HOW TO CHALLENGE STRING THEORY AT A COLLIDER

2412.13192:
MB, P. Christeas, J. Heckman, & R. Hicks
27xx.xxxxx: MB, J. Grumski-Flores,
J. Heckman, C. Keeler, & R. Hicks



"Thetis dipping Achilles into the River Styx" - Pierre Borel (1788)

Matthew Baumgart (ASU/YITP)

New Physics in the Dark Universe - YITP 2026-10-28

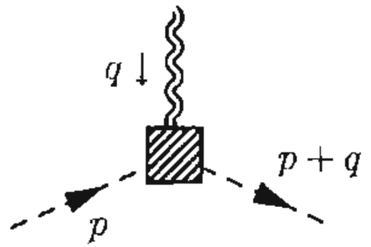
DO WE NEED QUANTUM GRAVITY?

- No experimental evidence to date for quantum gravity, but…
  - Why does $m_{\text{gravitational}} = m_{\text{inertial}}$?
  - Why is $S_{\text{Einstein-Hilbert}} = \int d^4x \sqrt{-g}\, R$?
  - Why does gravity couple to energy-momentum tensor $T_{\mu\nu}$?
- Having a **consistent theory of a massless spin-2 particle (graviton) answers these questions**.

$$F = m_{\text{inertial}}\, a$$

$$F = \frac{G\, m^{(1)}_{\text{gravitational}}\; m^{(2)}_{\text{gravitational}}}{r^2}$$

$$F = \frac{q^{(1)}\, q^{(2)}}{4\pi\, \epsilon_0\, r^2}$$

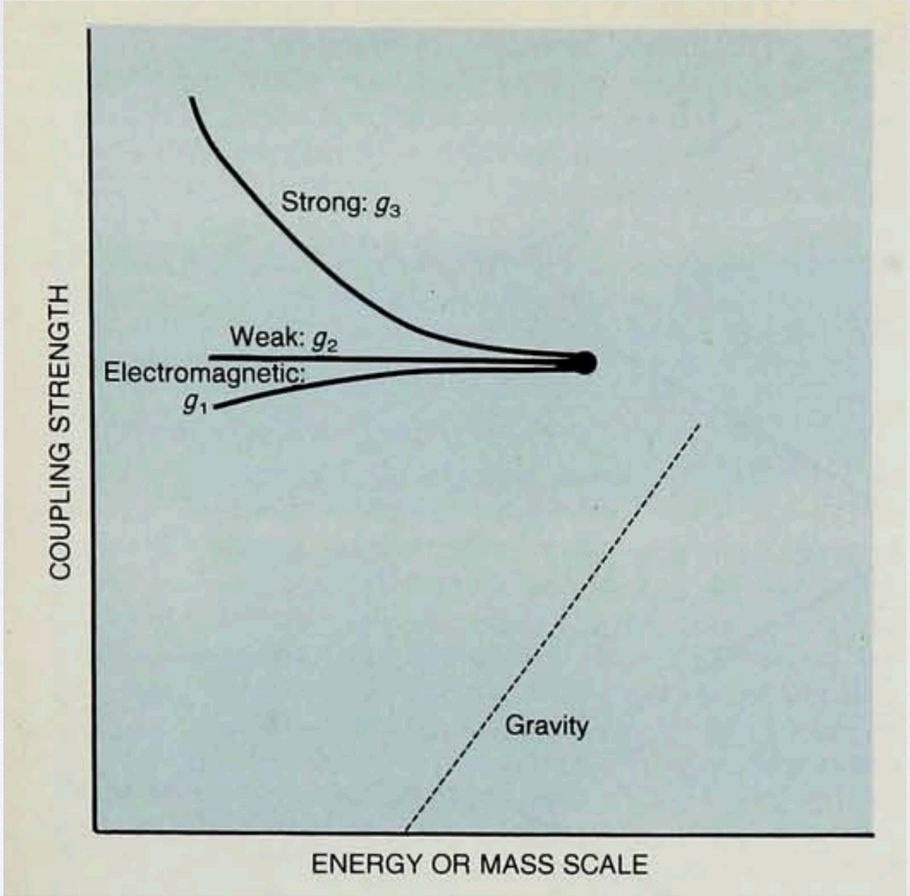


$$= -i\Gamma^{\mu\nu}(p,q) = -2ip^\mu p^\nu \tilde{F}\left(\frac{p\cdot q}{m^2}\right)$$

Weinberg Soft-Graviton Theorem (1965): Gravitational coupling proportional to m_{inertial}.

WHY STRING THEORY?

- Theory of quantum gravity fell into our lap from studying strong interaction.
- Theory of Everything that unites description of gravity, gauge forces and matter.
- Consistent quantum string theory → conformal invariance on worldsheet → Einstein's Equations at long distance!
- Concrete realization of holography (AdS/CFT)
- Concrete examples of black hole microstate counting → $S = \frac{A}{4G}$.
- Deep connections to QFT (we know the questions!):
  - Holography (including connections to heavy ions, cold atoms)
  - Geometric Engineering
  - Geometrization of entropy

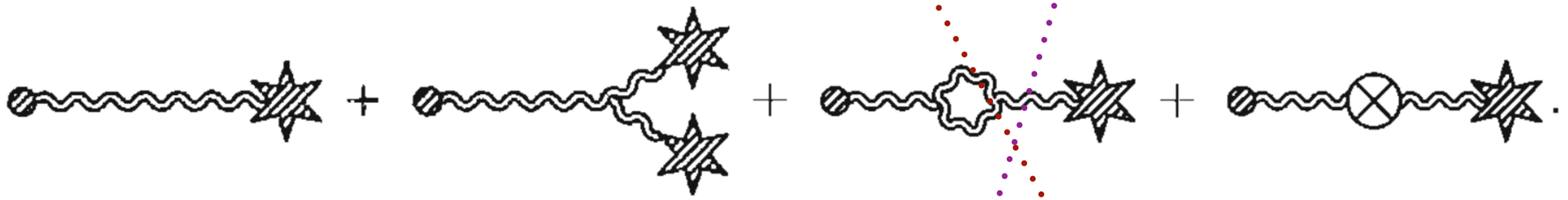


"Unification of Couplings"
Dimopoulos, Raby, Wilczek (1991)

EXPERIMENTAL QUANTUM GRAVITY IS HARD

$$h(r) = \frac{M_{\rm Sun}}{M_{\rm Pl}}\frac{1}{r}\left[1 - \frac{M_{\rm Sun}}{M_{\rm Pl}^2 r} - \frac{127}{30\pi^2}\frac{1}{M_{\rm Pl}^2 r^2} - 128\pi^2\frac{L_1 + L_2}{M_{\rm Pl}^2}\delta^3(\vec{r}) + \cdots\right],$$

corresponding to the Feynman diagrams



M. Schwartz: *Quantum Field Theory and the Standard Model*

$l_P \sim 10^{-35}$ m
$t_P \sim 10^{-43}$ s

Radiative correction to Newtonian potential $\sim 10^{-90}$.

Even if you could measure L_i, what would that tell you?

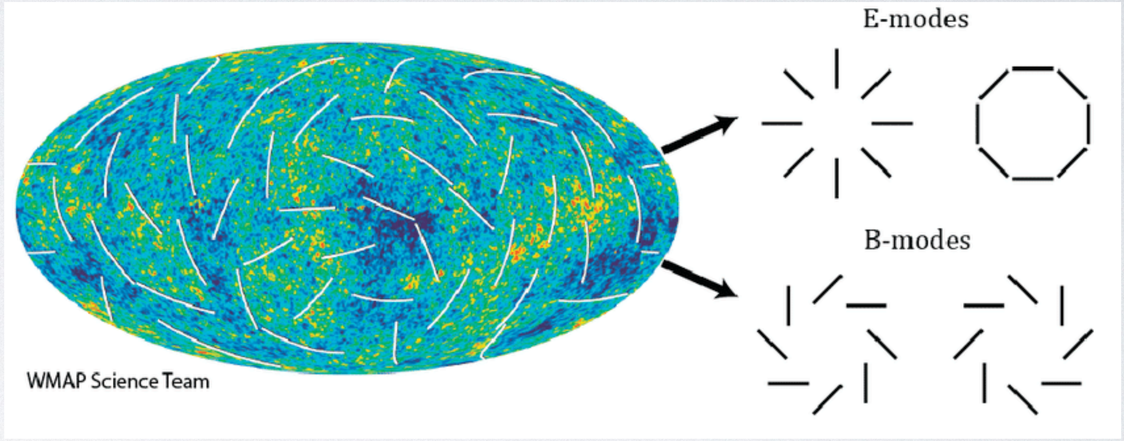
$$L_i\left(\frac{1}{M_{\rm Pl}^2}h\Box^2 h + \frac{1}{M_{\rm Pl}^3}h\Box^2 h^2 + \cdots\right)$$

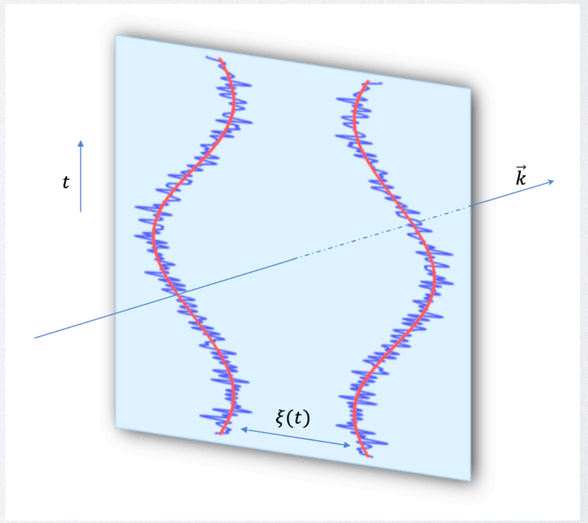
QUANTUM GRAVITY IN OUR LIFETIME?

