How to Falsify String Theory at a Collider

Jonathan J. Heckman

University of Pennsylvania

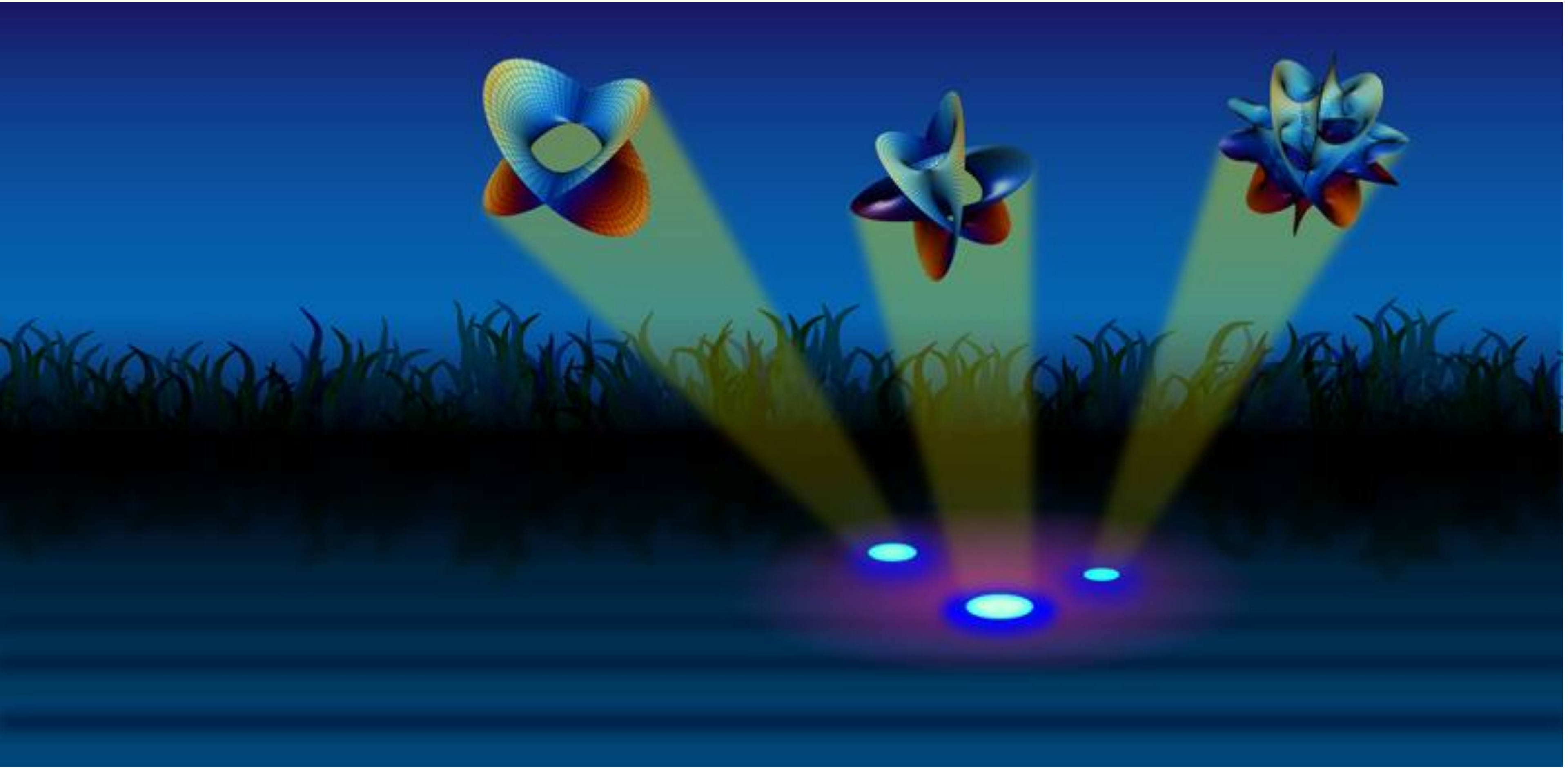
Based On

hep-ph/2412.13192: w/ Baumgart, Christeas, Hicks

¿Is String Theory Science?

Of course it is.

EFTs via String Theory



From https://physics.aps.org/articles/v12/115

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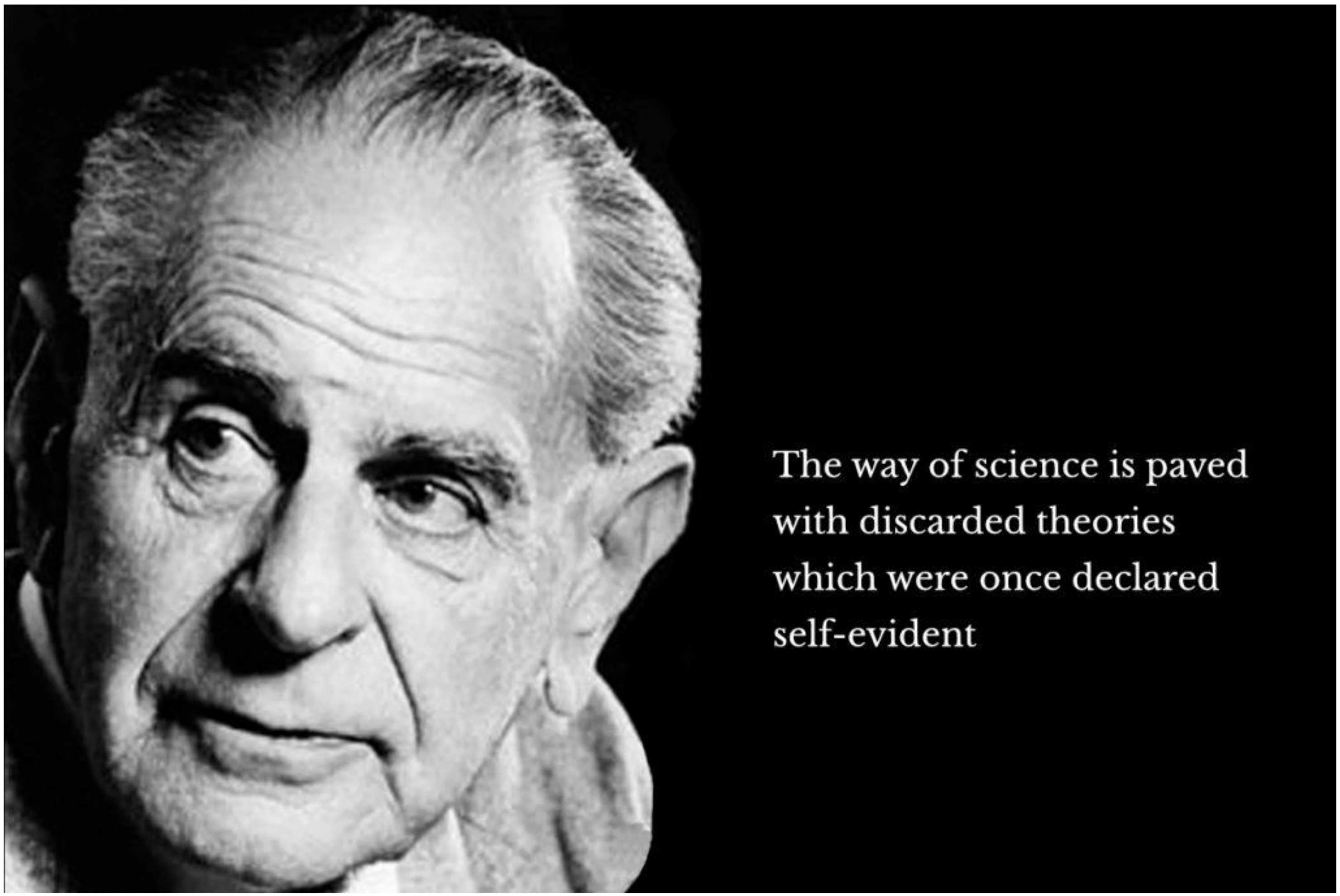


¿Is String Theory Science?

