A conformal extension of SUSY and its particle collider phenomenology

Work in collaboration with: J. Terning and C. Gao (arXiv:1909.04061)

Talk at IPM

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Outline

- Standard Model (SM) explains nature quite well, but has unsolved problems.
- One compelling extension is MSSM. But no evidence has been found.
- An extension of MSSM is to assume part of it is conformal.
- We will use AdS/CFT correspondence for model building and as a tool.
- We will focus on gluino. Collider signature of a conformal/continuum/un gluino is different than MSSM and may partly explain why we have not seen it yet.

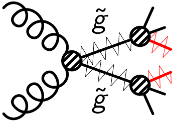
Minimal SuperSymmetric Standard Model (MSSM)

- Motivations: Naturalness, Dark Matter, Gauge Unification.
- SuperSymmetry: fermions $\Leftrightarrow$ bosons
- $Q\,|\phi\rangle = |\psi\rangle$, $Q\,|\psi\rangle = |\phi\rangle$. Q's are the SUSY charges and satisfy the SUSY algebra.
- Field content is

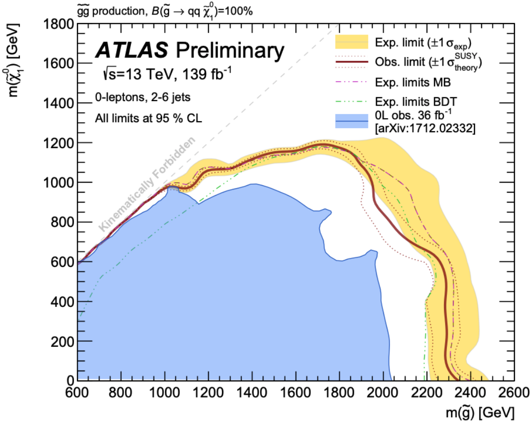
SM particle	spin	Partner	spin
q - quarks	$1/2$	$\tilde{q}$ - squark	0
l - leptons	$1/2$	$\tilde{l}$ - slepton	0
W	1	$\tilde{W}$ - wino	$1/2$
B	1	$\tilde{B}$ - bino	$1/2$
g -gluon	1	$\tilde{g}$ - gluino	$1/2$
H - Higgs	1	$\tilde{H}$ - Higgsino	$1/2$

MSSM: gluino searches

- Gluino has one of the biggest production cross-sections.



- The main Decay channel is 2jets+MET
- The MSSM gluino has been excluded up tp 2.3 TeV.



Effective Conformal Theory in IR

- Georgi brought up the idea and called the "stuff" un-particles
- Starting with a conformal theory and coupling it to MSSM and integrating out the conformal degrees of freedom, we are left with an effective theory.

$$S = S_{CFT} + S_{mix} + S_{elem.}$$

$$S \quad \rightarrow \quad S_{1PI}$$

- In a conformal theory the two point function is fixed.

$$\langle \phi(p)\phi(-p) \rangle = \frac{-i}{p^{2(2-\Delta)}}.$$

- Unitarity requires: $1 < \Delta$

Effective Conformal Theory in IR

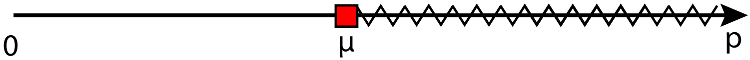
- We can describe the analytic properties of the two point function using the density function

$$\langle \mathcal{O}(p)\mathcal{O}(-p)\rangle \propto \int_0^\infty \rho(M^2)\frac{i}{p^2 - M^2 + i\epsilon}dM^2 \quad \text{Källén -Lehmann}$$

- A particle is a pole.
- For an unparticle there is a branch cut starting from zero; **continuum**
- e.g. analytic plane of the density function with a branch cut starting at zero:

The Soft Braking of the CFT

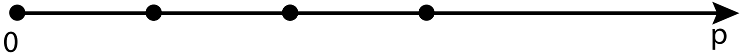
- To apply the unparticle idea to SM or MSSM particles we need to break the CFT
- Softly broken CFT shifts the branch point to μ



- An example is

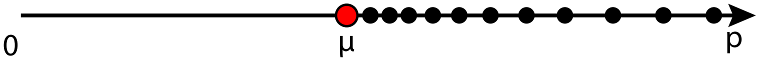
$$\langle \mathcal{O}(p)\mathcal{O}(-p)\rangle = \frac{-i}{(p^2-\mu^2)^{(2-\Delta)}}.$$

- In contrast, Hardly broken CFT gives an array of particles.



Deconstructing the Branch cut (continuum)

- It is much more obvious to keep track of things if we substitute the continuum with an array of particles.
- Can be done using pade approximation or in AdS/CFT using an IR brane.



- Since it is a regularization, the physics should not depend on the hard breaking.