- Gravitational field **fluctuates from quantum effects**.

$$\Delta_t \sim k^3 \langle \gamma_k^{ij} \gamma_{-k}^{ij} \rangle \sim \frac{H^2}{M_{\rm pl}^2}$$

- Scale-invariant spectrum says **nothing about UV completion** of quantum gravity.
- Some intriguing proposals
  - Cohen-Kaplan-Nelson Bound / Holographic arguments
    $\Longrightarrow$ **QG cutoffs are much lower than M_{Pl}!**
  - Interferometer length fluctuation (Verline/Zurek)
  - Similar proposal leveraging squeezed states (Parikh, Wilczek, Zahariade)
- **Can't rule on sting theory**.

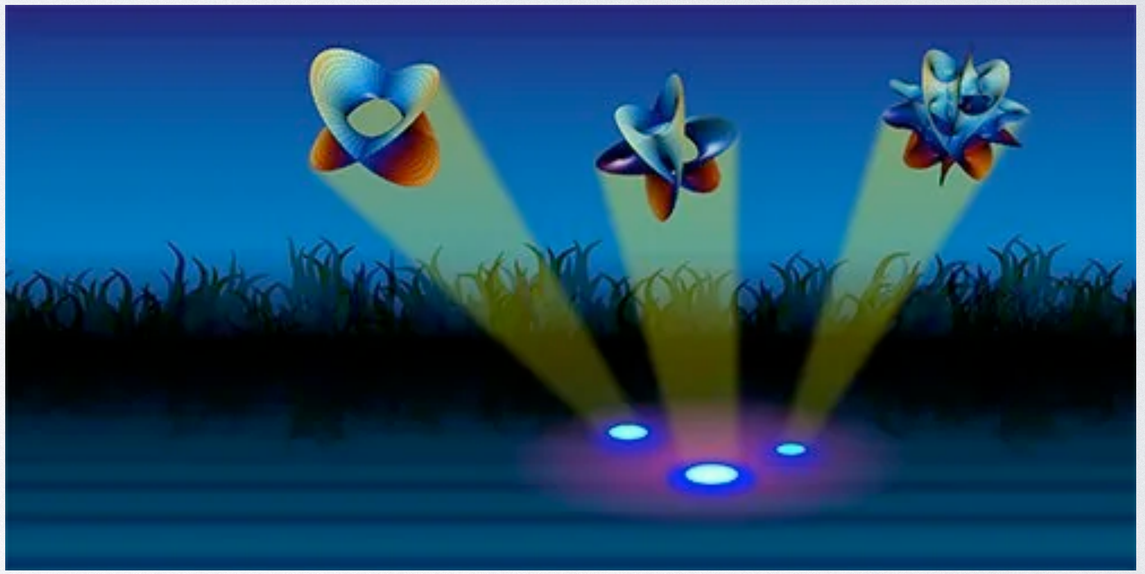




2010.08205:Parikh, Wilczek, Zahariade

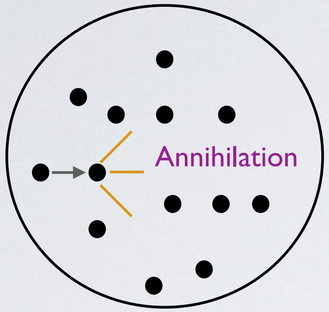
STRING THEORY'S ACHILLES HEEL

- Theories of quantum gravity shoud have:
  - No global symmetries
  - "Completeness of the Spectrum"
- **String theory has never just been a theory of quantum gravity**.
- **It is a Theory of Everything**.
- **Attack the non-gravitational parts** of theory.



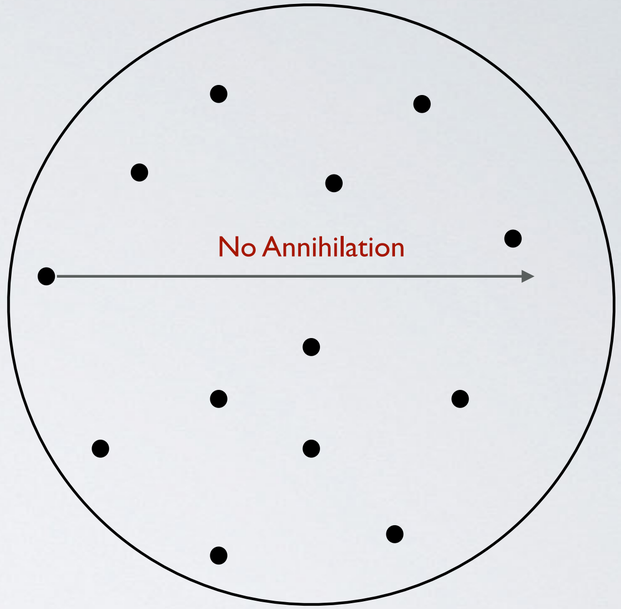
Swampland Program:
Only some low-energy EFTs get UV-completed to Consistent theory of Quantum Gravity.

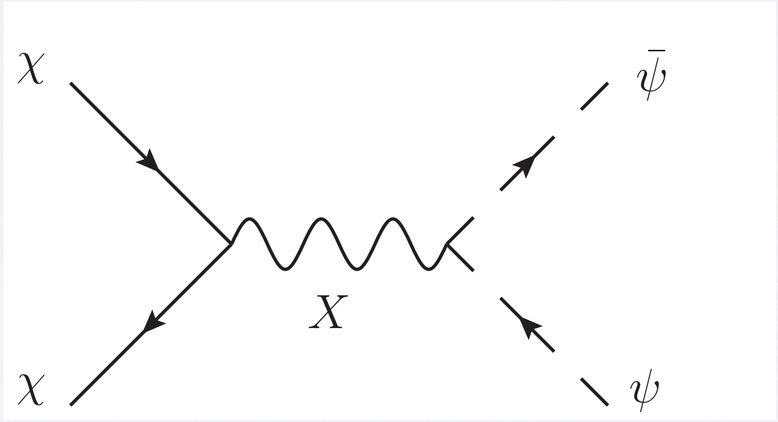
WHY WIMPs?



Cosmic Expansion

DM density decreases:
Annihilation & expansion





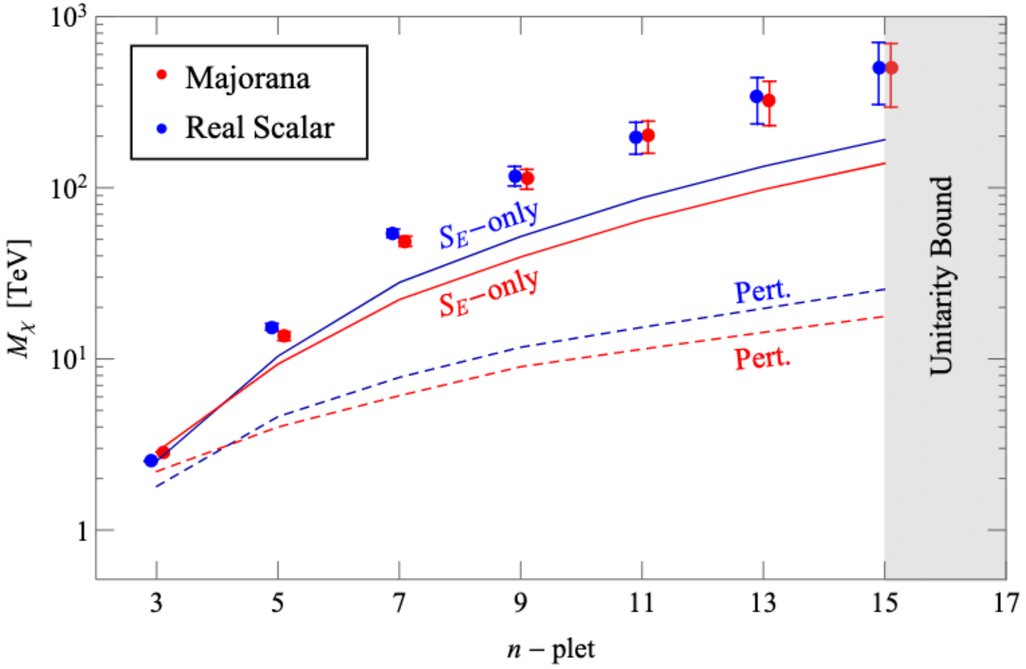
$\langle\sigma v\rangle_{annihilation} \sim C\, \alpha^2/M_\chi^2$

WIMP: Weakly-Interacting Massive Particle

WHY "JUST N-PLET"?

