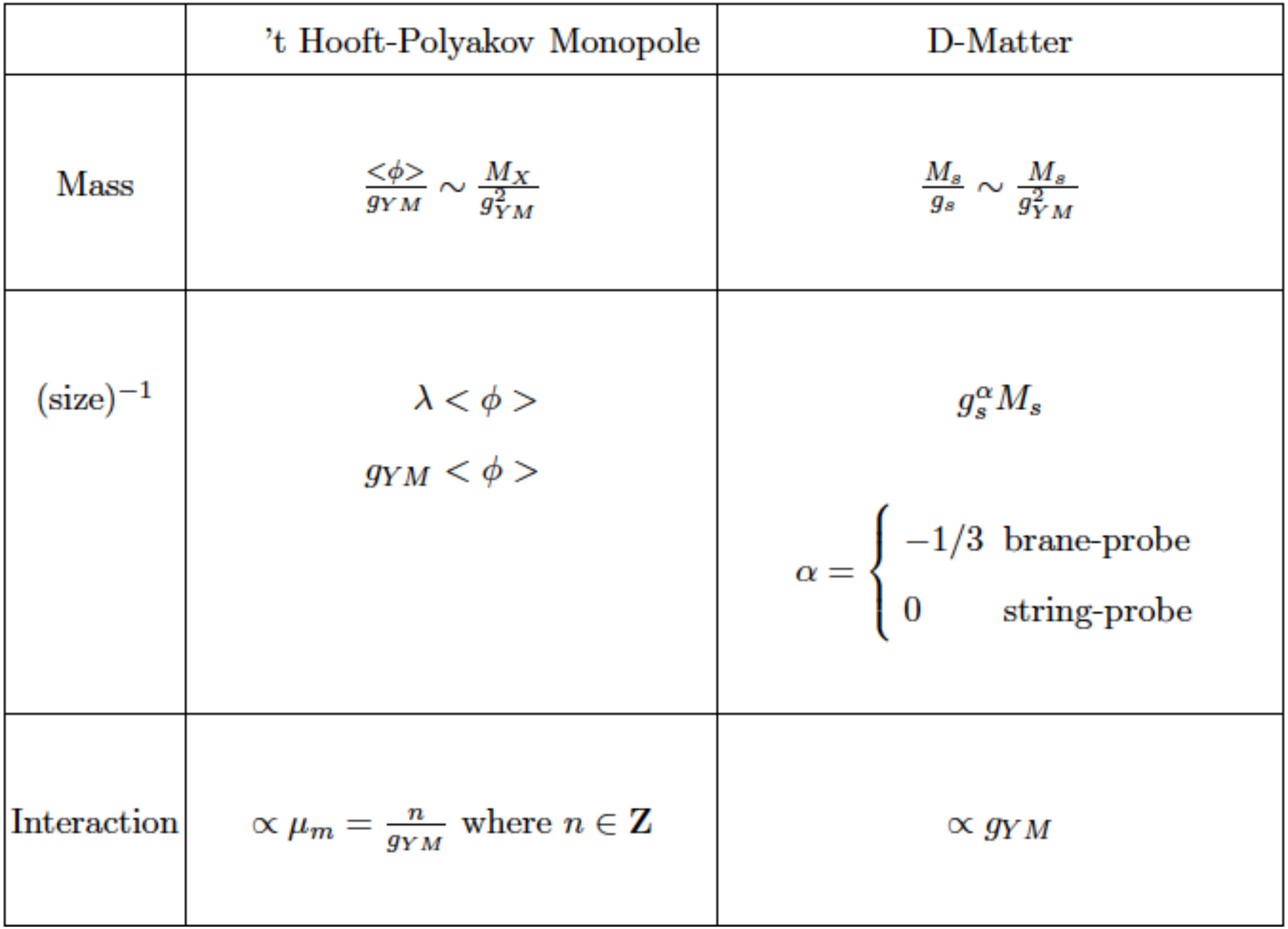
G Shiu L-T Wang 2003
J Ellis, NEM, Wesmuckett 2004