Using AdS/CFT correspondence

- AdS/CFT provides a weakly coupled dual for the strongly coupled CFT.
- Finding the interactions is always possible from the first principles.
- Deconstruction is easier using an IR brane.

A brief introduction to AdS/CFT

- Many 5D theories can be written in terms of a 4D holographic theories

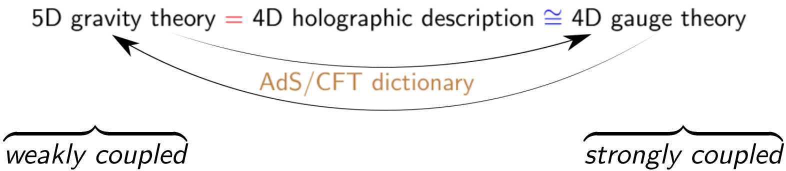
$$S_{5D} \to S_{4D}^{eff} = S_{SM} + S_{new}$$

- Maldacena first purposed a duality in string theory.

  Type II B String theory on $AdS_5 \times S^5 \cong N = 4$ SUSY Yang-Mills

- Soon after it was purposed that

$$\text{Any 5D gravity theory on } AdS_5 \cong \text{Some CFT}$$



A brief introduction to AdS/CFT

- AdS: Maximally symmetric space-time with (-) C.C.
- Space-time symmetry (Poincare) of AdS_5 matches that of a 4D CFT: SO(4,2)
- Masses in 5D are related to the scaling dimension in 4D. E.g. for scalar: $m^2 = \Delta(\Delta - 4)$.
- In a coordinate system the metric reads for AdS_5

$$ds^2 = \frac{1}{z^2}\left(\eta^{\mu\nu} dx_\mu dx_\nu - dz^2\right)$$

- One symmetry of this metric is $x \to \lambda x, z \to \lambda z$.
- A 4D theory is scale invariant (conformal) if $x \to \lambda x, E \to E/\lambda$

energy scale of 4D CFT $\Longleftrightarrow 1/z$

AdS/Broken CFT

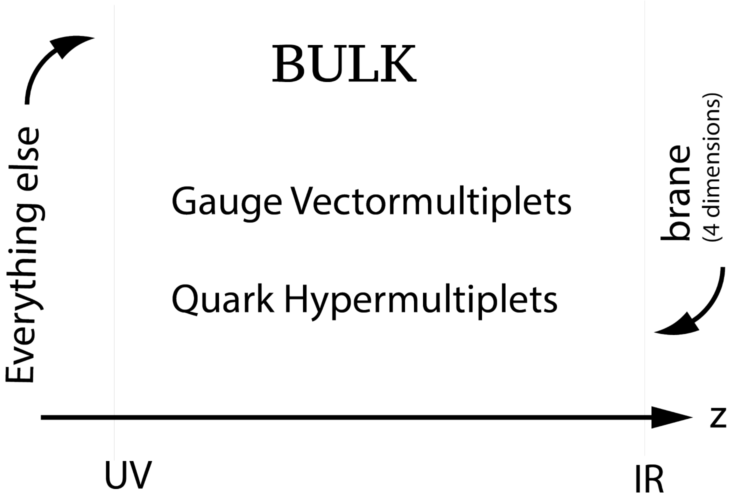
- Adding a UV brane at $\epsilon \ll 1$: No more invariance under $z \to \lambda z$, CFT is broken
  - $E \propto 1/\epsilon$ is large, CFT is broken in UV by Irrelevant operators
  - We can add fields on this brane, they are not part of CFT, they are *elementary*
- IR brane: hard braking of the CFT
  - If nothing is happening in IR (large z), the CFT is preserved: RS II model
  - If we add another brane, an IR brane, in 5D we get K.K. modes: RS I model
- Soft braking of the CFT: There are other ways to deviate from the AdS_5: Change the background smoothly; add mass terms that depend on the coordinate z, ...

$$ds^2 = e^{-2A(z)}\left(\eta^{\mu\nu}dx_\mu dx_\nu - dz^2\right), \qquad A(z)_{AdS} = \log(z/R)$$

$$S_{bulk} \supset \frac{1}{2}\int d^4xdz\sqrt{g}\left(\partial_M h\partial^M h - M^2(z)h^2\right)$$

Field content

- Gauge fields in 5D correspond to global symmetries of the 4D theory.
- They can be gauged in 4D theory by boundary condition in 5D theory
- 5 Dimensions



Hypermultiplets in AdS

- A $\mathcal{N} = 1$ SUSY in 5D contains 4 real scalars and 2 majorana fermions.

$$S_5 = -\int d^4xdz\sqrt{g}\left(|\partial_M\phi^{(i)}|^2 + M_i^2|\phi^{(i)}|^2 + i\bar{\Psi}\Gamma^M D_M\Psi + h.c. + m_i\bar{\Psi}\Psi\right)$$

- SUYS in 5D relate the masses (In 5D P does not commute with Qs)/
- Dimension of the 4D CFT fields are related to 5D masses by the dictionary
- Check: The dimensions are related as expected in a 4D CSUSY: $\Delta_\psi = \Delta_{\phi^1} + 1/2 = \Delta_{\phi^2} - 1/2$.