- New **electroweak multiplets ("heavy neutrinos")** are **natural** thermal-relic **WIMP dark matter**.
  - **3-plet** (**wino** of supersymmetry)
  - **5-plet** (Cirelli/Fornengo/Strumia) **"Minimal Dark Matter"**
    $\mathcal{O} \sim \chi LHHH$

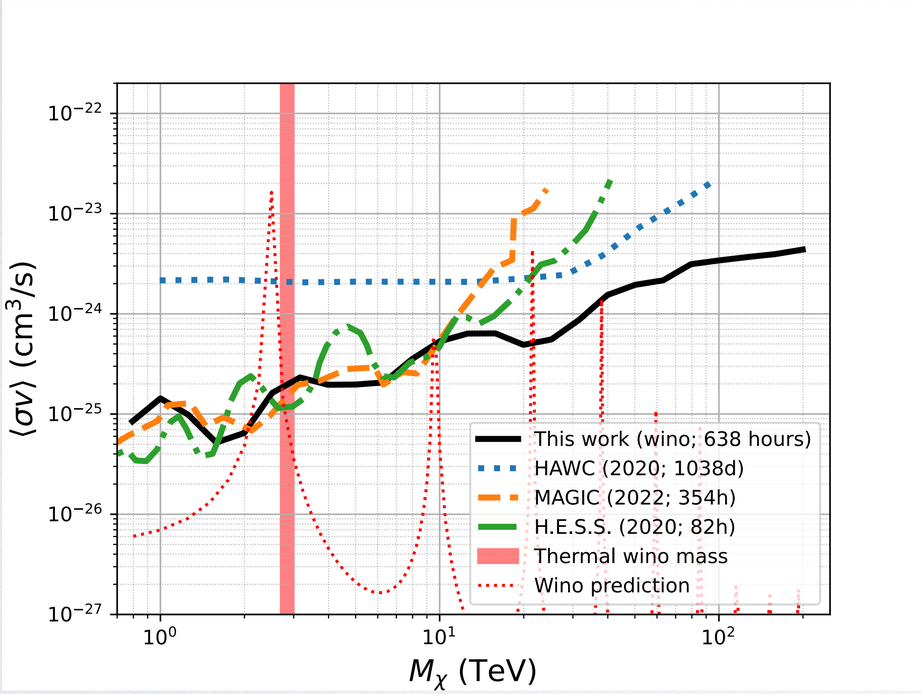
    Cosmologically stable with $\Lambda \sim 10^{19}$ GeV.
- Can **push to n~13**



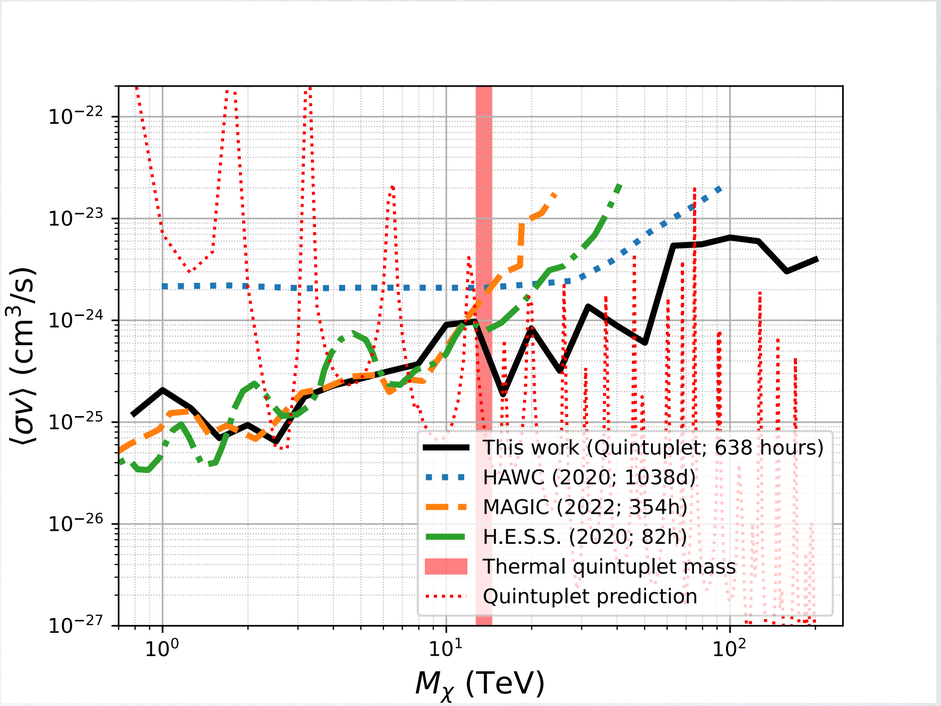
2107.09688: Bottaro et al. Simple thermal relic masses for real reps of SU(2)

"CURRENT" LIMITS ON N-PLET DARK MATTER

WINO



QUINTUPLET

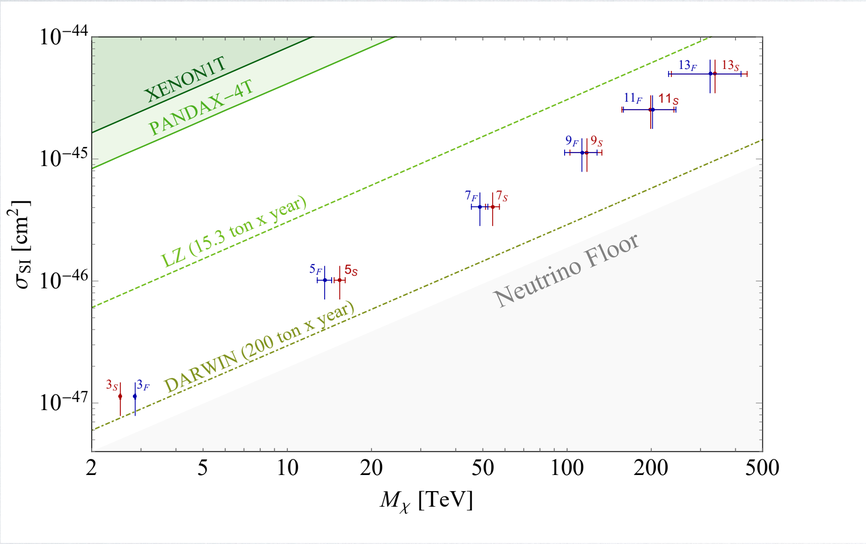


VERITAS wino limit

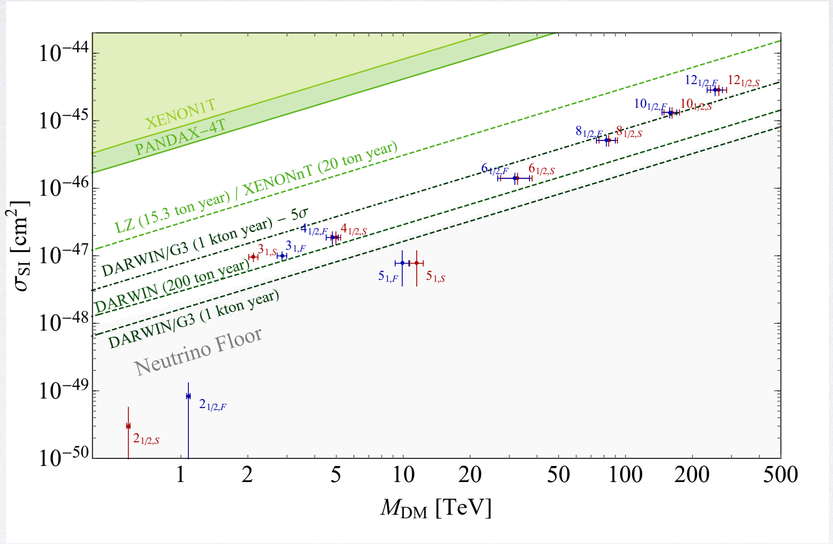
MB, O. Calcerano, C. McGrath,
E. Pueschel, J. Quinn, & D. Tak, VERITAS Collaboration

VERITAS submitted to PRD

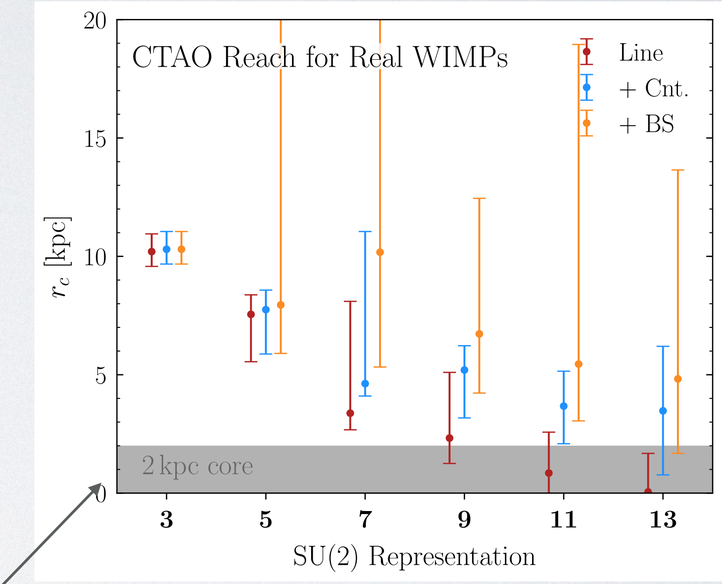
FUTURE LIMITS ON N-PLET DARK MATTER



2107.09688: Bottaro et al.



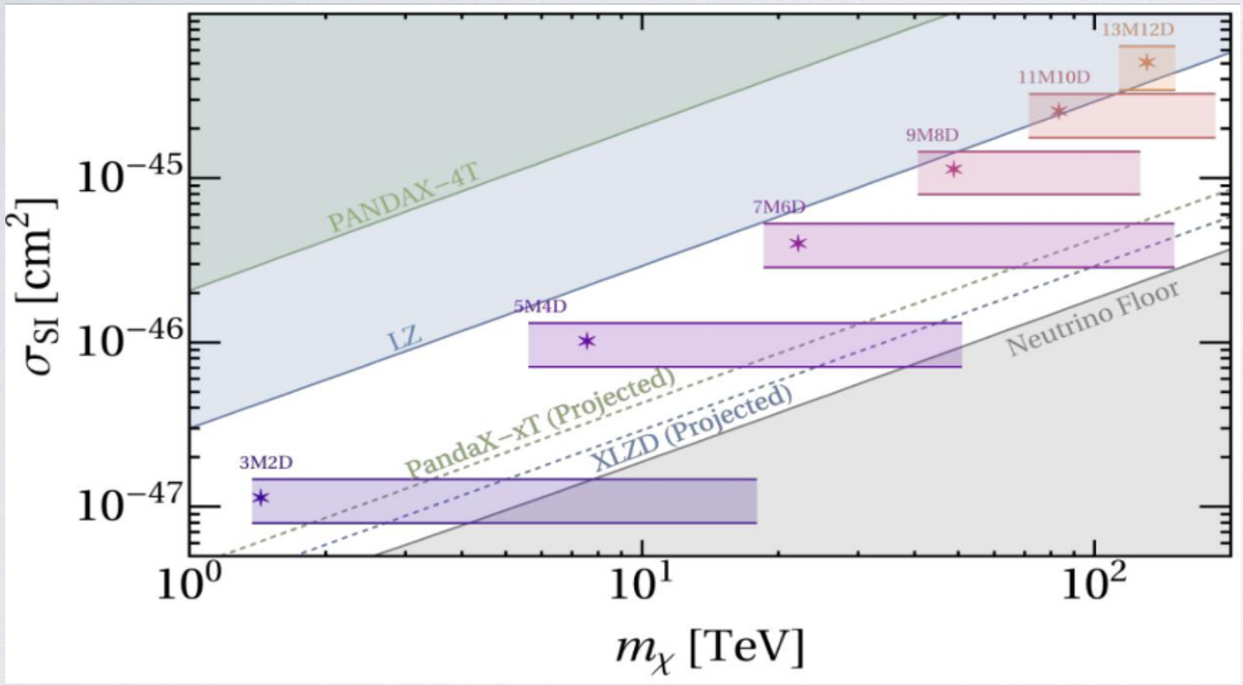
2205.04486: Bottaro et al.