Q1: Is string theory verifiable?

¿Is String Theory Science?

Q1: Is string theory verifiable?

Q2: Is string theory falsifiable?

¿Is String Theory Science?

Q1: Is string theory verifiable?

¿Is String Theory Science?

Q1: Is string theory verifiable?

A1: On the right track; successes include:

- Long distance limit: GR + QM
- Many contributions to quantum gravity
- Motivated BSM scenarios
- Many QFT insights (esp. at strong coupling)

¿Is String Theory Science?

QQ1: So what should experimentalists look for?

¿Is String Theory Science?

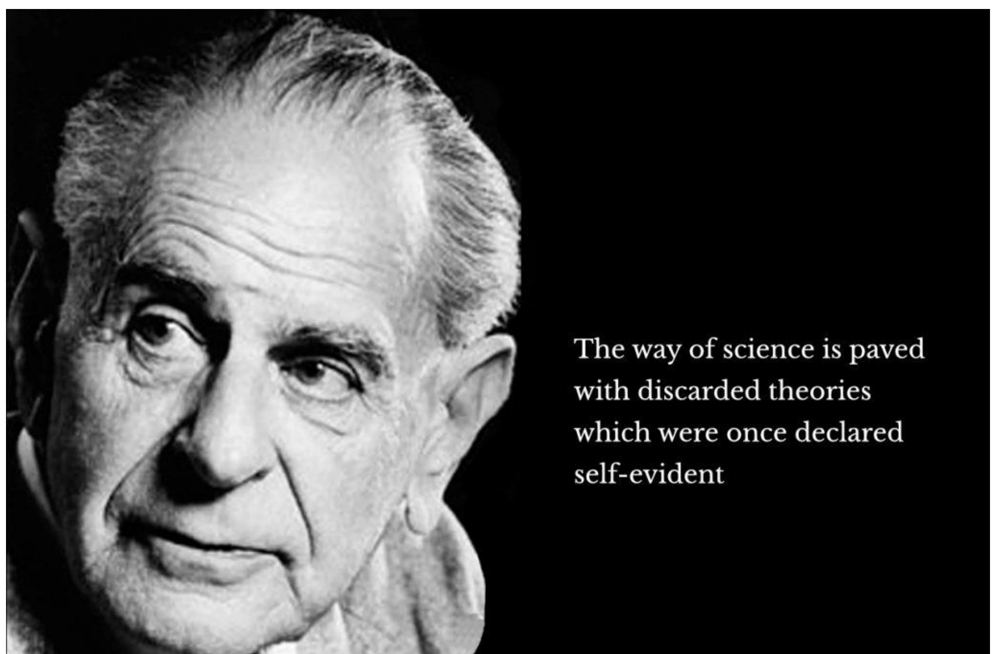
QQ1: So what should experimentalists look for?

AA1: Perhaps too early to say, but...

- string-motivated pheno scenarios
- $\cdots$

¿Is String Theory Science?

Q2: Is string theory falsifiable?



¿Is String Theory Science?

Q2: Is string theory falsifiable?

AA2: Perhaps too early to say, but...

- pheno scenarios which can't be realized
- $\Lambda_{cc} > 0$ (somewhat controversial)
- ¿¿¿Concrete collider scenarios???

¿Is String Theory Science?

Q2: Is string theory falsifiable?

AA2: Perhaps too early to say, but...

- pheno scenarios which can't be realized
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A String-Killer Scenario

Take the Standard Model and add ONE new field:

$$\mathcal{L}_{\text{BSM}} = \mathcal{L}_{\text{SM}} + \frac{1}{2}\overline{\chi}(i\gamma^\mu D_\mu - M)\chi$$

$\chi = \chi^C$ in real $n \geq 5$-dim rep of $SU(2)_L$

Not realized in ANY string scenario?!?!

Plan of the Talk

- Strings $\cap$ "just n-plet" $= \{\}$ (very likely)
- Pheno of the "just n-plet" scenario
- Experimental Limits
- Summary / Future

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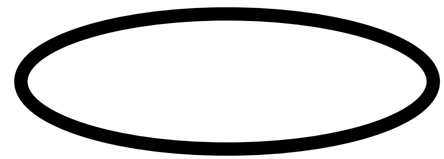
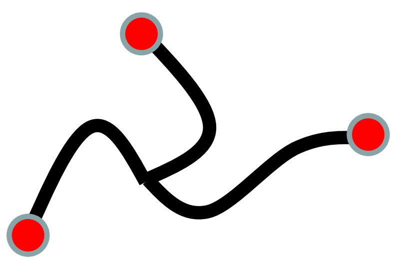
$$\text{Strings} \cap \text{"just } n\text{-plet"} = \{\}$$

Stringy Routes to Matter

Open Strings



Closed Strings



Strongly Coupled
Bound States

???

Stringy Routes to Matter

Open Strings

Standard Model

Gauge Group: $SU(3)_C \times SU(2)_L \times U(1)_Y/\Gamma$

Matter in *small* reps:

	$\mathrm{SU}(3)_c$	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$
L	1	2	$-1/2$
e_R	1	1	-1
Q	3	2	$1/6$
u_R	3	1	$2/3$
d_R	3	1	$-1/3$