Hypermultiplets in AdS

- The soft braking is achieved by promoting the mass to a coordinate dependent mass: $mR \to c + \mu z$. c is related to the scaling dimension of the fields via AdS/CFT
- The equations of motion in 5D solve to give

$$\psi^{(1)}(p,z) = \psi_4^{(1)}(p)\left(\frac{z}{R}\right)^2 f^{(1)} \quad \phi^{(1)}(p,z) = \phi_4^{(1)}(p)\left(\frac{z}{R}\right)^{3/2} f^{(1)}$$

$$\psi^{(2)}(p,z) = \psi_4^{(2)}(p)\left(\frac{z}{R}\right)^2 f^{(2)} \quad \phi^{(2)}(p,z) = \phi_4^{(2)}(p)\left(\frac{z}{R}\right)^{3/2} f^{(2)}$$

- where

$$\begin{aligned} f^{(1)}(p,z) =& M(\kappa, \frac{1}{2} + c, 2\sqrt{\mu^2 - p^2}z) + BW(\kappa, \frac{1}{2} + c, 2\sqrt{\mu^2 - p^2}z) \\ f^{(2)}(p,z) =& -A\frac{2c(1+2c)\sqrt{\mu^2 - p^2}}{p} M(\kappa, -\frac{1}{2} + c, 2\sqrt{\mu^2 - p^2}z) \\ & - B\frac{p}{\mu + \sqrt{\mu^2 - p^2}} W(\kappa, -\frac{1}{2} + c, 2\sqrt{\mu^2 - p^2}z) \end{aligned}$$

- B is set by IR B.C.

Vectormultiplets in AdS

- A $\mathcal{N}=1$ vector supermultiplet consist of 5D gauge field A_M, two weyl gaugino λ_1, λ_2 and a scalar field Σ.

$$S_{5D} = \int d^4xdz\sqrt{g}\Bigg(-\frac{1}{4}F^{aMN}F^a_{MN} + \frac{1}{2}D_M\Sigma^a D^M\Sigma^a - \frac{1}{2}m^2_\Sigma\Sigma^a\Sigma^a + i\bar{\psi}^a\Gamma^M D_M\psi^a + m_\psi\bar{\psi}^a\psi^a - gf_{abc}\bar{\psi}^a\Sigma^b\psi^c\Bigg)$$

- The soft braking is achieved by a z-dependent dilation. The solution are

$$\lambda^{(1)}(p,z) = \lambda^{(1)}_4(p)e^{\mu z}\left(\frac{z}{R}\right)^2 h^{(1)} \quad A_\nu(p,z) = A_{\nu 4}(p)e^{\mu z}\left(\frac{z}{R}\right)^{1/2} h^{(1)}$$

$$\lambda^{(2)}(p,z) = \lambda^{(2)}_4(p)e^{\mu z}\left(\frac{z}{R}\right)^2 h^{(2)} \quad \Sigma(p,z) = \Sigma_4(p)e^{\mu z}\left(\frac{z}{R}\right)^{3/2} h^{(2)}$$

- where $h^{(i)}$ are $f^{(i)}$ evaluated at $c=1/2$

Deconstruction and SUSY braking

- Adding an IR brane and requiring that field vanish at this boundary brakes continuum into KK modes. e.g.

$$\psi(x,z) = \sum_n \psi_4^n(x)\Big(\frac{z}{R}\Big)^2 f^{(1)}(m_{\psi_n}, z)$$

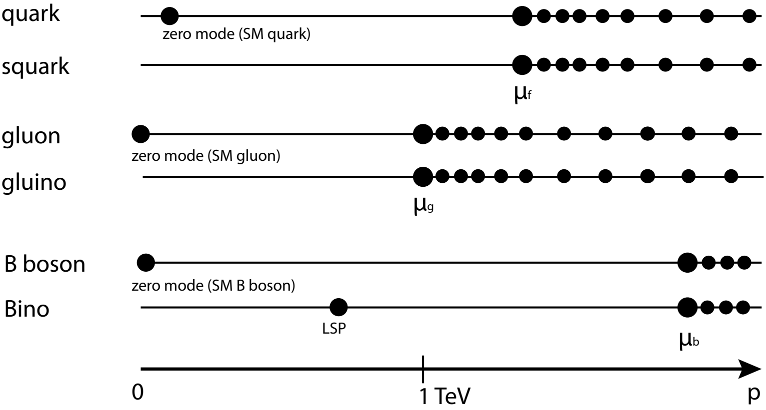
- The spectrum consist of a zero mode + a chain of closely spaced KK modes above μ.
- The IR brane is a regulator and the physics should be independent of its location.
- SUSY braking is achieved by adding a mass term on the UV brane

$$S_{UV} = \frac{1}{2}\int d^4xdz\Big(-\phi^{(1)*}M^2_{\not{SUSY}}R\phi^{(1)} + h.c.\Big)\delta(z-R)$$

- By choosing the right mass we can move the zero mode of the Superpartners into their continuum.