M_S = STRING MASS SCALE (≥ TeV phenomenologically)
$g_s < 1$ = (WEAK) STRING COUPLING

⚠

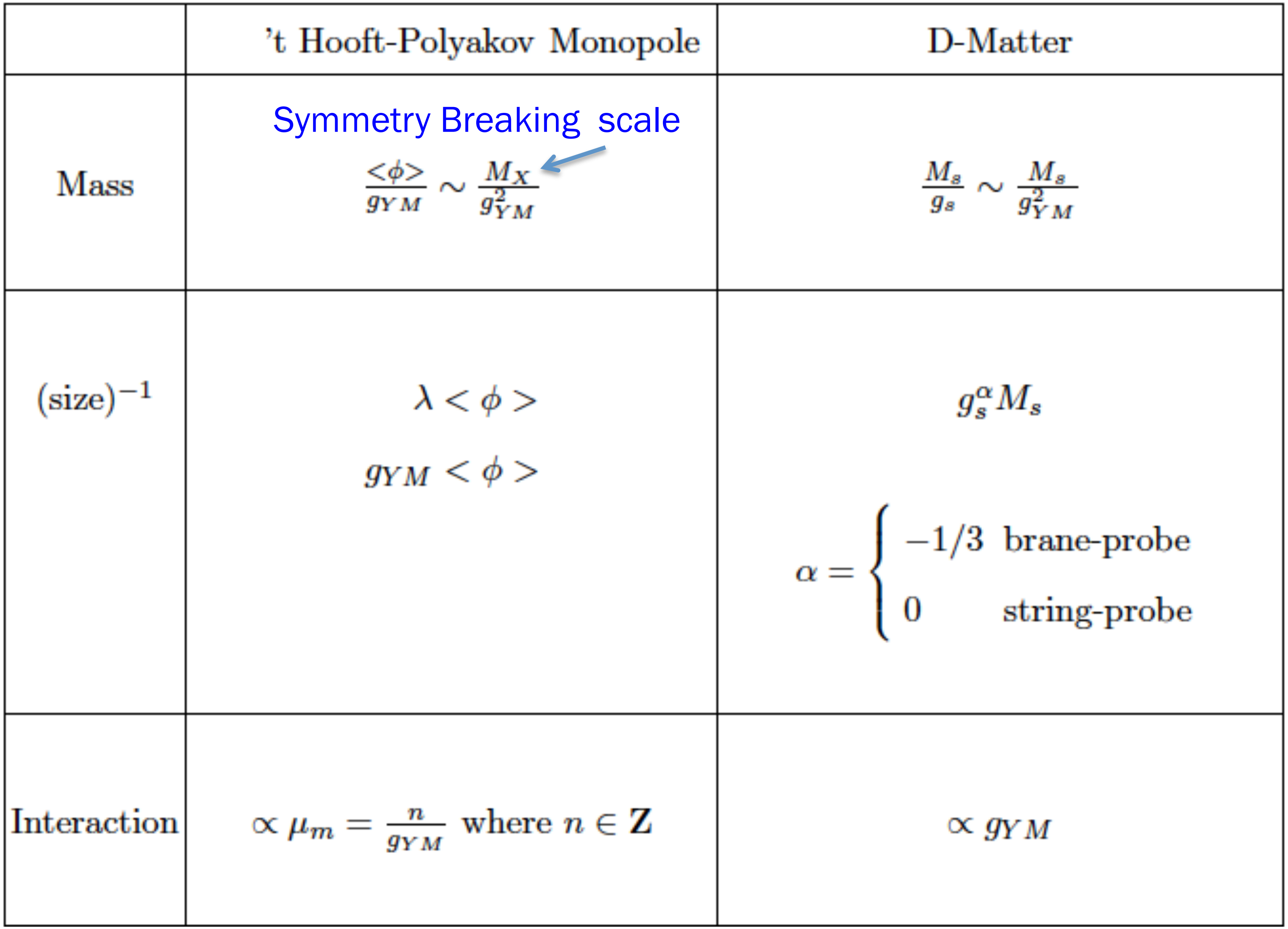
Can play the role of a kind of Dark matter/dark energy fluid