Standard Model

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Min. Quiver Standard Model

Berenstein Pinansky ’06; many stringy quiver SMs

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
L	1	$\square$	$-1/2$
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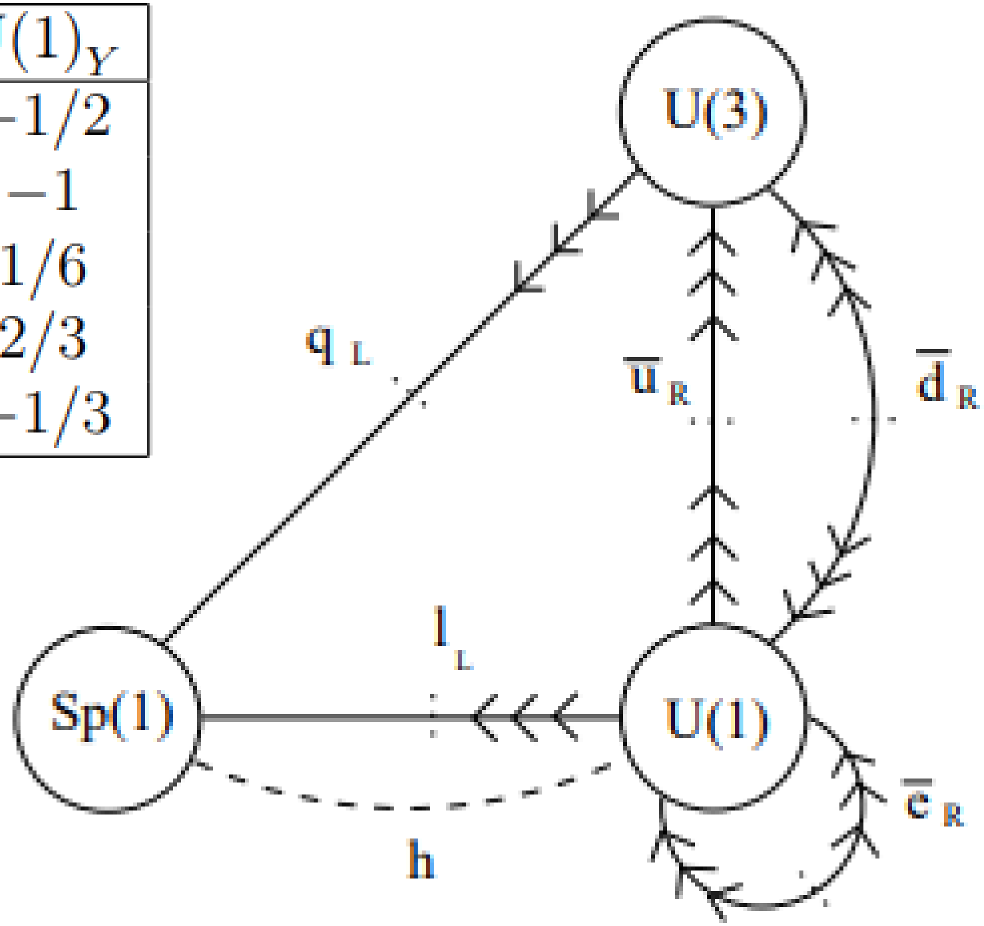
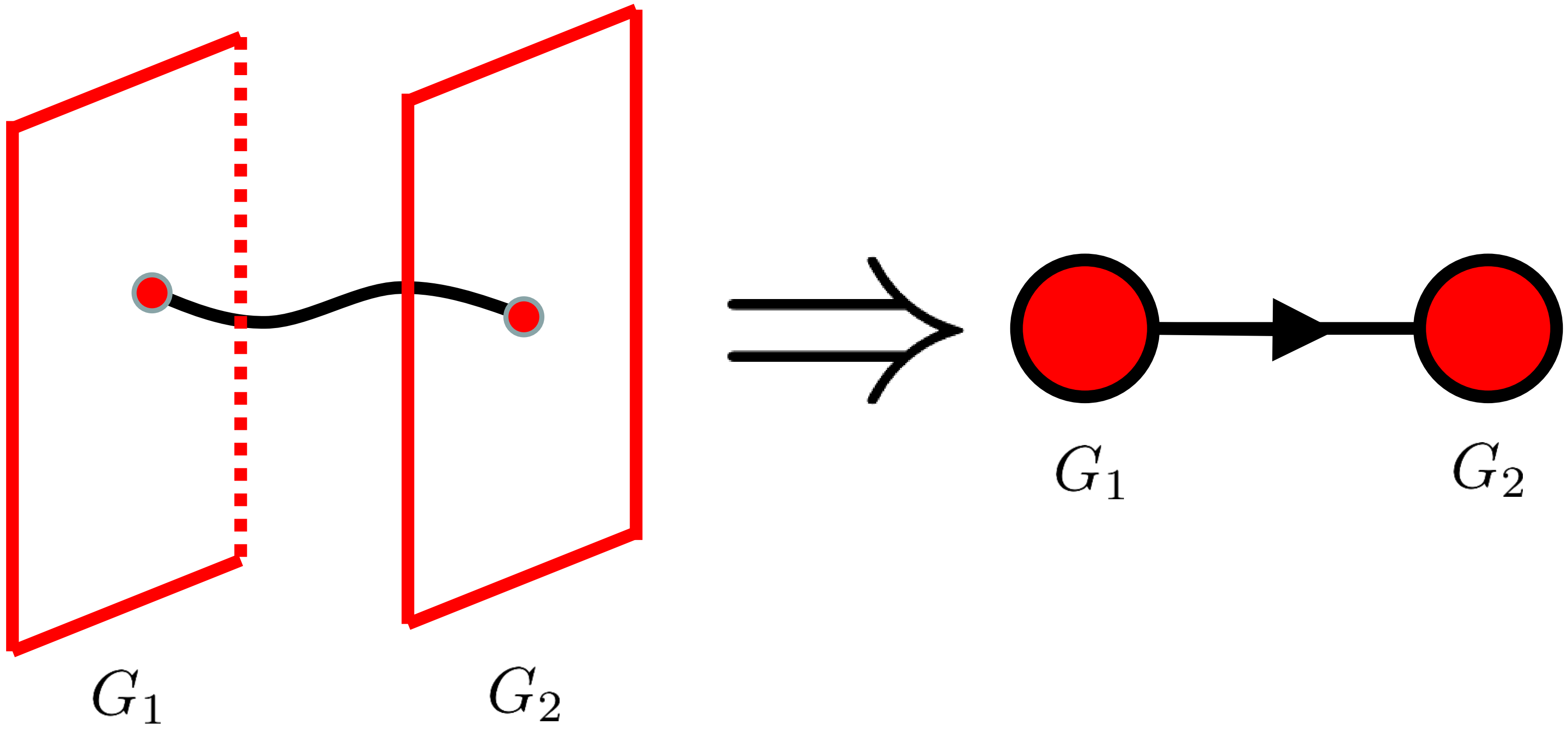
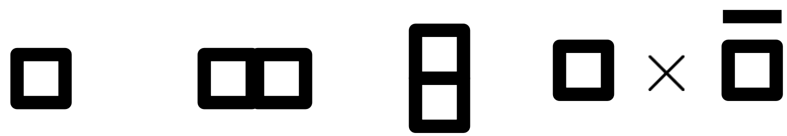


Strings & Quivers



One- & Two-Index Reps

Gauge Groups: $SU(N), SO(N), Sp(N)$

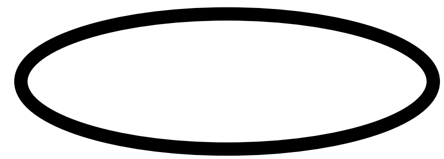
Representations: 

5-plet of $SU(2)$??? 

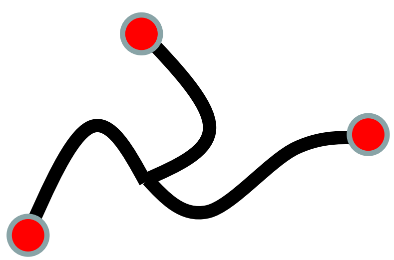
(Note: $SO(3) \neq SU(2)$...)

Stringy Routes to Matter

Open Strings



Closed Strings



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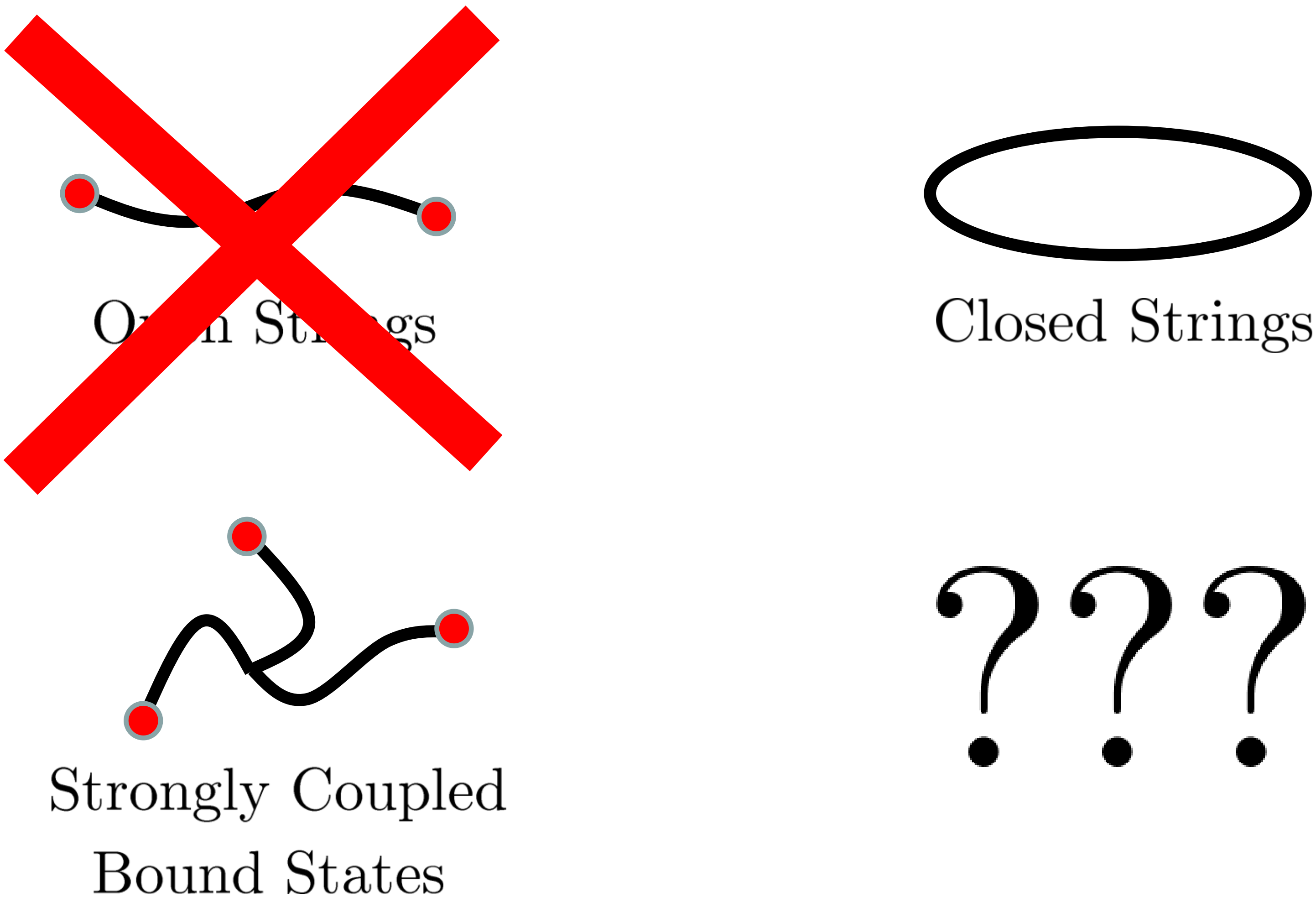