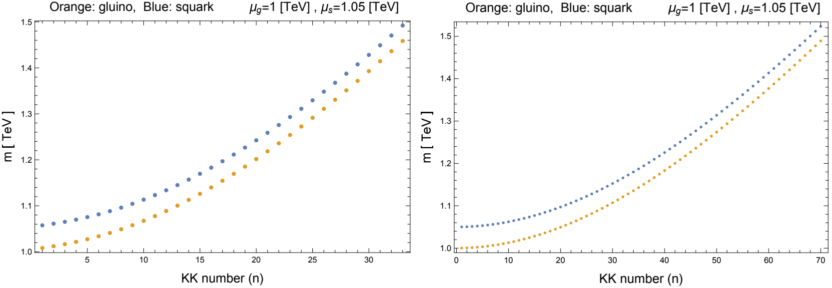
Gluino, Squark, and LSP

- The spectrum of the fields we consider in this work are shown below after the soft and hard breaking of the CFT.



The spectrums

- For example, for two different choices of z_{IR}, we have as follow.
- Once a gluino is produced, it will decay to a lighter squarks, and the squarks to a lighter gluino and so forth.



(a) $z_{IR} = 100\ \mathrm{TeV}^{-1}$ (b) $z_{IR} = 200\ \mathrm{TeV}^{-1}$

Figure: gluino and squark KK spectrum.

Production and decay of KK modes

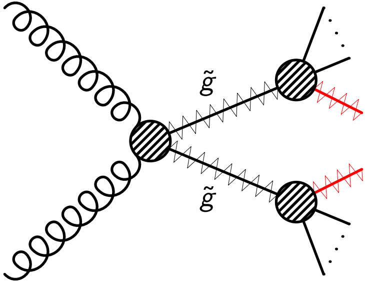
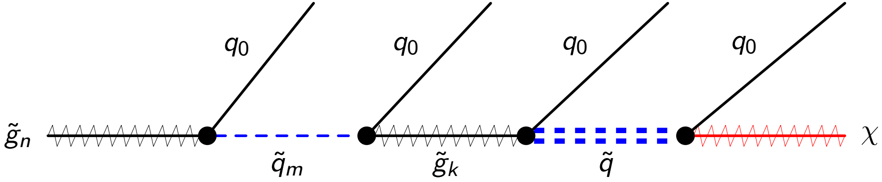


Figure: Pair production and decay of gluino continuum at LHC. The solid black lines are the SM quarks and the red lines correspond to LSP.



Interaction

- We can start from 5D and integrate over the fifth dimension to get the effective 4D interaction.

$$S_{int} = \int d^4xdz\left(\frac{R}{z}\right)^3\frac{g_5}{\sqrt{2}}(\tilde{g}^a\bar{q}T^a\tilde{q} + h.c.)$$

$$\mathcal{L}_{int} \supset \frac{g_5}{\sqrt{2}}T^a\sum_{n,m}c_1(m_{\tilde{g}^n}, m_{\tilde{q}^m})\bar{\tilde{g}}_4(p_m)\tilde{q}_4(k_n)\bar{q}_4^0(k_n - p_m)$$

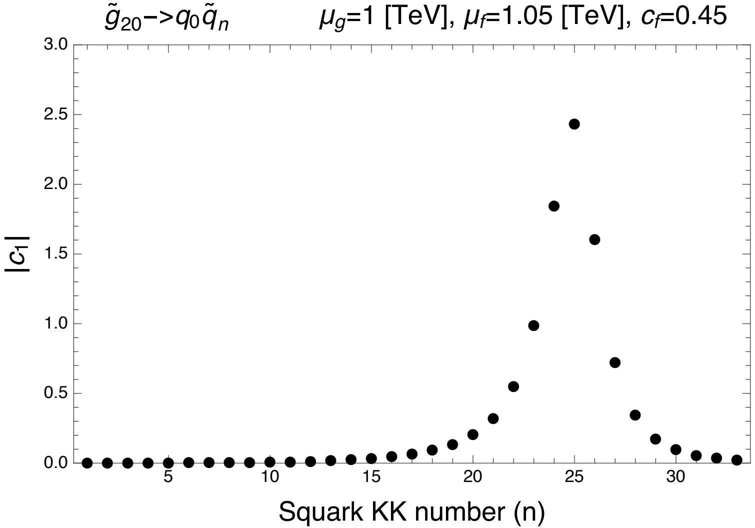
where the vertex coefficient can be read off:

$$c_1(m_{\tilde{g}^n}, m_{\tilde{q}^m}) = \mathcal{N}^*_{\tilde{g}}(\mu_g, m_{\tilde{g}^n})\mathcal{N}^*_q(\mu_f, 0)\mathcal{N}_{\tilde{q}}(\mu_f, m_{\tilde{q}^m})\times \int_R^{z_{IR}} dz\left(\frac{z}{R}\right)^{1/2} e^{(\mu_g-\mu_f)z}\left(\frac{z}{R}\right)^{-c}\mathfrak{f}^{(1)}(m_{\tilde{q}^m}, z)^*\mathfrak{h}^{(1)}(m_{\tilde{g}^n}, z)$$