2507.15937:
MB, S. Bottaro, D. Redigolo, N. Rodd, T. Statyer

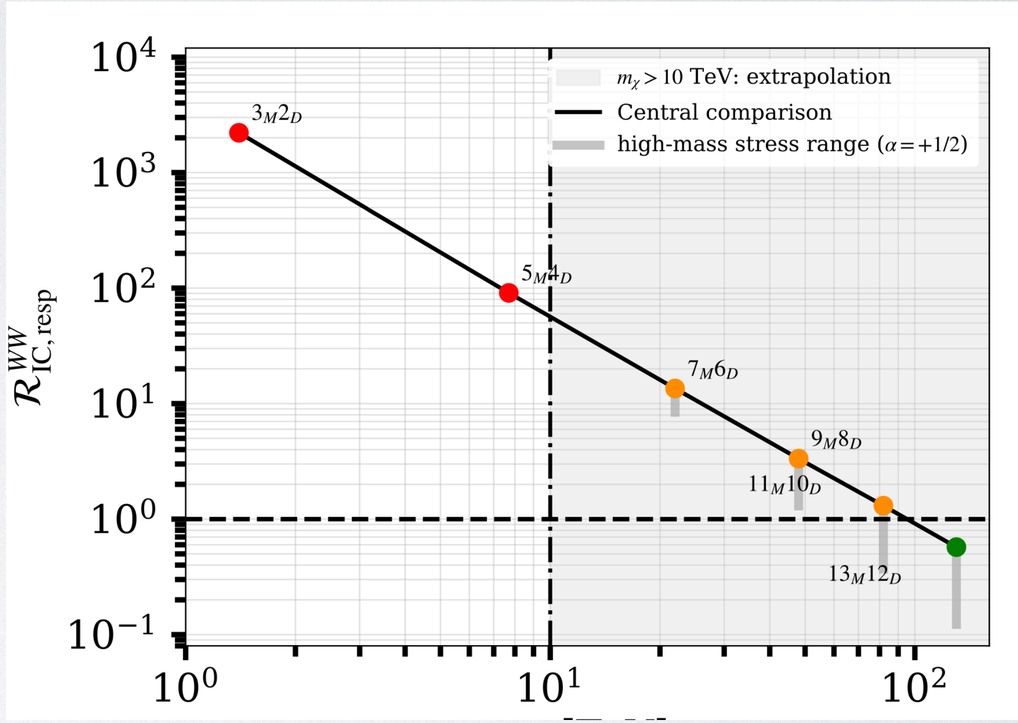
Hooper: 1608.00003 limit of 2 kpc

LARGE N-PLETS IN THE NEWS



Mixed thermal-relic **EW multiplets to explain LZ**

2609.04144: Smirnov, Griffith & Beacom



Largest representations evade overproduction of neutrinos at IceCube

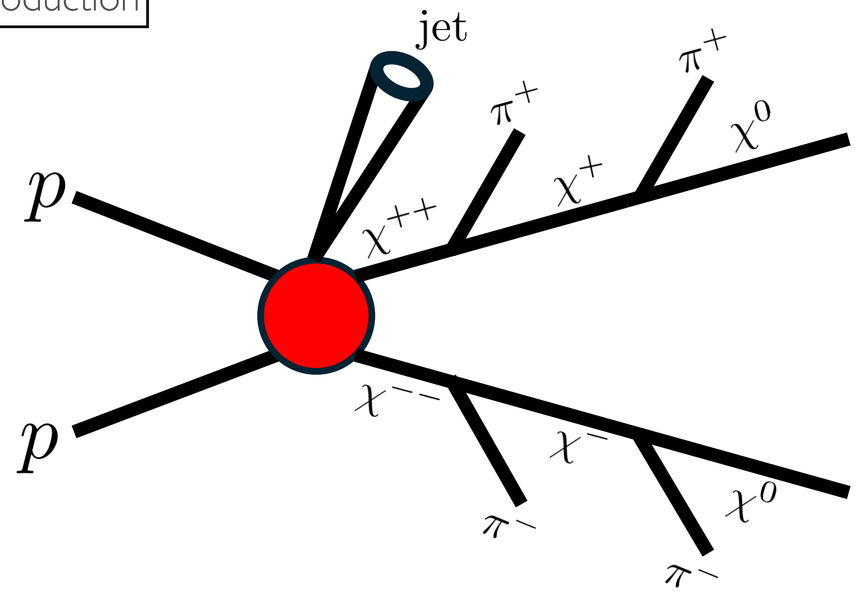
2609.19174: Di Mauro

2609.02823: LZ (Is it dark matter?)

WHAT IF IT'S NOT THE DARK MATTER?

- **Dark matter** gives us **"permission"** to think about **multiplets beyond MSSM**.
- **Relaxing dark matter assumption** allows for **visibility at LHC**.
- Why would we care?
  - Bottom-up (why not?)
  - Top-down (**profound implications for quantum gravity**)

Quintuplet production



Real n-plet → Tower of charged states

$Q_{max} = (n-1)/2$

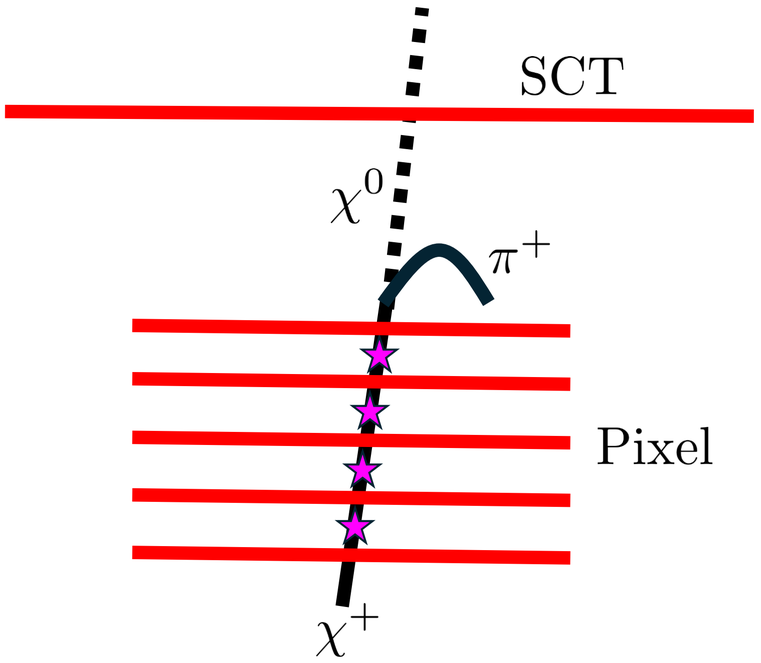
NEW MULTIPLET PHENO

Electroweak multiplets have narrow, radiative mass splittings. Long lifetimes.

ΔM~170 MeV

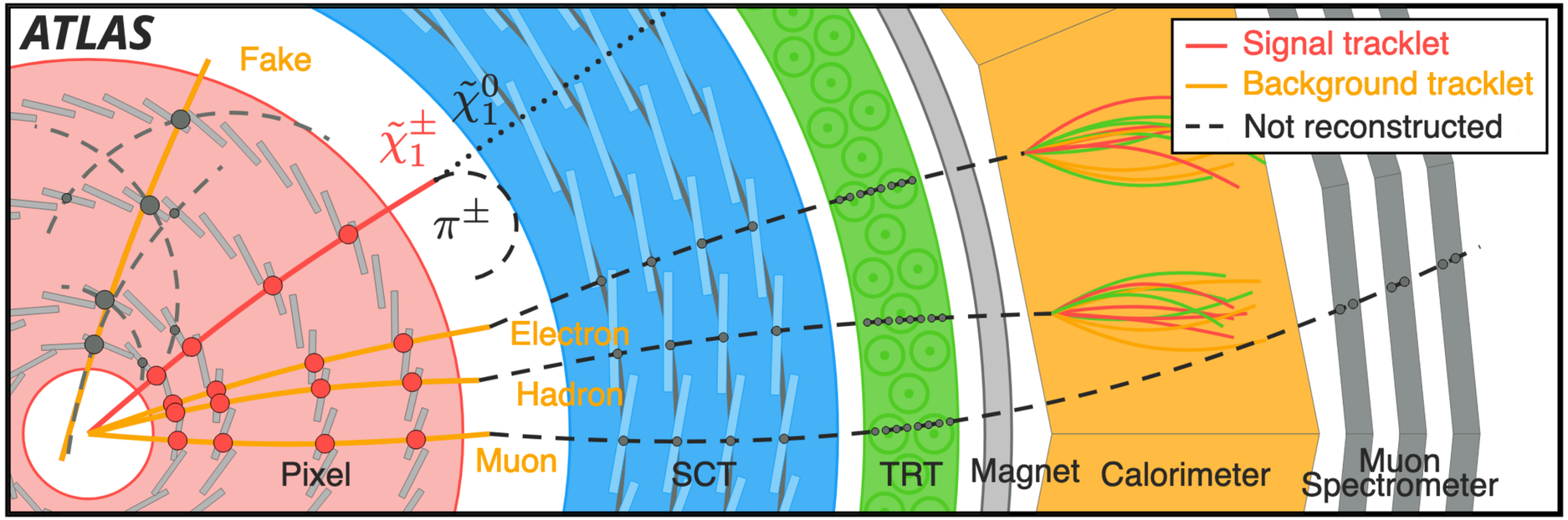
$$\Gamma(\chi^+ \to \pi^+ \chi^0) = (n^2 - 1)\frac{G_F^2 V_{ud}^2 (\Delta M)^3 f_\pi^2}{4\pi}\sqrt{1 - \left(\frac{M_\pi}{\Delta M}\right)^2} \quad (\text{BR} \sim 97.7\%)$$