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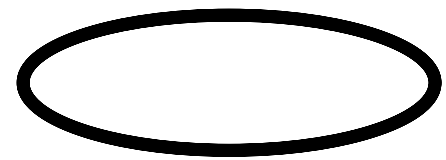


Closed Strings

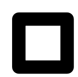
Heterotic Strings

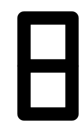
A Common Model Building Route: E_8 Vector Bundles

Approach of Candelas Horowitz Strominger Witten '85

$$E_8 \supset SU(5)_{\text{GUT}} \times SU(5) \supset SU(3) \times SU(2) \times U(1)/\mathbb{Z}_6 \times \ldots$$

$$248 \to (24,1) + (1,24) + (5,10) + (\overline{5},\overline{10}) + (10,\overline{5}) + (\overline{10},5)$$





Low index reps again!

Aldazabal Font Ibanez Uranga '94; Dienes Faraggi March-Russell '95; Dienes March-Russell '96; Dienes '96; ...

Free Fermion Models

An Older Route: Higher Kac-Moody Levels?!

$SU(2)_k : c = \frac{3k}{k+2}$

Spin$-j$ primary: $h_j = \frac{j(j+1)}{k+2}$

Massless: $h = 1$; Tachyon: $h < 1$

Dressing: $\mathcal{O}_{\text{full}} = \mathcal{O}_j \mathcal{O}_{\text{extra}}$

Success?

Spin$-j$ primary: $h_j = \frac{j(j+1)}{k+2}$

$j = 2, k = 4 \Rightarrow h_j = 1!$

No Success

Spin$-j$ primary: $h_j = \frac{j(j+1)}{k+2}$

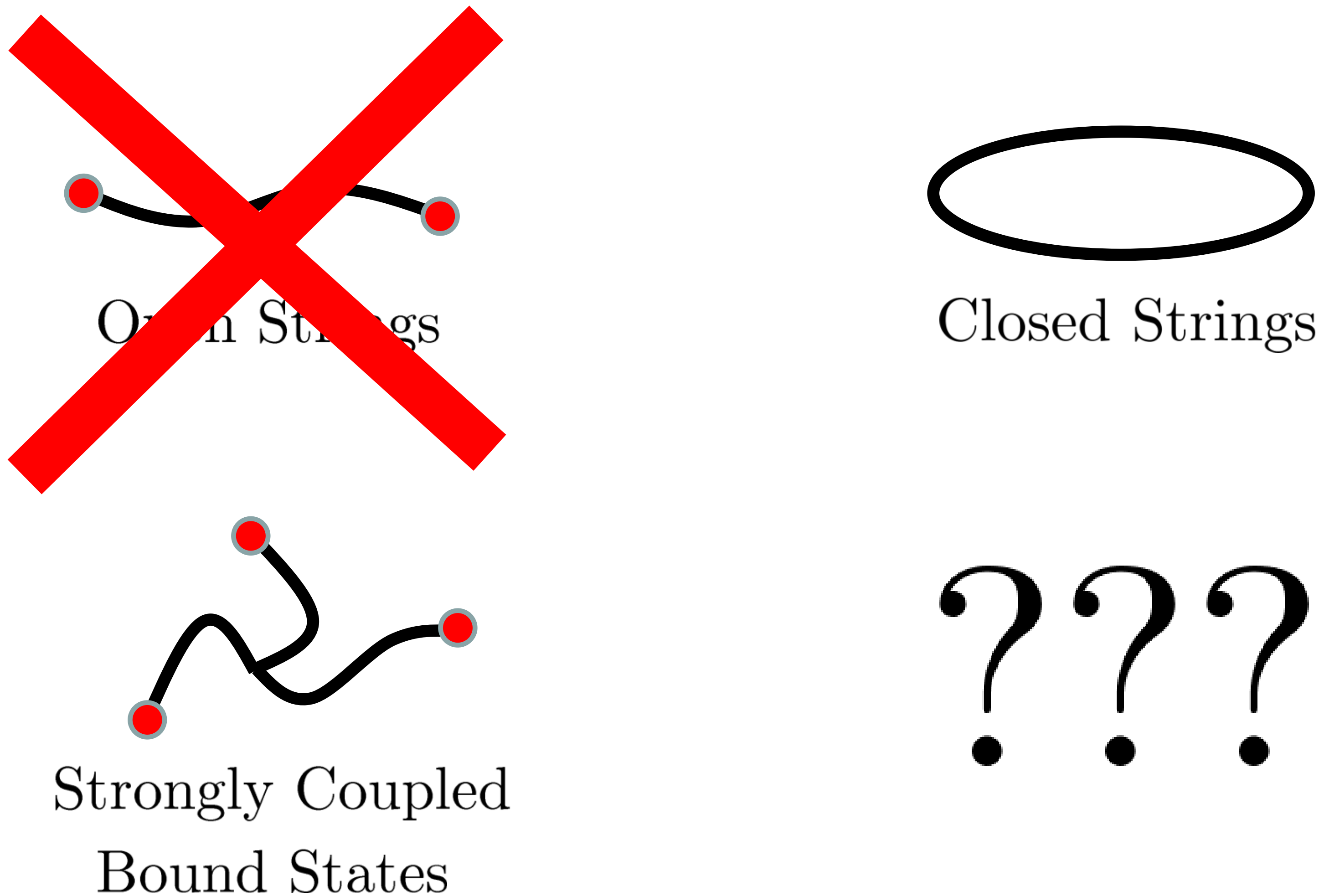
$j = 2, k = 4 \Rightarrow h_j = 1!$

But...