D-matter vs Monopoles



	't Hooft-Polyakov Monopole	D-Matter
Mass	$\frac{<\phi>}{g_{YM}} \sim \frac{M_X}{g^2_{YM}}$	$\frac{M_s}{g_s} \sim \frac{M_s}{g^2_{YM}}$
$(\text{size})^{-1}$	$\lambda < \phi >$ $g_{YM} < \phi >$	$g_s^{\alpha} M_s$ $\alpha = \begin{cases} -1/3 & \text{brane-probe} \\ 0 & \text{string-probe} \end{cases}$
Interaction	$\propto \mu_m = \frac{n}{g_{YM}}$ where $n \in \mathbf{Z}$	$\propto g_{YM}$

D-matter vs Monopoles



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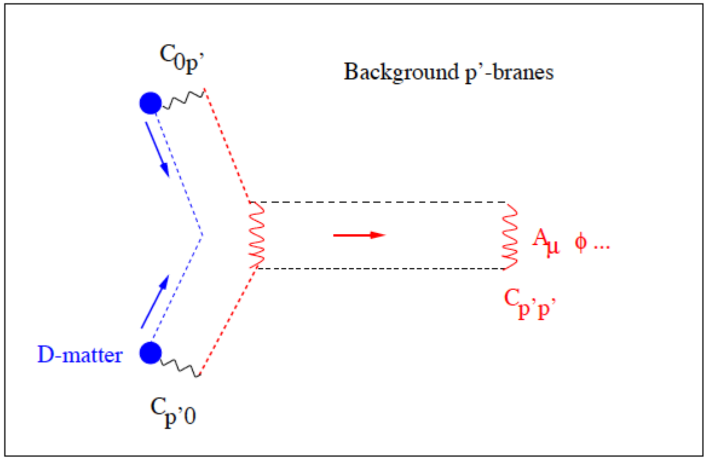
Interaction	NON-PERTURBATIVE $\propto \mu_m = \frac{n}{g_{YM}}$ where $n \in \mathbf{Z}$	PERTURBATIVE ⚠ $\propto g_{YM}$

D-matter/SM matter interactions



Via exchange of open strings stretched between D-particle and p' (D-brane) world

$$\propto g_D \overline{D}\, D \times \text{SM Gauge Bosons}$$

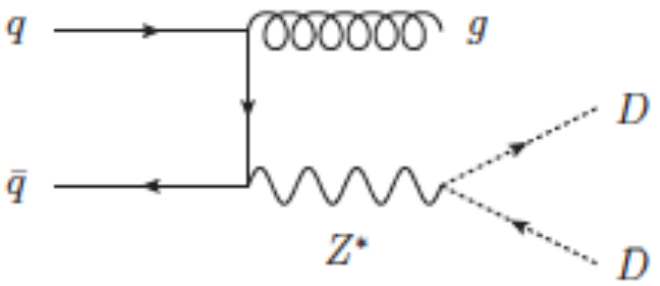
D-matter Mass spectrum

$$M^2_{\mathrm{D}^\star} = M^2_D + n\, M^2_s \qquad n \in \mathbf{Z}^+$$

$M_D \sim M_s/g_s$ Lightest D-matter (stable, play role of DM)

Can be produced @ LHC if $M_s = O(10\ \text{TeV})$

e.g.