- The exponential $exp[\mu_g - \mu_f]$ divergent for$\mu_f > \mu_g$. So we take $\mu_g < \mu_f$.

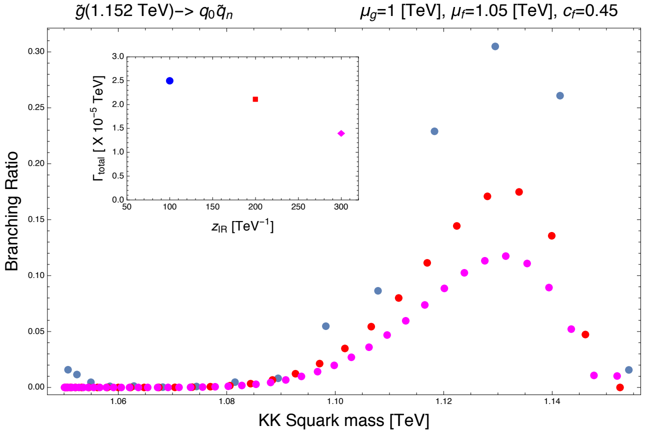
Interaction

- The coupling between the 20th KK gluino, zero mode quark, and KK squarks. With $z_{IR} = 100\ \mathrm{TeV}^{-1}$.



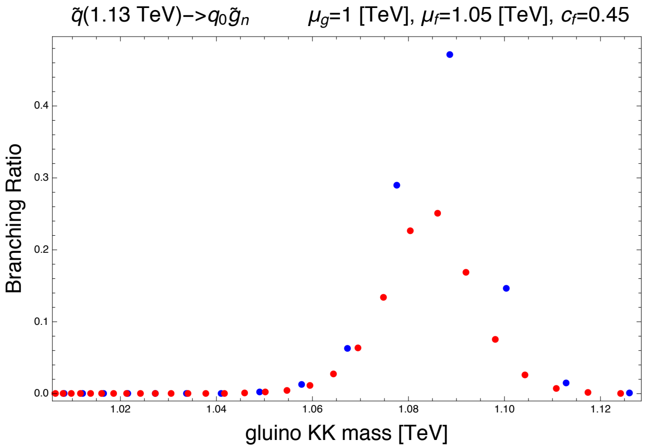
Two body decay of gluinos

- Examples of decay probabilities of one KK gluino with mass $> \mu_f$, decaying to the zero mode quark and a lighter KK squark. The branching ratios for different choices of z_{IR}: 100 TeV^{-1} (blue), 200 TeV^{-1} (red), and 300 TeV^{-1} (pink) are shown.



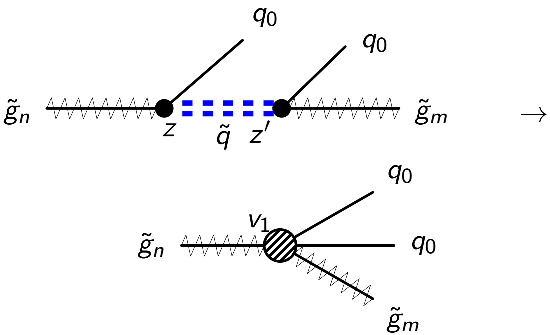
Two body decay of squarks

- Examples of decay probabilities of a KK squark with mass $> \mu_g$, decaying to the zero mode quark and a lighter KK gluino. The BR is plotted for different choices of z_{IR}: 100 TeV^{-1} (blue), and 200 TeV^{-1} (red).