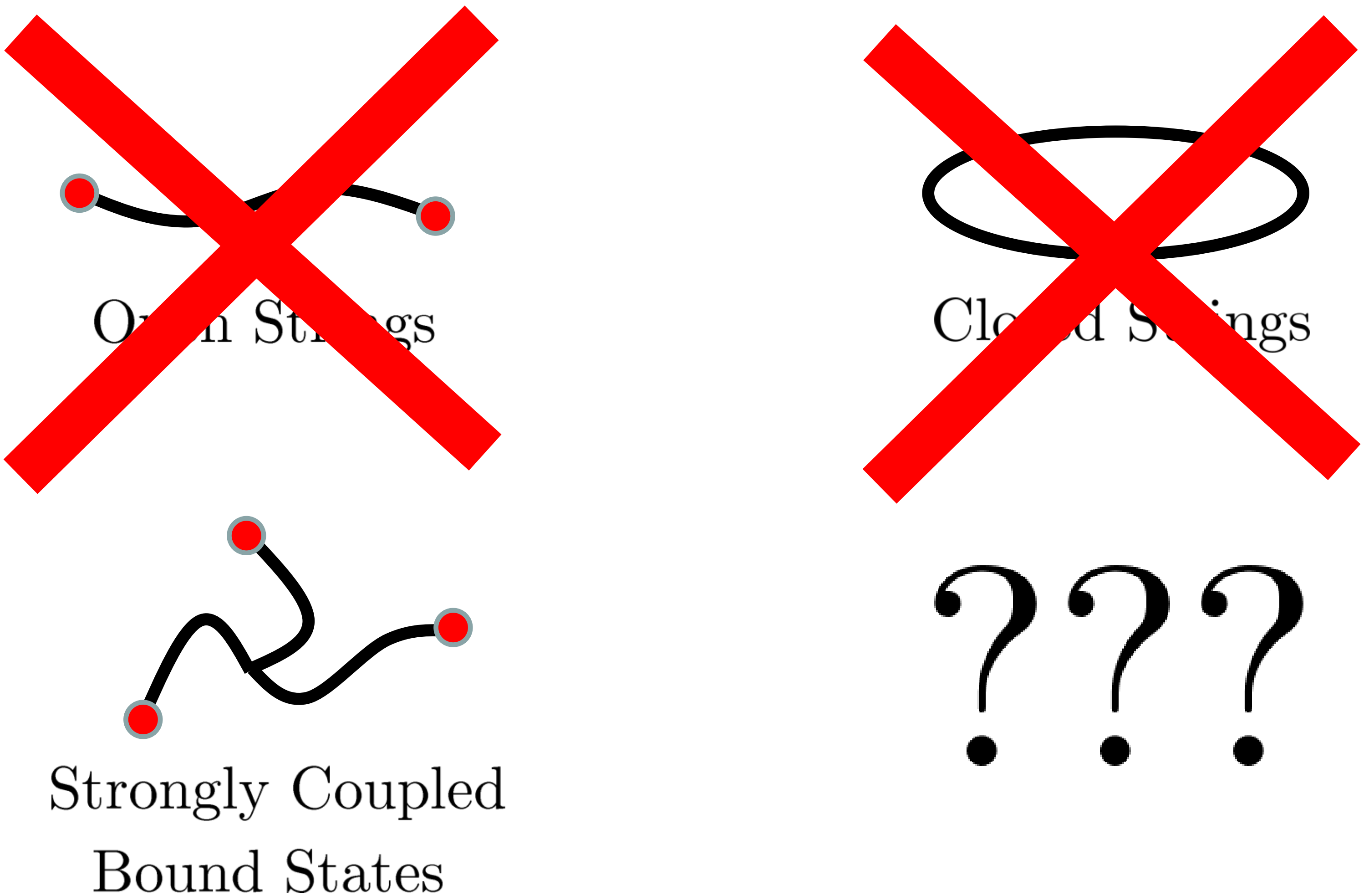
$l < j \Rightarrow h_l < h_j$. What about Spin-$l$ states???

Very hard to remove these!!! (proof?)

Stringy Routes to Matter



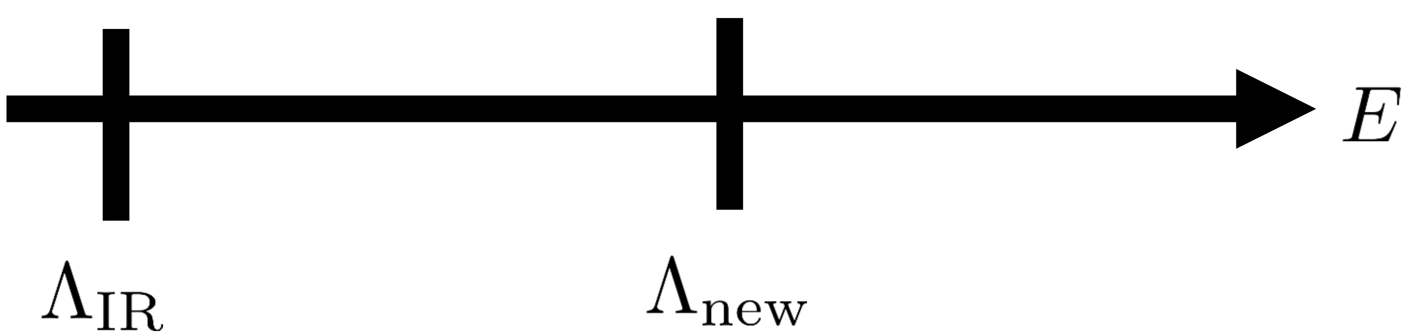
Stringy Routes to Matter



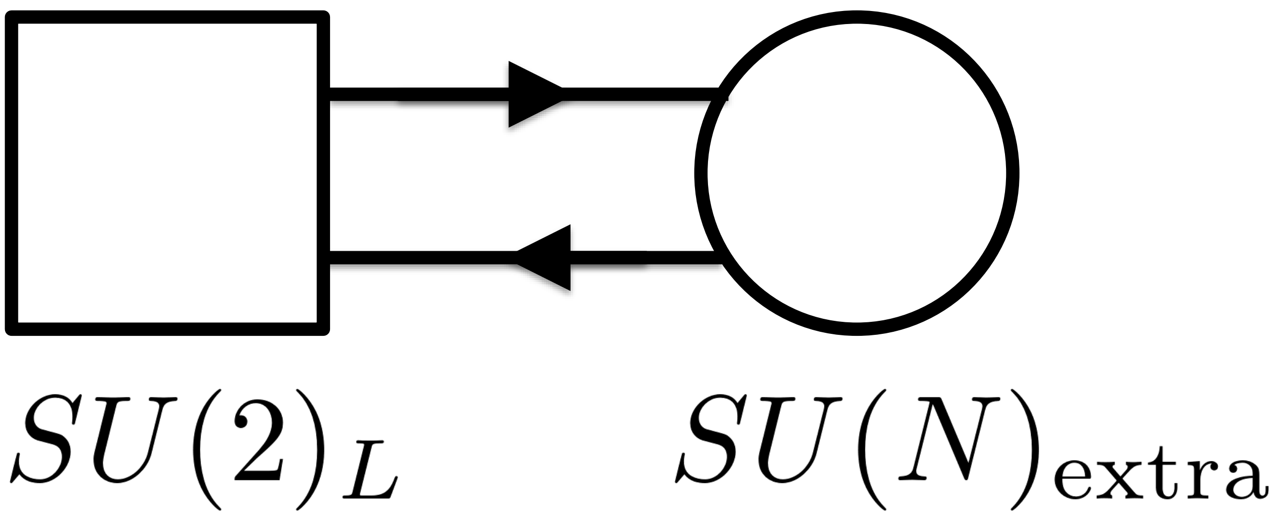
Can Strong Coupling Help?

n-plet as a composite object?

$$\chi_{\square\square\square\square} \sim \frac{1}{\Lambda_{\text{new}}^{11/2}} \psi_{\square}\psi_{\square}\psi_{\square}\psi_{\square}$$