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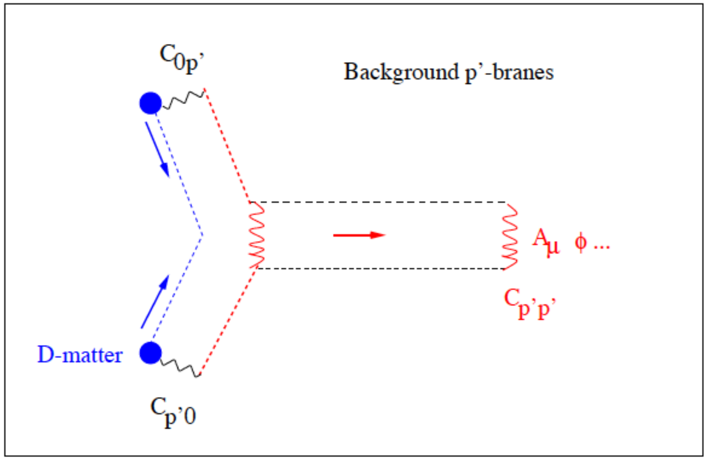

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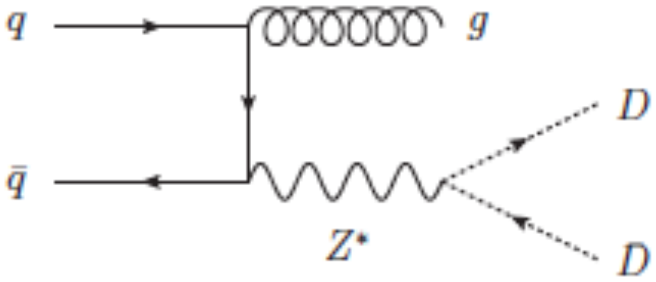
$M_D \sim M_s/g_s$ Lightest D-matter (stable, play role of DM) e.g.

Excited states can be electrically (or magnetically) charged → can be highly ionizing → relevant to MoEDAL

Can be produced @ LHC if M_s = O(10 TeV)



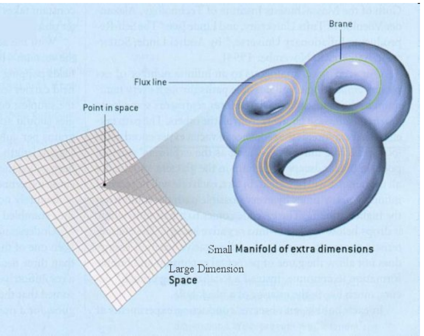
Black-Hole Remnants in Large extra dimensions

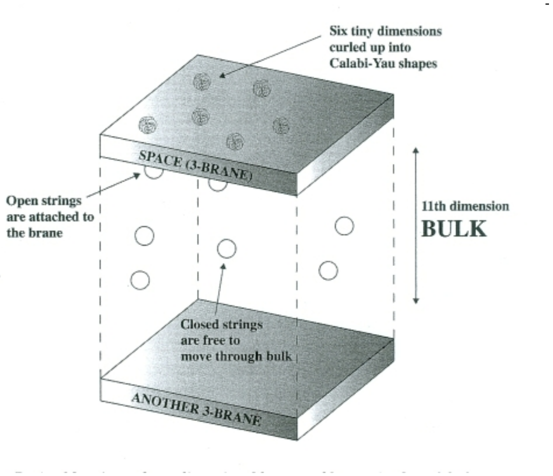
Large Extra dimension models motivated by string theory

Arkani-Hamed
Dimopoulos, Dvali
(string models)

Randall Sundrum
(brane models)