$$\tau \approx \frac{24}{n^2 - 1} 0.06\,\text{ns}$$



"Disappearing track" at ATLAS
decays before traversing entire tracking system

RECAST THE WINO

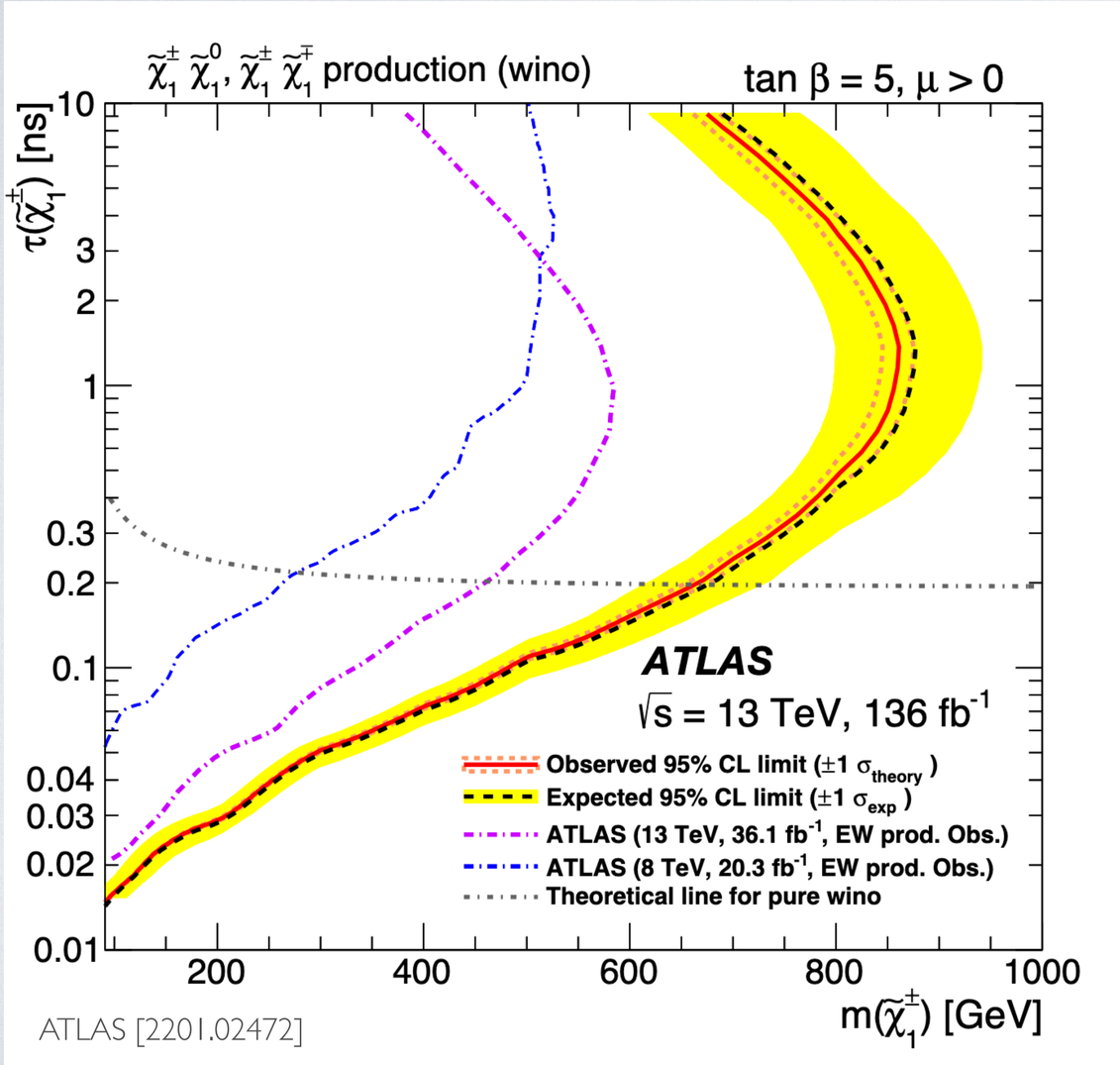


All decays prompt except for $\chi^\pm \rightarrow \chi^0 \pi^\pm$

They all look like winos!

ATLAS [2201.02472] and CMS [2309.16823] look for winos!

ATLAS WINO LIMIT



ATLAS [2201.02472]

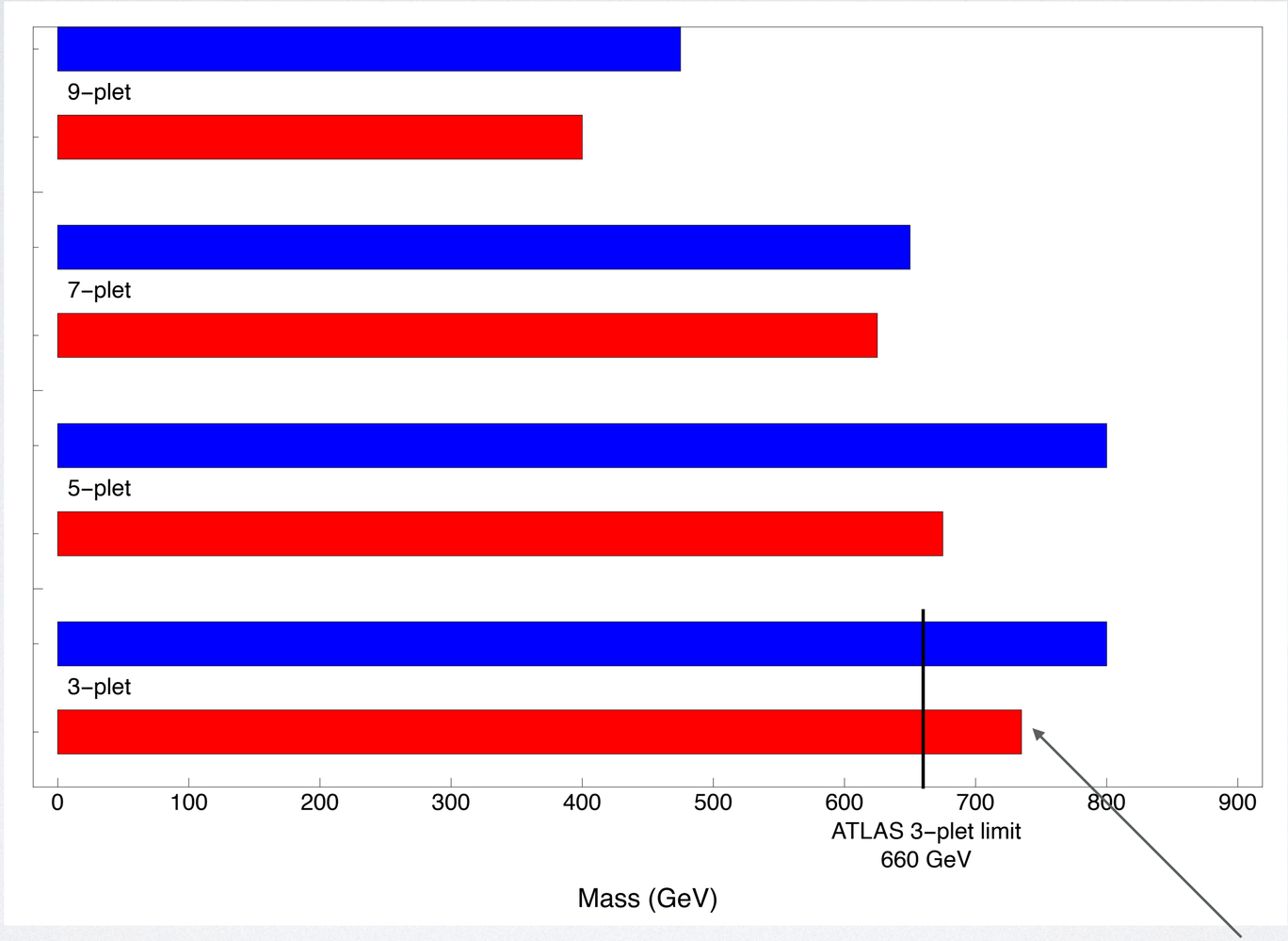
Signal region	Electroweak production
Number of electrons and muons	0
Number of pixel tracklets	≥ 1
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 200
Number of jets (p_{T} > 20 GeV)	≥ 1
Leading jet p_{T} [GeV]	> 100
Second and third jet p_{T} [GeV]	–
$\Delta\phi_{\mathrm{min}}^{\mathrm{jet}-E_{\mathrm{T}}^{\mathrm{miss}}}$ (up to 4th jet with p_{T} > 50 GeV)	> 1.0

Cut & Count search

Just 3-plet ruled out to 660 GeV

Similar CMS limit ~650 GeV

RECAST ATLAS N-PLET LIMITS



95% CL on new Multiplet masses

HL projection - 3/ab

Current limit - 136/fb

More aggressive than ATLAS by ~75 GeV
Different test statistic?