Example



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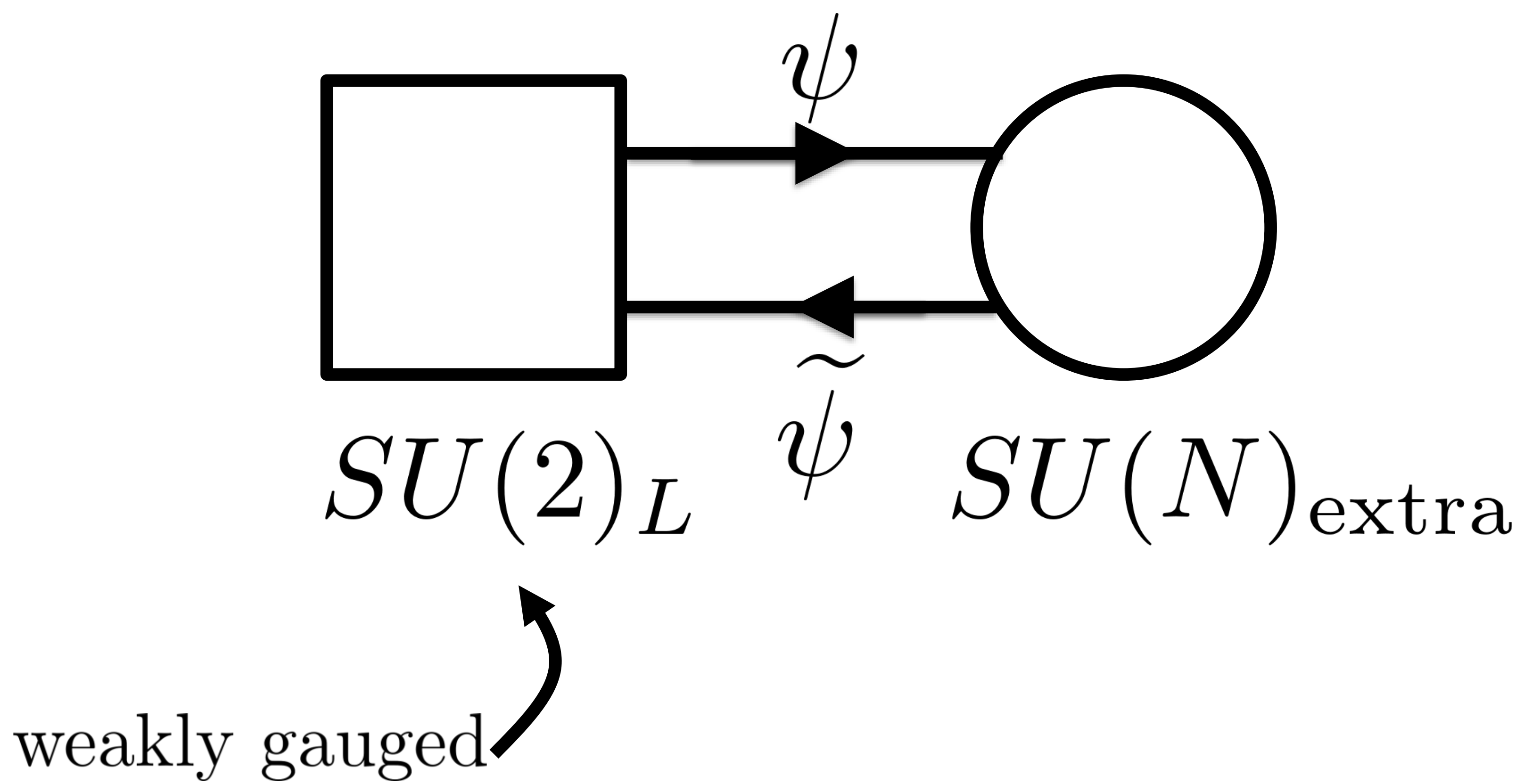

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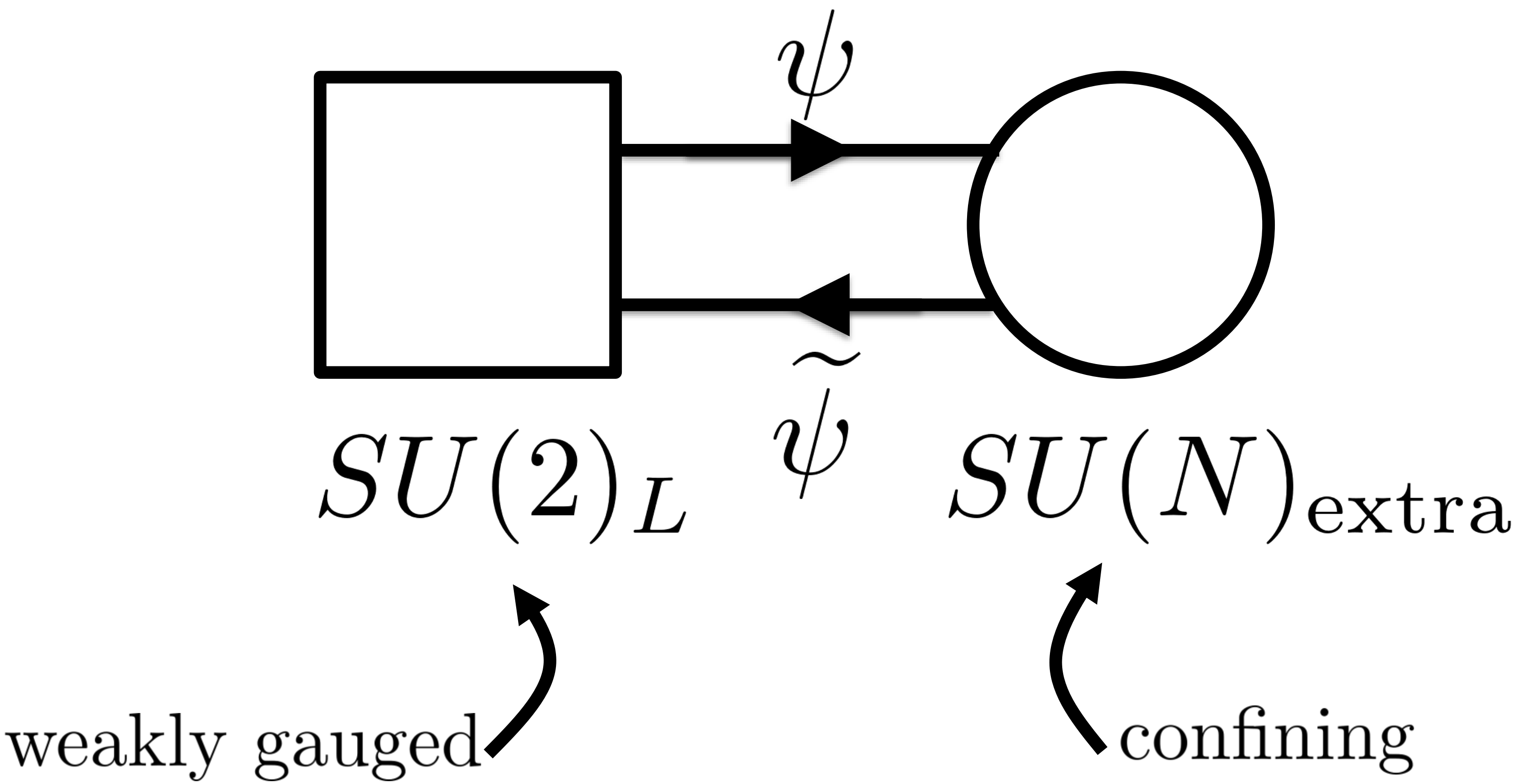
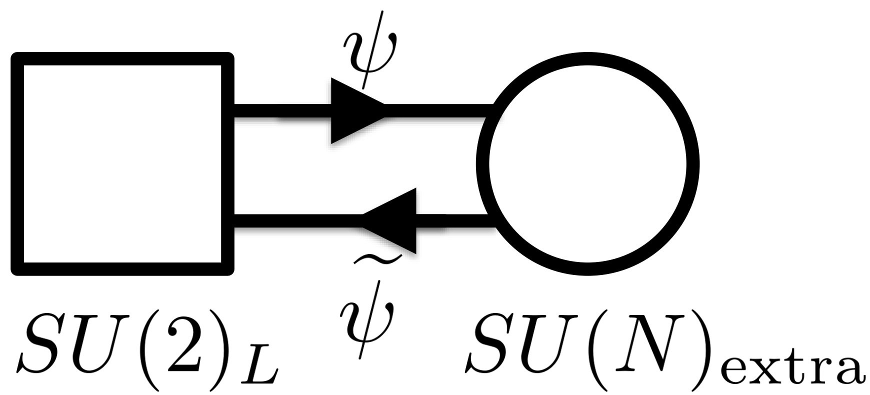


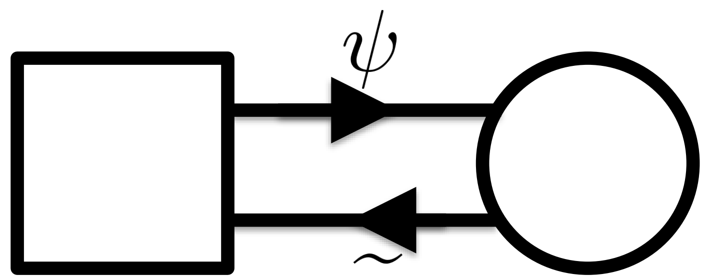
ψ
$\widetilde{\psi}$
$SU(2)_L$
$SU(N)_{\text{extra}}$
weakly gauged
confining

Example



$$¿\chi_{i_1 \ldots i_N} \sim \varepsilon_{g_1 \ldots g_N} \psi^{g_1}_{i_1} \ldots \psi^{g_N}_{i_N}?$$

Generic Issue: Pions!