Both relevant
for providing
resolution of
the hierarchy
problem
in field theory



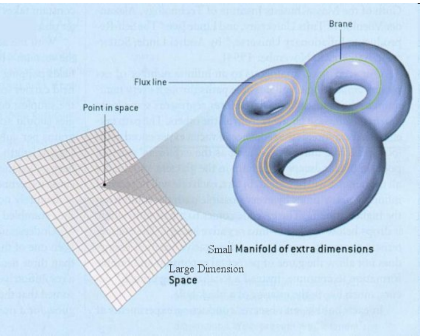


Stringy effects @ low
scales (TeV) possible

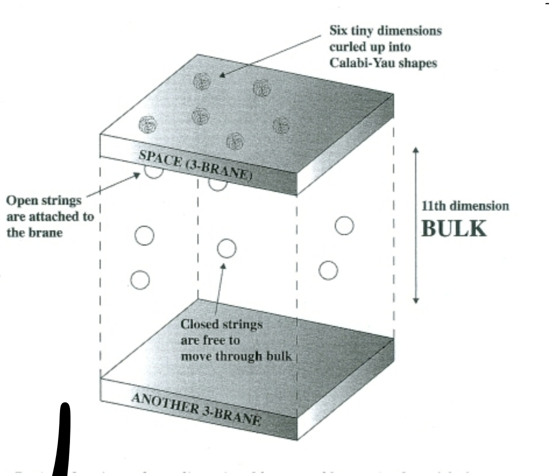
Large Extra dimension models motivated by string theory

Arkani-Hamed Dimopoulos, Dvali (string models)

Randall Sundrum (brane models)



Both relevant for providing resolution of the hierarchy problem in field theory



Stringy effects @ low scales (TeV) possible

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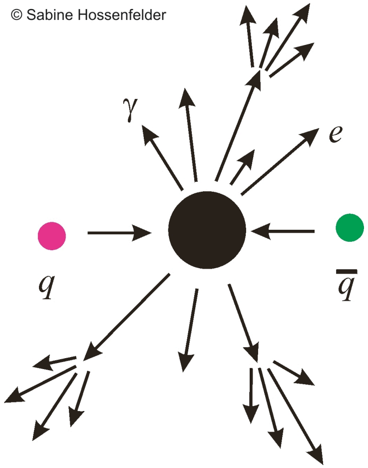


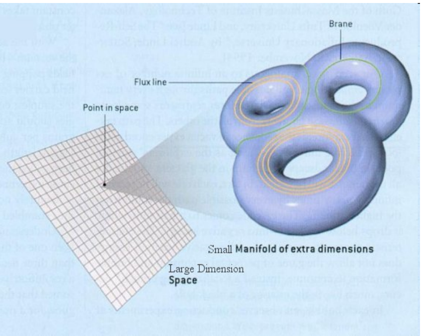
Dimopoulos, Landsberg

Formation of TeV Black Holes (BH) by high energy SM particle Collisions

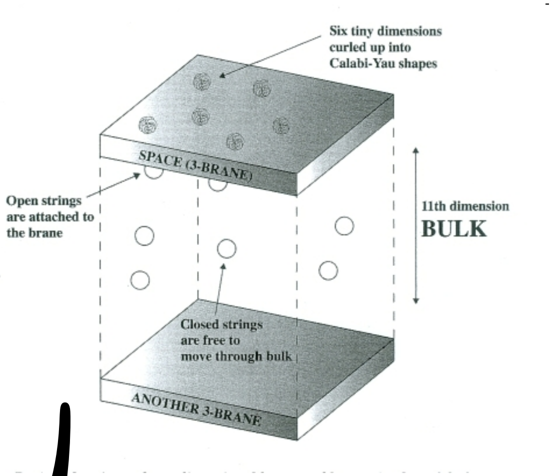
Large Extra dimension models motivated by string theory

Arkani-Hamed
Dimopoulos, Dvali
(string models)

Randall Sundrum
(brane models)



Both relevant
for providing
resolution of
the hierarchy
problem
in field theory



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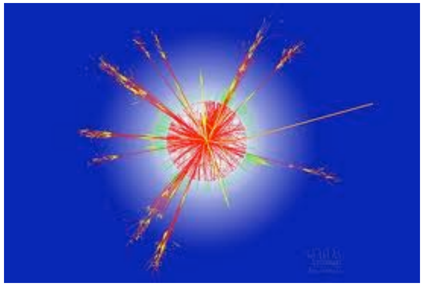
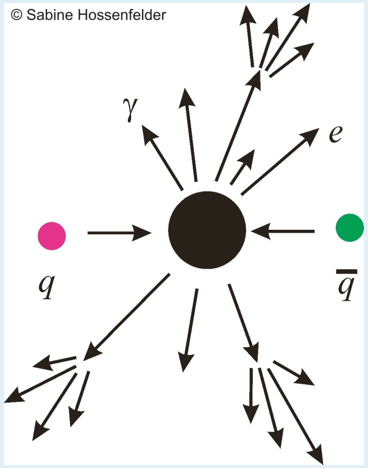