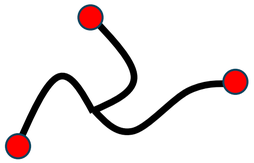
2412.13192
MB, P. Christeas, J. Heckman, & R. Hicks

BUILDING N-PLETS FROM STRINGS

- **Open strings** carry **Chan-Paton factors** at ends (single fundamental gauge indices, like having only spin-1/2)
- String ends terminating on D-branes.
- Get 1 and 2 index representations (fundamental, adjoint, etc.)
- 5 of SU(2) needs four indices (symmetrized tensor of four fundamentals)



Open Strings



Strongly Coupled Bound States

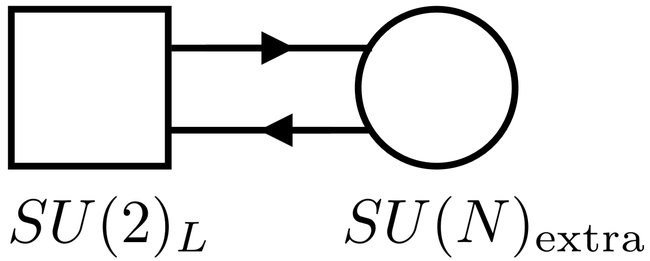
STRONG COUPLING

- Given perturbative challenges, **make a bound state of lower reps**?

$$\mathcal{B} = \varepsilon_{g_1 \cdots g_N} \psi^{g_1}_{(s_1,f_1)} \cdots \psi^{g_N}_{(s_N,f_N)}$$

- Fermi statistics symmetrize flavor/ spacetime-spin → SU(2) quintuplet, but spacetime spin 2.

- How to **get a composite fermion in a large representation without a pion**?



Matter fields charged under SU(N)
With SU(2) ⊂ SU(N_F) flavor symmetry

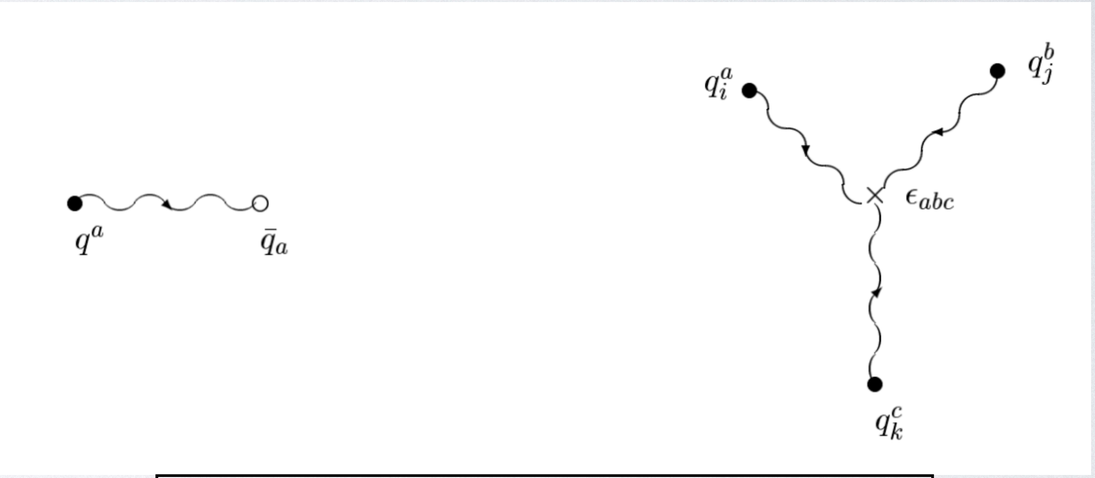
QCD INEQUALITIES

- In **vectorlike theories or chiral theories with an even number of flavors** (for path integral measure positivity)

$$M_B \geq \frac{3}{2} m_\pi$$

- At **large N_c** this becomes parametric

$$M_B \geq \frac{N_c}{2} m_\pi$$

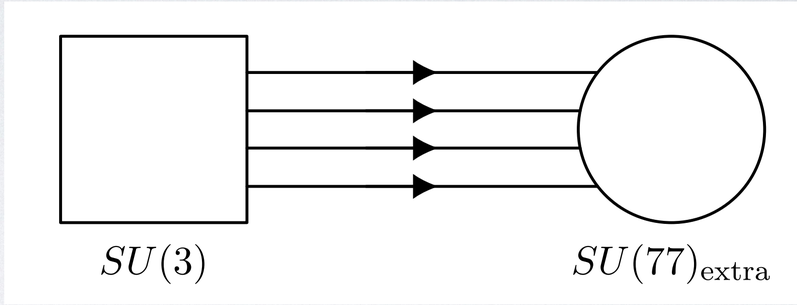


hep-ph/9911532: S. Nussinov & M. Lampert
Quarks exchanging chromoelectric flux tubes "strings" in hadrons.
$M_{ijk} \geq (m_{ij} + m_{jk} + m_{ki})/2$

See also 1408.6919: Detmold (review)

ANOMALY MATCHING

- Use **'t Hooft anomaly matching** and **force exotic representation** in to spectrum?
- I.e. **confinement without Chiral Symmetry Breaking**.
- Exotic representations lead to very large gauge groups in the UV…
- E.g. Have $SU(3)_L \times SU(3)_R$ global symmetry. States emerge from confining gauge theory. **Symmetrized four-index tensor in SU(3) from fundamentals requires an SU(77) gauge theory**.

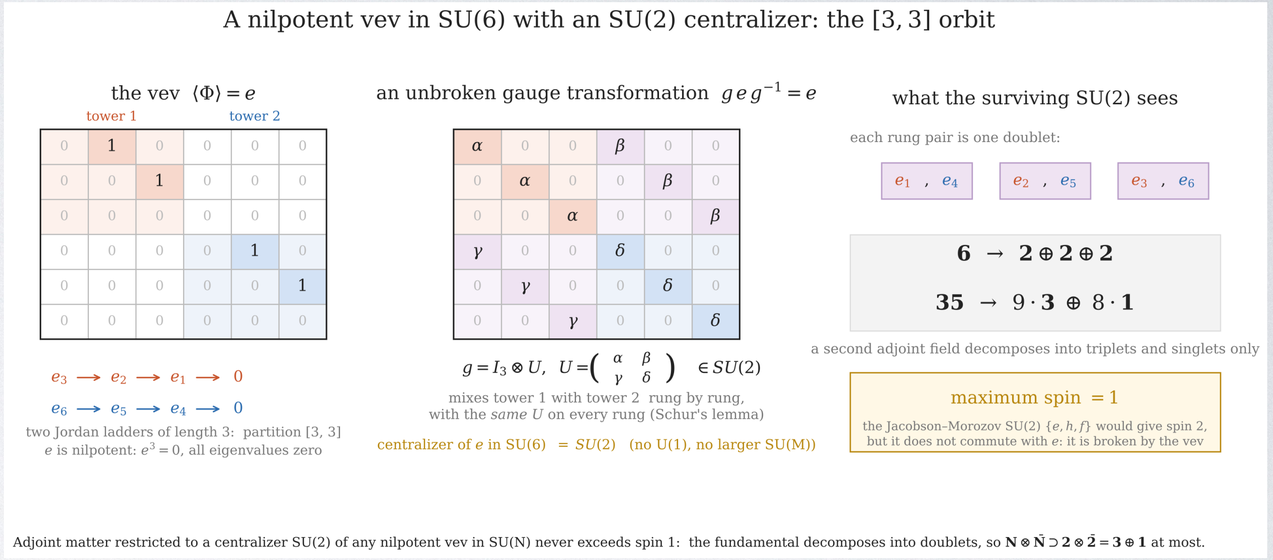


Irrep	$\dim(\mathbf{r})$	$2T(\mathbf{r})$	$A(\mathbf{r})$
$\square$	N	1	1
$\mathbf{Ad}$	N^2-1	$2N$	0
$\square\square$	$\frac{N(N-1)}{2}$	$N-2$	$N-4$
$\square\!\square$	$\frac{N(N+1)}{2}$	$N+2$	$N+4$
$\square\!\square\!\square$	$\frac{N(N-1)(N-2)}{6}$	$\frac{(N-3)(N-2)}{2}$	$\frac{(N-3)(N-6)}{2}$
$\square\!\square\!\square$	$\frac{N(N+1)(N+2)}{6}$	$\frac{(N+2)(N+3)}{2}$	$\frac{(N+3)(N+6)}{2}$
$\square\!\square$ $\square$	$\frac{N(N-1)(N+1)}{3}$	N^2-3	N^2-9
$\square\!\square$ $\square\!\square$	$\frac{N^2(N+1)(N-1)}{12}$	$\frac{N(N-2)(N+2)}{3}$	$\frac{N(N-4)(N+4)}{3}$
$\square\!\square\!\square\!\square$	$\frac{N(N+1)(N+2)(N+3)}{24}$	$\frac{(N+2)(N+3)(N+4)}{6}$	$\frac{(N+3)(N+4)(N+8)}{6}$
$\square$ $\square\!\square\!\square$	$\frac{N(N+1)(N-1)(N-2)}{8}$	$\frac{(N-2)(N^2-N-4)}{2}$	$\frac{(N-4)(N^2-N-8)}{2}$

hep-th/0306119: J. Terning

LARGE REPS FROM HIGGSING?