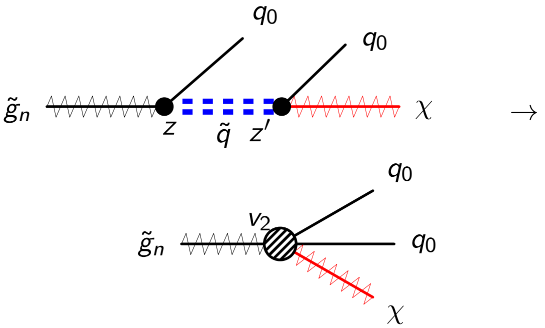
Three body decay of gluinos

- When $m_g < m_q$, the only way the gluino can decay is through a three body decay through an off-shell squark.
- It is easier to use the 5D holographic propagator for the squark instead of summing over infinite number of off-shell KK squarks.
- For $\tilde{g}^n \to q_L^0 \bar{q}_L^0 \tilde{g}^m$



Three body decay of gluinos

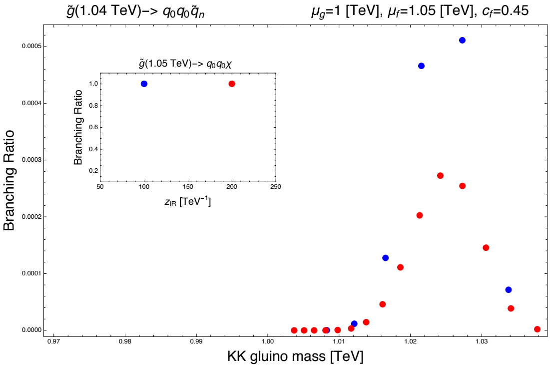
- Another decay channel is $\tilde{g}^n \to q_L^0 \bar{q}_L^0 \tilde{\chi}^0$, where χ is the LSP



- The LSP in our model is the zero mode of Bino.

Three body decay of gluinos

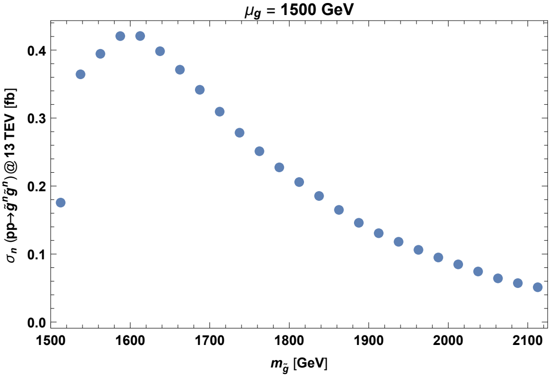
- Examples of decay probabilities of a KK gluino with mass $< \mu_f$ for different choices of z_{IR}: 100 TeV^{-1} (blue), and 200 TeV^{-1} (red). The small graph shows the probability of its decay to LSP, which is assumed to be massless.



- We can see that the gluino predominantly will decay to LSP in a 3-body decay.

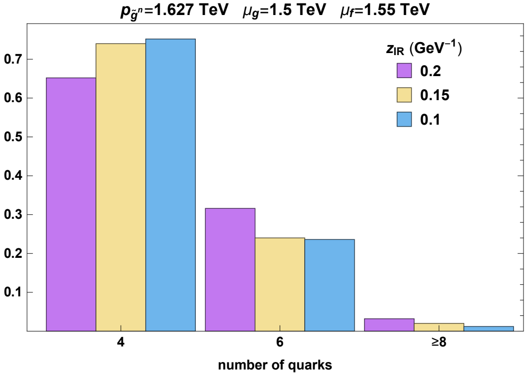
Collider Phenomenology: Setting μ_g.

- As our benchmark value we will use $\mu_g = 1.5$ TeV^{-1}.
- The cross-section for production of such continuum gluino would be close to that of a MSSM gluino with mass 1.65 TeV^{-1}. So we compare to this MSSM gluino.
- The first 20 KK modes account for around 85% of the total cross section. So we approximate the continuum with these KK modes.



Collider Phenomenology: Setting z_{IR}.

- We have already shown that the result does not depend on the z_{IR}. We choose $z_{IR} = .1\ \text{GeV}^{-1}$. As a check



Collider Phenomenology: Setting μ_f.

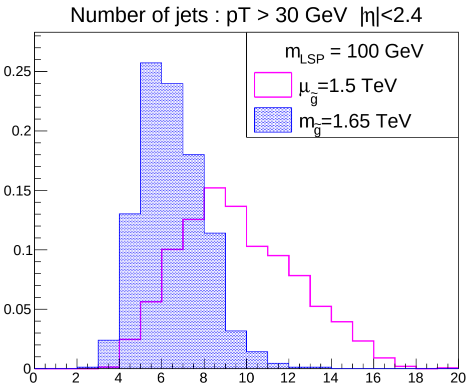
- To set μ_f, we first remind ourselves that $\mu_f < \mu_g$ does not work in these models since some of the couplings become divergent.
- For $\mu_f \gg \mu_g$ the phenomenology highly depends on the LSP mass
  - If $m_\chi \ll \mu_g$, all the gluino KK modes will promptly decay to the LSP+Jets. This would be very similar to MSSM gluino.
  - If $m_\chi \approx \mu_g$, the decay chain will end with gluinos with a very big lifetime. Displaced searches would be sensitive to this corner of parameter space, but we will not consider it here.
- We choose instead $\mu_g < \mu_f = 1.55$ TeV^{-1}. The KK gluinos will go throw a long decay chain.