Formation of TeV Black Holes (BH) by high energy SM particle Collisions

BH produced in proton-proton collisions can carry **electric charge**

Charged BH Hawking evaporate but not completely → certain fraction of final
BH **remnants** carry charge (BH$^{\pm}$)

BH formed from proton-proton collisions are formed from interactions of valence quarks (carry largest available momenta of partonic system) → *BH average charge 4/3* → after evaporation to stable remnants, some accumulated net charge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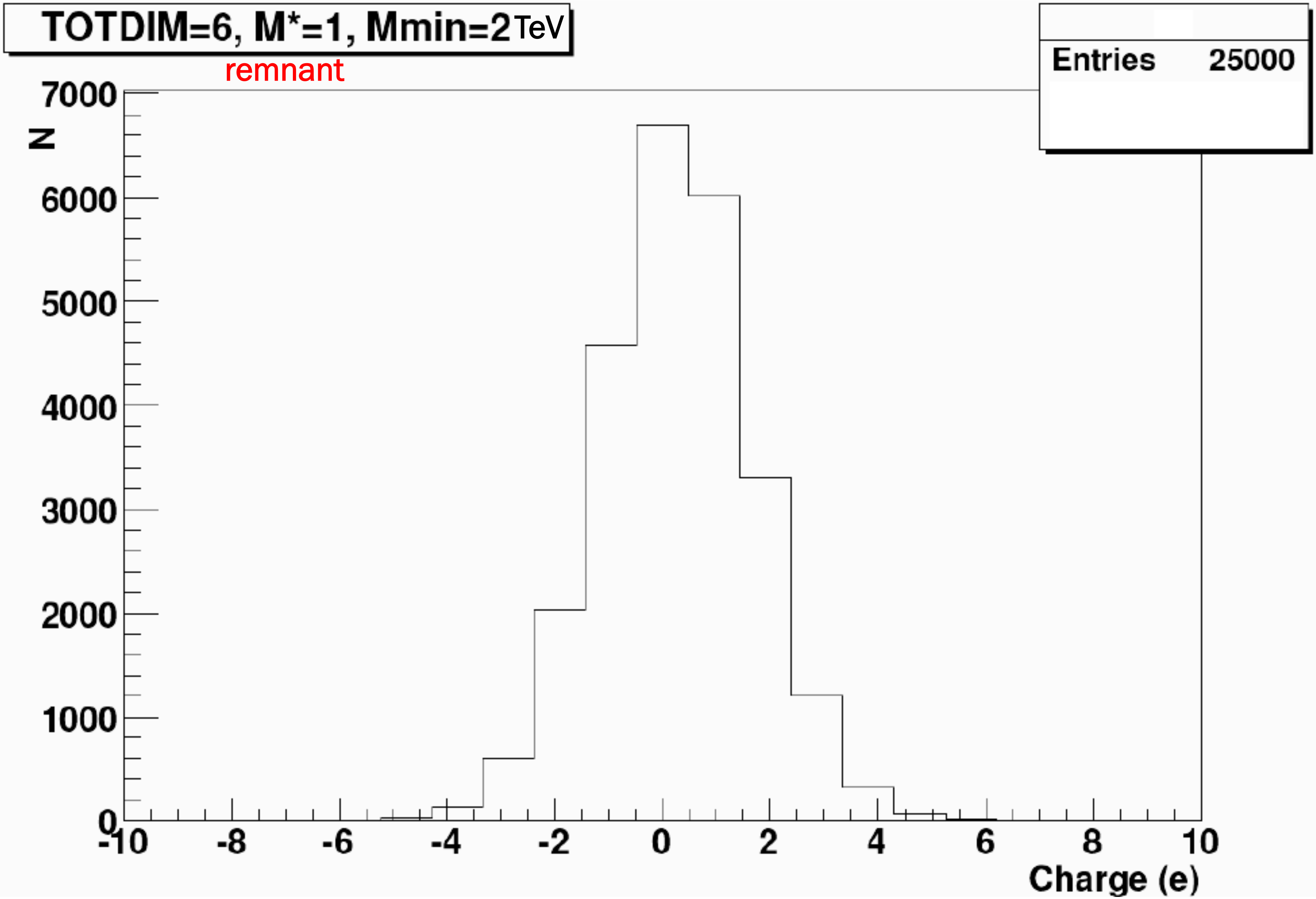
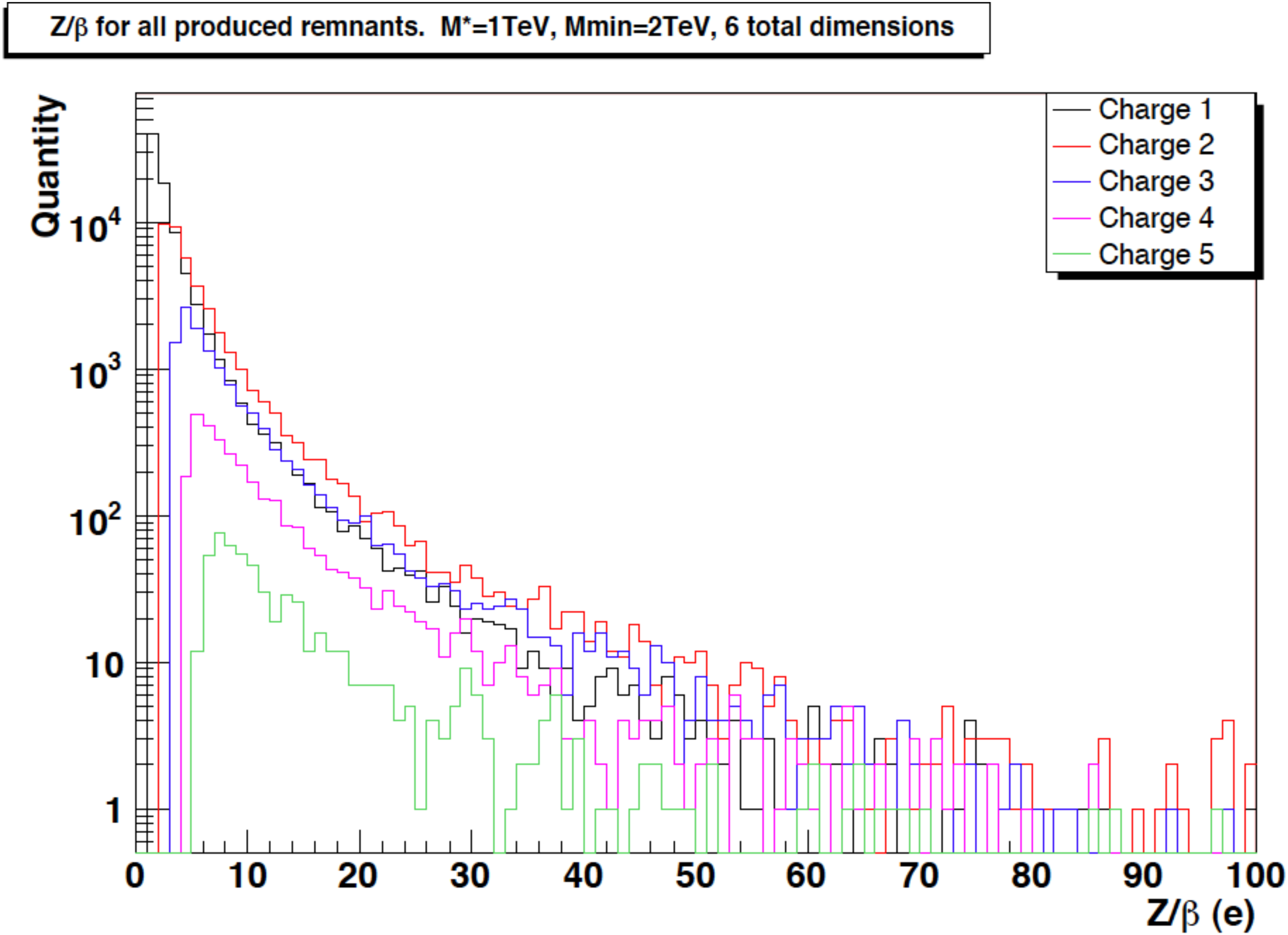
Most of BH **remnants** carry charge zero or one (in units of electron charge) smaller but non negligible fraction carry multiple charges → highly ionizing, relevant to MoEDAL