- Let "String Theory" mean start in the UV with at most two-index representations.
- For classical Lie groups, breaking with a single vev is a well-defined math problem.
- **Surviving SU(2)** from such breakings are two-dimensional, either explicitly or in degeneracy space. Isospin ≤ 1
- Computational study of 248 (adjoint) of E_8 can generate quintuplet but also triplet.



$$\mathrm{S}\Big[\prod_i (\mathrm{U}(r_i))^i_\Delta\Big]/\{\text{scalar matrices in SL}(N)\} \qquad \text{when } G=\mathrm{SU}(N),$$

$$\mathrm{S}\Big[\prod_{i\,\text{odd}} (\mathrm{O}(r_i))^i_\Delta \times \prod_{i\,\text{even}} (\mathrm{Sp}(r_i/2))^i_\Delta\Big] \qquad \text{when } G=\mathrm{SO}(2N+1),$$

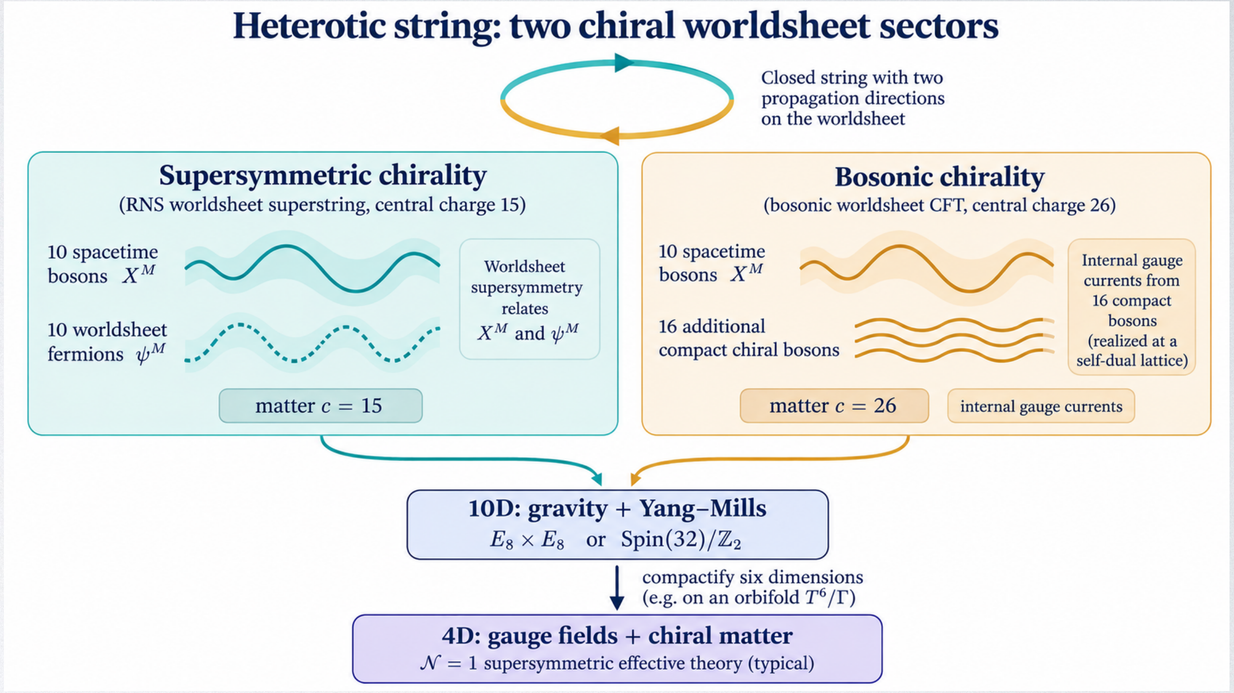
$$\mathrm{S}\Big[\prod_{i\,\text{odd}} (\mathrm{O}(r_i))^i_\Delta \times \prod_{i\,\text{even}} (\mathrm{Sp}(r_i/2))^i_\Delta\Big]/\mathbb{Z}_2 \qquad \text{when } G=\mathrm{SO}(2N),$$

$$\Big[\prod_{i\,\text{odd}} (\mathrm{Sp}(r_i/2))^i_\Delta \times \prod_{i\,\text{even}} (\mathrm{O}(r_i))^i_\Delta\Big]/\mathbb{Z}_2 \qquad \text{when } G=\mathrm{Sp}(N),$$

Surviving gauge groups from nilpotent VEVs
r_i is Jordan-block degeneracy
1203.2930: Chacaltana, Distler, Tachikawa

HETEROTIC STRING: HYBRID VIGOR

- Closed string has independent **left** and **right**-propagating modes
- Can make **right-propagating** those of the **superstring**, **left-propagating** the old **bosonic string**
- Extra DOF on bosonic side give **non-abelian gauge theory** (Kac-Moody algebra at for current zero modes reduces to Lie Algebra)
- These DOF constrained to have **SO(32)** or **E_8xE_8** gauge theory
- **Orbifold compactifications** to 4D give **discrete choices** of boundary conditions that break gauge groups and **determine matter representations**.



Gross, Harvey, Martinec, Rohm (1985)

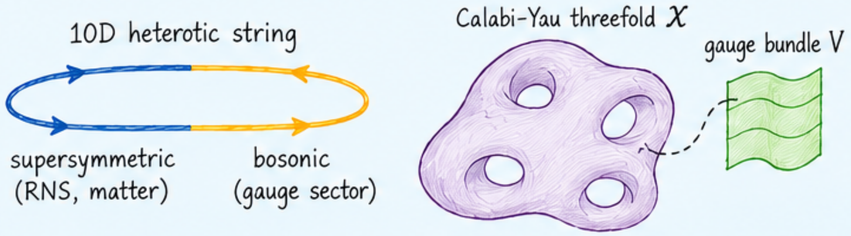
$$[J^a_m, J^b_n] = i f^{ab}{}_c J^c_{m+n} + k\, m\, \kappa^{ab} \delta_{m+n,0}$$

level-k

STANDARD MODEL FROM STRING THEORY

1. Heterotic Calabi–Yau Compactifications

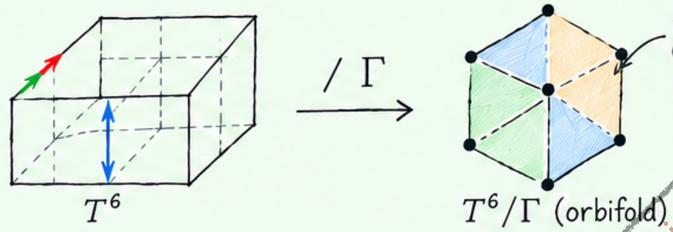
Compactify the heterotic string on a Calabi–Yau threefold with a gauge bundle (or orbifold with discrete identifications).



- 10D gauge group $E_8 \times E_8$ or $\mathrm{Spin}(32)/\mathbb{Z}_2$
- Compactify on a Calabi–Yau (or orbifold) with a nontrivial gauge bundle
- Can yield exactly the MSSM spectrum with three chiral generations
- Many explicit models (e.g. line bundle and stable bundle constructions)

2. Heterotic Orbifolds (and Free-Fermionic Models)

Compactify on a toroidal orbifold, e.g. T^6/Γ, with discrete identifications that break the gauge symmetry and produce chiral matter.

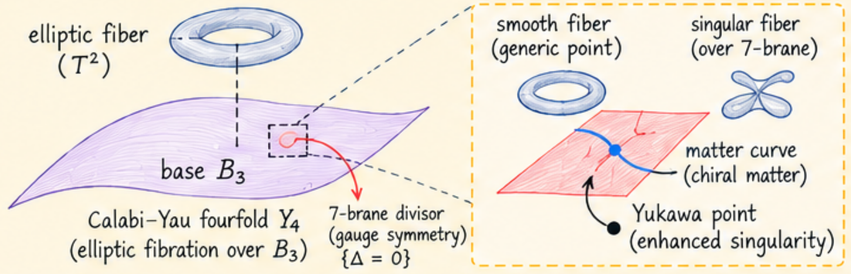


- Discrete orbifold action (e.g. $\mathbb{Z}_{6-II}$, $\mathbb{Z}_2 \times \mathbb{Z}_2$) breaks $E_8 \times E_8$ or $\mathrm{Spin}(32)/\mathbb{Z}_2$
- Chiral matter from twisted sectors at fixed points
- Large number of MSSM-like models (the "mini-landscape")
- Free-fermionic constructions provide a complementary, equivalent description at special points in moduli space

No Large Rep in isolation...yet

3. F–theory Compactifications

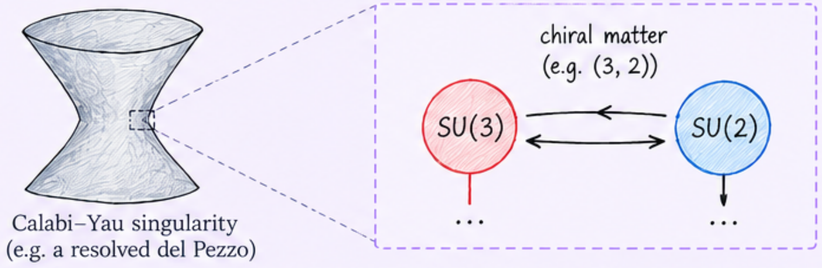
Use an elliptically fibered Calabi–Yau fourfold with 7-branes. Gauge groups and chiral matter arise from geometry and fluxes.