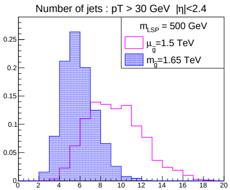
Collider Phenomenology

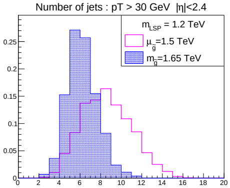
- We will use four species of squarks, $\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}$.
- We will present our results for three masses of LSP: 0.1, 0.5, and 1.2 TeV
- The production of the first two KK gluino is done in MADGRAPH
- The decay of the KK gluino is done in Mathematica
- The resulting decay particles are then passed throw PYTHIA 8 for showering and hadronization
- The detector simulation is done via DELPHES 3

Simulation: Number of jets

- As expected, there are more jets than MSSM.

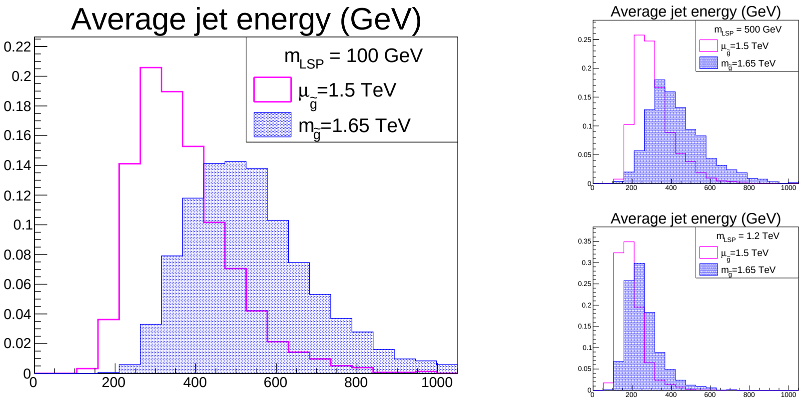






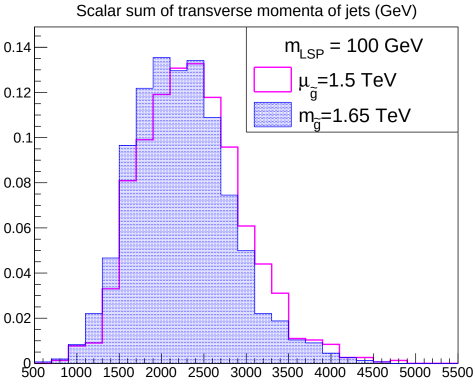
Simulation: Average jet energy

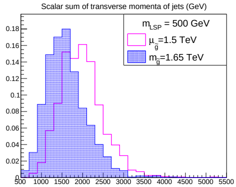
- Since the initial gluino will carry approximately the same energy as in MSSM, the average jet energy will be lower.
- In continuum case, the 2-body decay jets (most of the jets) are much less energetic than the 3-body Jets.
- In MSSM case, gluino decays predominately throw 3-body. As LSP mass increases, these jets become less energetic.

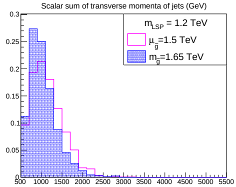


Simulation: Scalar sum of P_Ts.

- The H_T is very similar, the continuum case is slightly higher since there are more jets.

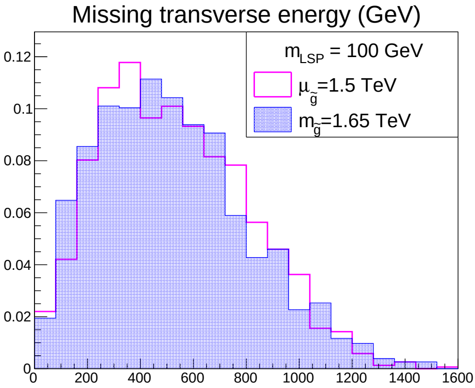


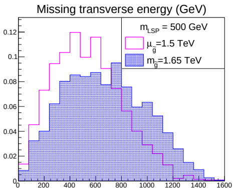


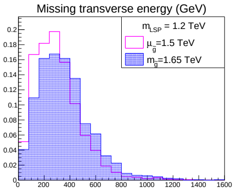


Simulation: Missing transverse momentum (MET)

- Again, since there are more jets, they distribute themselves more evenly in transverse plane, hence lower MET.
- In low LSP mass region the 3-body jets are very energetic and put the other jets in a shade
- In high LSP mass region all the jets are very soft and there are lots of cancellation of PT and MET