Estimated number of BH remnants vs charge using PYTHIA event generator & CHARIBDIS program for BH decay


TOTDIM=6, M*=1, Mmin=2TeV
remnant
Entries 25000
N
0
1000
2000
3000
4000
5000
6000
7000
-10
-8
-6
-4
-2
0
2
4
6
8
10
Charge (e)


Z/β for all produced remnants. M*=1TeV, Mmin=2TeV, 6 total dimensions
Quantity
10^4
10^3
10^2
10
1
0
10
20
30
40
50
60
70
80
90
100
Z/β (e)
Charge 1
Charge 2
Charge 3
Charge 4
Charge 5

Conclusions - Outlook

- **Topic of talk:** Several Instances where highly ionizing massive particles can appear @ the LHC energy range in **non supersymmetric** scenarios

- Such **charged massive** particles vary from Q-balls to extra-dimensional TeV mass Black Hole remnants and D-matter

- Can be relevant for MoEDAL Physics if **long lived & slowly moving, highly ionizing → may be undetectable in ATLAS & CMS, good targets for MoEDAL?**

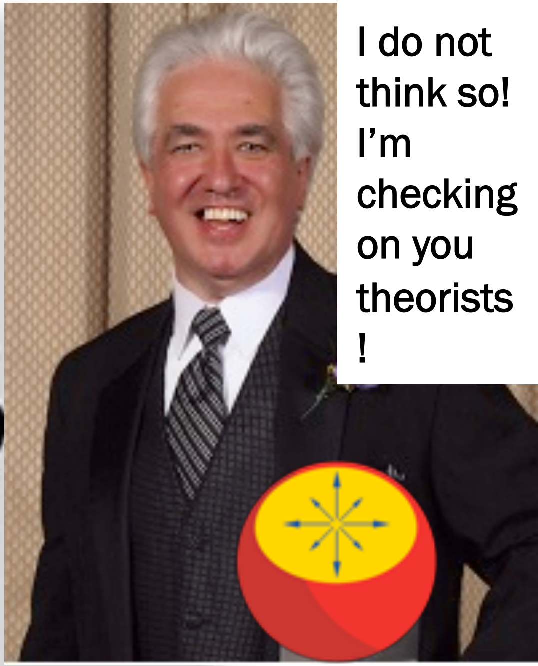
Conclusions - Outlook

- PROSPECTS LOOK GREAT FOR LHC Expts
- FUTURE LOOKS BRIGHT FOR MoEDAL - MAY DETECT NOT ONLY MONOPOLES BUT OTHER EXOTICS AS WELL & **probably exclusively …**
- MAY BE SURPRISES ARE AROUND THE CORNER EVEN FOR THEORISTS

…Carry on Searching …

Conclusions - Outlook

Conclusions - Outlook



I do not think so! I'm checking on you theorists !

MoEDAL