- Gauge symmetry from 7-brane singularities (elliptic fiber degenerations)
- Chiral matter localized on curves; Yukawa couplings at enhancement points
- Very large numbers of constructions with the exact chiral SM spectrum
- Natural geometric setting for GUTs and realistic local model building

4. Type IIB D-Branes at Singularities

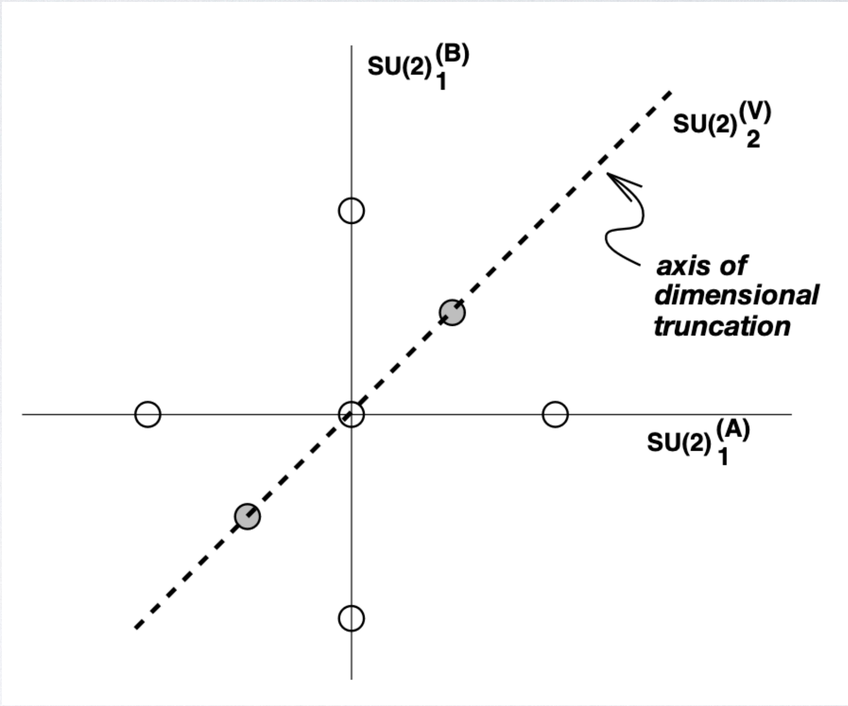
Place stacks of D-branes at a Calabi–Yau singularity (or in a flux compactification). Chiral matter arises from open strings at brane intersections or on fractional branes.



- D-brane stacks realize gauge groups (e.g. via D3-branes at singularities)
- Chiral matter from open strings (bifundamentals in quiver gauge theories)
- Explicit three-family models with global embeddings and moduli stabilization
- Rich set of local and global constructions with realistic features (flavor, symmetries, etc.)

FREE-FERMION MODELS

- Compactify heterotic string on a torus. At **special radius**, worldsheet bosons →pair of noninteracting fermions (**fermionization**).
- **Discrete choices of boundary conditions**, orbifold symmetries, and projection phases for 64 worldsheet fermions **determine the surviving gauge groups and matter representations**.
- One-loop string amplitude is a torus. Pairs of boundary conditions (around the string, around timelike direction) give phases constrained by **modular invariance** and allow us to **project out states. (GSO Projection)**.
- A triplet of worldsheet fermions generates $SU(2)_2$ Kac-Moody. **Taking two triplets gives massless quintuplet….**

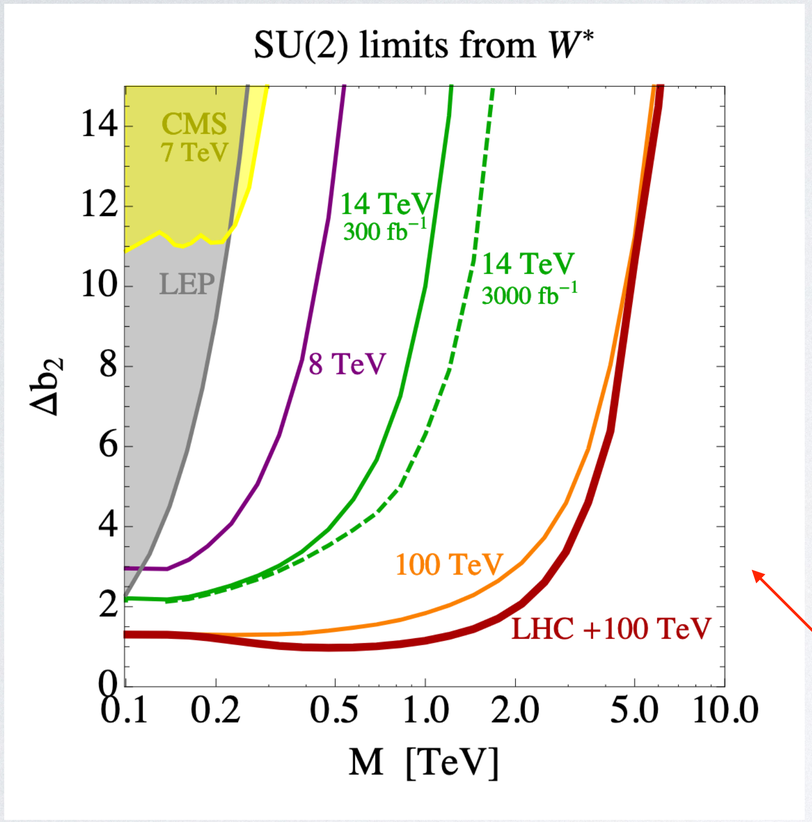


Charging fields under multiple $SU(2)_i$ and taking diagonal adds the levels
hep-th/9604112: Dienes, March-Russell

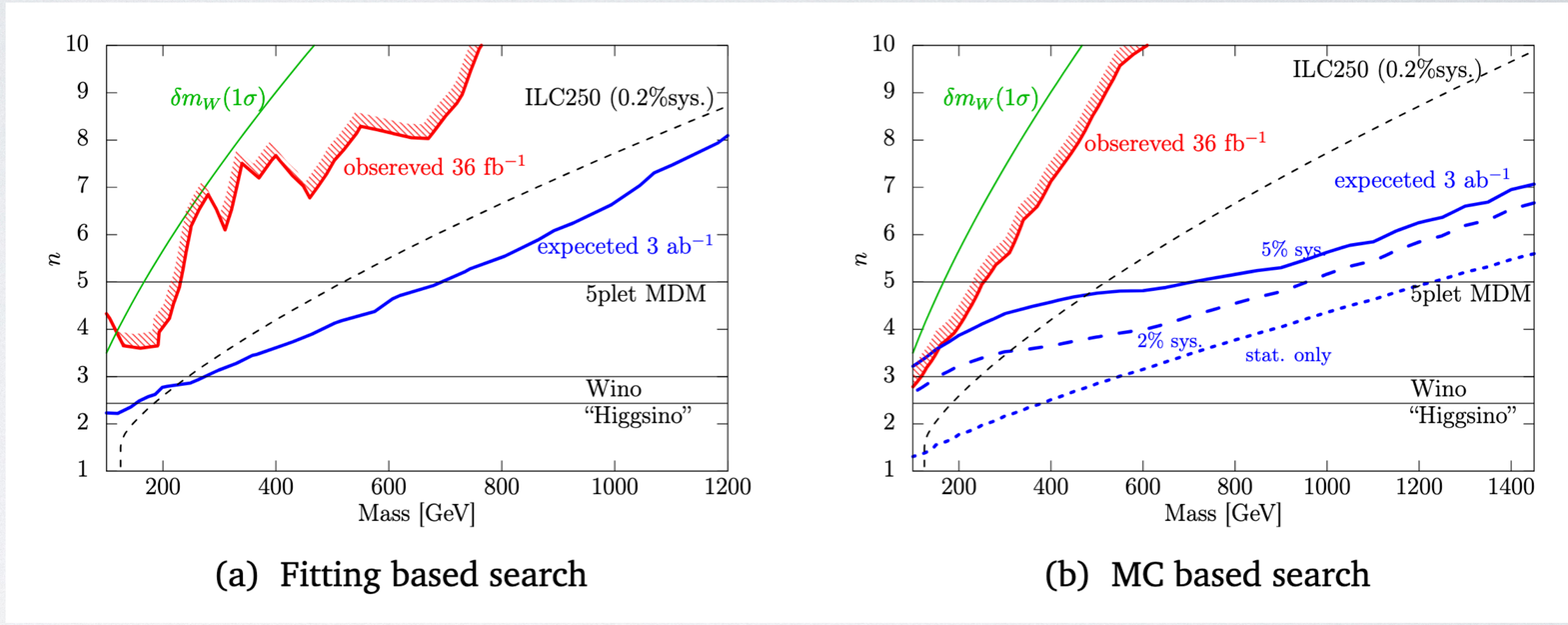
$$h_j = \frac{j(j+1)}{k+2}$$

Need j=2, k=4 to get weight-1 massless states

FUTURE LIMITS



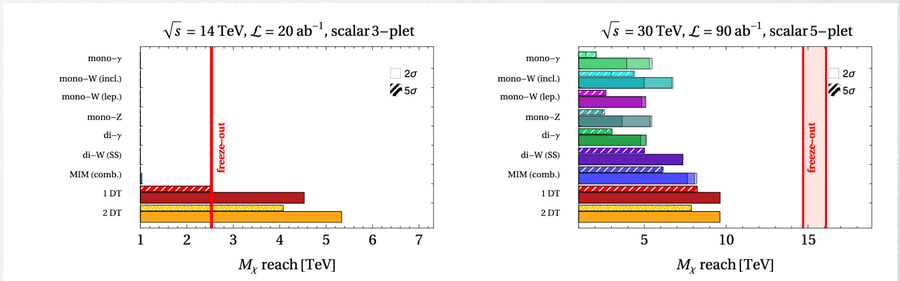
5-plet → $\Delta b_2 = 10$
1410.6810: D. Alves, J. Galloway, J. Ruderman, J. Walsh



1711.05499: S. Matsumoto, S. Shirai, M. Takeuchi

Stringent future constraints from modified Drell-Yan

2107.09688: S. Bottaro et al.
μ-collider



GOING FORWARD

- **Can free-fermion orbifold construction give quintuplet, SU(2) gauge theory (with doublets) and avoid a Landau pole sitting right over our head…**
- How does one get the rest of the Standard Model? Bigger reps? Can one get the 126 of SO(10)?
- Quintuplet in GUTs (2412.19660: Toma embeds 5 of SU(2) in 200 of SU(5))
- What analysis techniques can **strengthen limits on new electroweak states?**