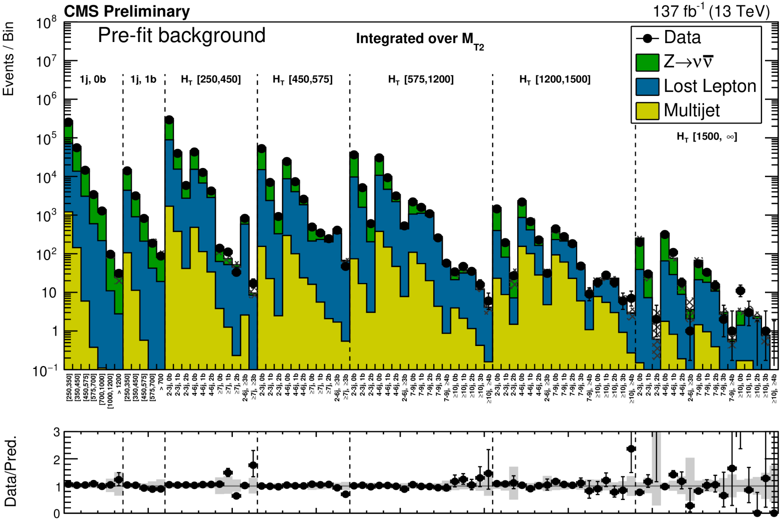
Result

- Given the (many) assumptions we made, the signature of the continuum gluino are
  - More jets than MSSM, around 10 jets.
  - Slightly higher H_T
  - Slightly lower P_T
- Traditional SUSY searches has already excluded 10 jets signals!
- Using the cuts in CMS-PAS-SUS-19-005, for 10j0b we have

$(\mu_{\tilde{g}}, m_{\mathrm{LSP}})$ GeV	Initial @137fb^{-1}	$H_T >$1500&$\mathrm{M_{T2}} >$400 &$p_{\mathrm{T}}^{\mathrm{miss}} >$30 GeV	$10j0b$	$\Delta\phi(p_{\mathrm{T}}^{\mathrm{miss}}, j_{1,2,3,}$ > 0.3
(1500,100)	706	667	121	86
(1500,500)	706	584	105	75
(1500,1200)	706	119	27	20

Result

- From CMS-PAS-SUS-19-005:



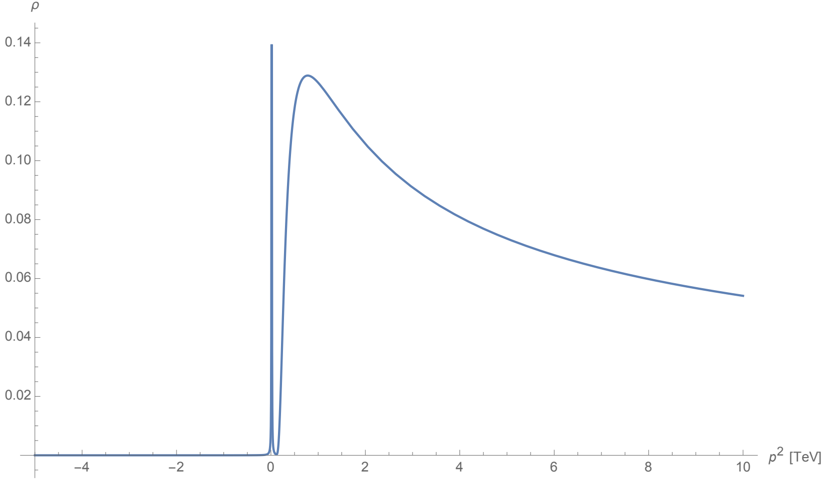
Conclusion

- We have implemented a conformal extension of MSSM in AdS spacetime
- We have softly broken the CFT and further broke it via an IR brane to simplify simulation
- We have shown that the results are independent of the regulating brane
- The signature has much more jets but it is still ruled out via traditional SUSY searches
- However these models are much less restrict than MSSM. One can search further:
  - Continuum LSP?
  - What about long lived continuum gluino?

Thank You

Density function

- The absolute value of the density function for a SM particle is shown.
- The branch cut starts at two particle threshold and is of order of α^2



A simple case: 5D gravity + scalar

- In 5D (bulk)

$$S_{bulk} \supset \frac{1}{2} \int d^4x dz \sqrt{g} \Big(\partial_M h \partial^M h - m^2 h^2 \Big) \qquad (1)$$

- AdS_5 has a boundary at $z = 0$: Regulate it with a *brane* at $z = \epsilon$
- partially F.T. and use Bulk-boundary propagator (i.e. green function)

$$h(x, z) = \int \frac{d^4p}{(2\pi)^4} e^{-ip\cdot x} h(p, z)$$
$$h(p, z) = h_\epsilon(p) \mathcal{K}(p, z)$$

- Use the e.o.m. to solve for $\mathcal{K}$
- Plug the solution + apply e.o.m. + take the limit $\epsilon \to 0$

$$S_{bulk} \to \int \frac{d^4p}{(2\pi)^4} h_\epsilon(p) p^{2(2-\Delta)} h_\epsilon(-p), \qquad \Delta = 2 - \sqrt{m^2 + 4}$$