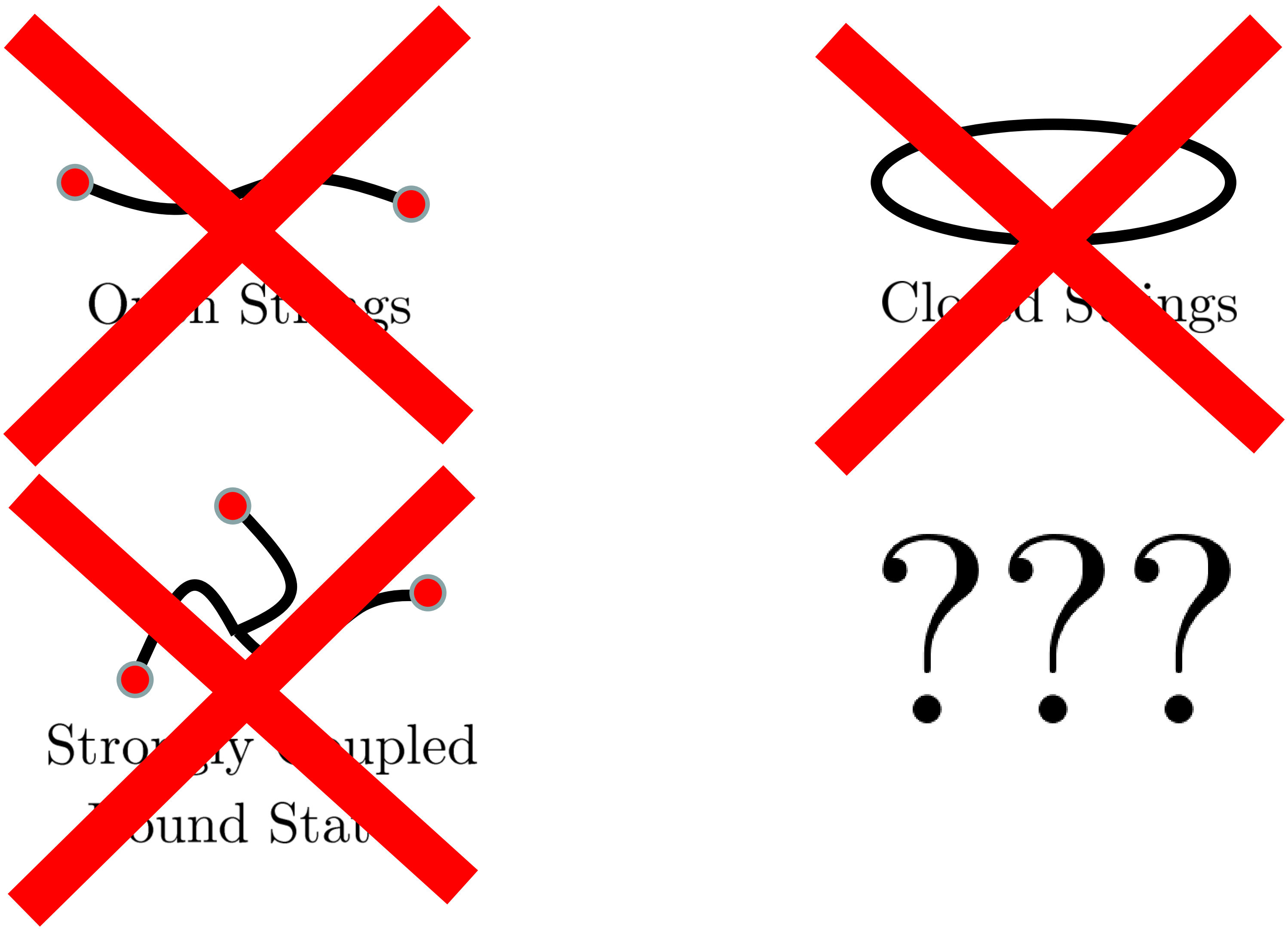
$$¿\chi_{i_1 \ldots i_N} \sim \varepsilon_{g_1 \ldots g_N} \psi^{g_1}_{i_1} \ldots \psi^{g_N}_{i_N}?$$

$\pi^j_i \sim \psi^g_i \widetilde{\psi}^j_g$ (generically lighter!)

(c.f. QCD inequalities)

Weingarten '83; Vafa Witten '84; + many

Stringy Routes to Matter



???

¿Just n-plet Scenario?

- Not in known string landscape
- Very difficult to build contrived models
- Sharp No-Go Theorem for all possibilities?
- Scenario is bad news for strings

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Pheno of “just n-plet”

Just n-plet Scenario

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Pheno Motivation

- Falsifying String Theory?!
- Minimal Dark Matter ($n = 5$)
- Dark Matter Scenarios with $n \geq 5$
- Why not?

DFTT40/2005 IFUP–TH/2005-34

Minimal Dark Matter

Marco Cirelli[a], **Nicolao Fornengo**[b], **Alessandro Strumia**[c].

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[b] *Dipartimento di Fisica Teorica, Università di Torino and INFN, Sez. di Torino, via P. Giuria 1, I-10125 Torino, Italia*

[c] *Dipartimento di Fisica dell'Università di Pisa and INFN, Italia*

Abstract

A few multiplets that can be added to the SM contain a lightest neutral component which is automatically stable and provides allowed DM candidates with a non-standard phenomenology. Thanks to coannihilations, a successful thermal abundance is obtained for well defined DM masses. The best candidate seems to be a $\mathrm{SU}(2)_\mathrm{L}$ fermion quintuplet with mass 4.4 TeV, accompanied by a charged partner 166 MeV heavier with life-time 1.8 cm, that manifests at colliders as charged tracks disappearing in $\pi^\pm$ with 97.7% branching ratio. The cross section for usual NC direct DM detection is $\sigma_{\rm SI} = f^2\, 1.0\cdot 10^{-43}\,\mathrm{cm}^2$ where $f \sim 1$ is a nucleon matrix element. We study prospects for CC direct detection and for indirect detection.

1 Introduction

The Dark Matter (DM) problem calls for new physics beyond the Standard Model (SM). Its simplest interpretation consists in assuming that DM is the thermal relic of a new stable neutral particle with mass $M \sim T_0^{1/2} G_\mathrm{N}^{-1/4} \sim$ TeV where $T_0 \sim 3\,\mathrm{K}$ is the present temperature of the universe and G_N is the Newton constant. Attempts to address the Higgs mass hierarchy

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Thermal relics ⇒ 13.6 TeV...

Mitridate Redi Smirnov Strumia '17
Bottaro Buttazzo Costa Franceschini Panci Redigolo Vittorio '22
Baumgart Rodd Slatyer Vaidya '23

ts
simplest interpretation consists in assuming that DM is the thermal relic of a new stable neutral particle with mass $M \sim T_0^{1/2} G_N^{-1/4} \sim$ TeV where $T_0 \sim 3\,$K is the present temperature of the universe and G_N is the Newton constant. Attempts to address the Higgs mass hierarchy

Focus: $n = 5, 7, 9$

Main Requirement: α_2^{-1} still perturbative

$$\frac{d\alpha_2^{-1}}{d\log\mu} = \frac{19/6}{2\pi} - \frac{1}{2\pi}\frac{(n+1)!}{(n-1)!3!}$$

Require $\Lambda_{\mathrm{Landau}} \gtrsim 5M \Rightarrow n \leq 9$

Enter the n-plet

χ transforms in Sym^{n-1} (fund)

Electric Charge: $U(1)_z \subset SU(2)_L$

$$\chi^{Q_{\max}}, ..., \chi^{+}, \chi^{0}, \chi^{-}, ..., \chi^{-Q_{\max}}$$

$$Q_{\max} = \frac{n-1}{2}$$

Enter the 5-plet

χ transforms in Sym^4 (fund)

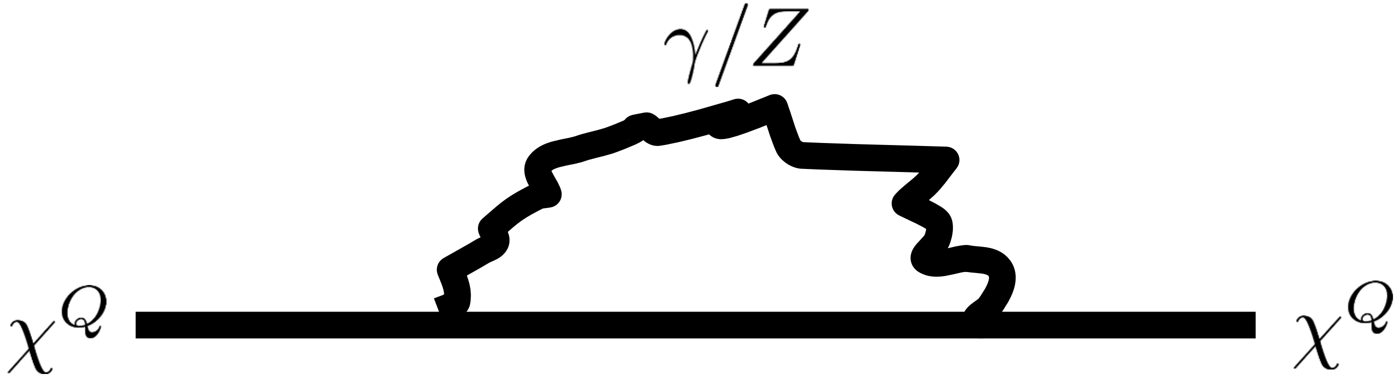
Electric Charge: $U(1)_z \subset SU(2)_L$

$\chi^{++}, \chi^{+}, \chi^{0}, \chi^{-}, \chi^{--}$

$Q_{\max} = 2$

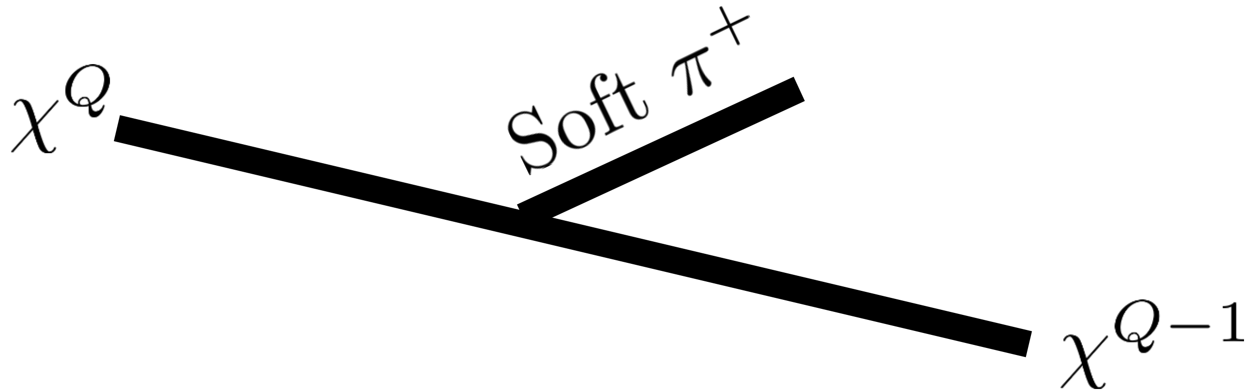
Mass Splittings

$$M_Q - M_{Q'} \sim (Q^2 - Q'^2) \times 166 \text{ MeV}$$



$\chi^{(0)}$ is the lightest state!

Decays

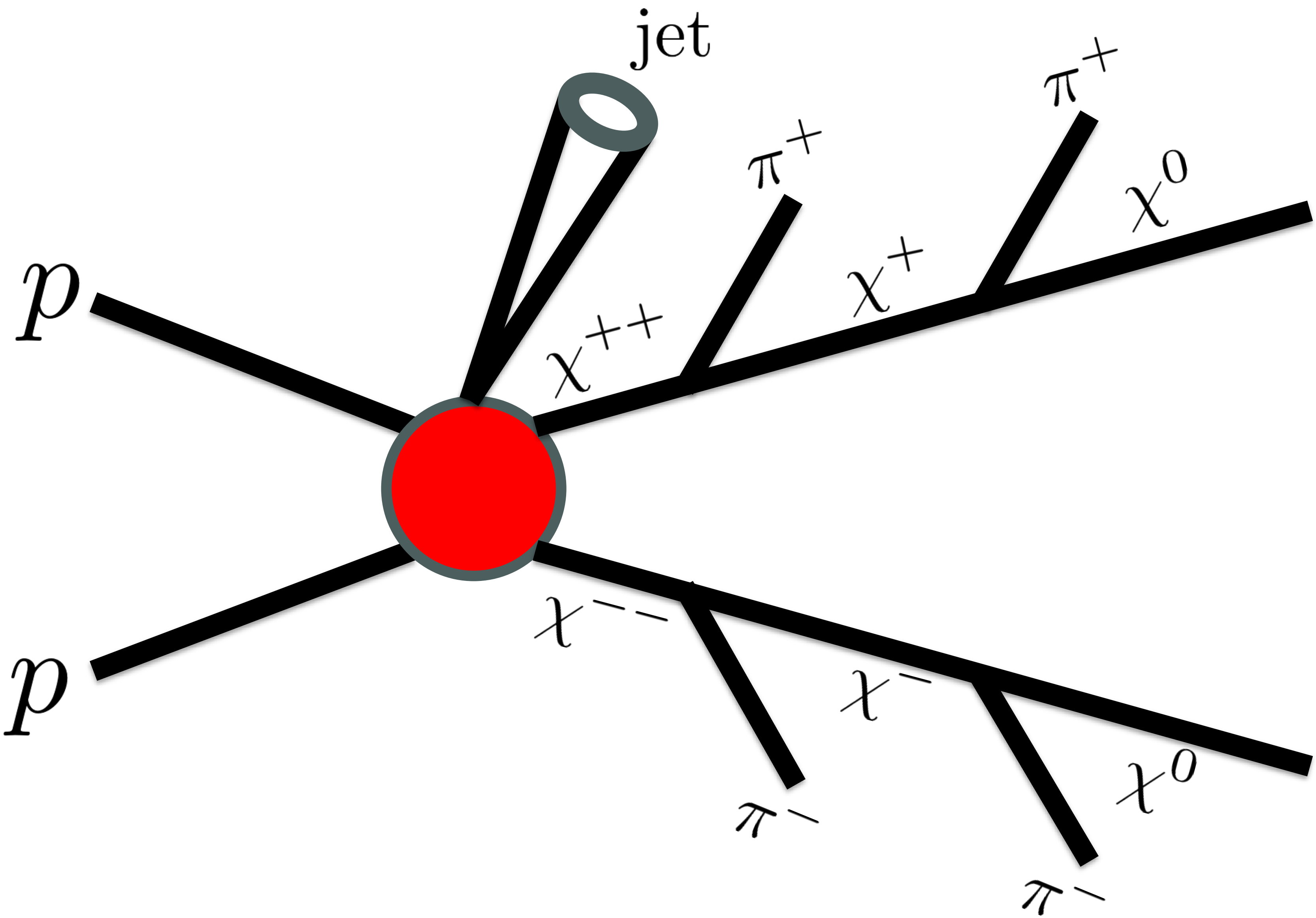


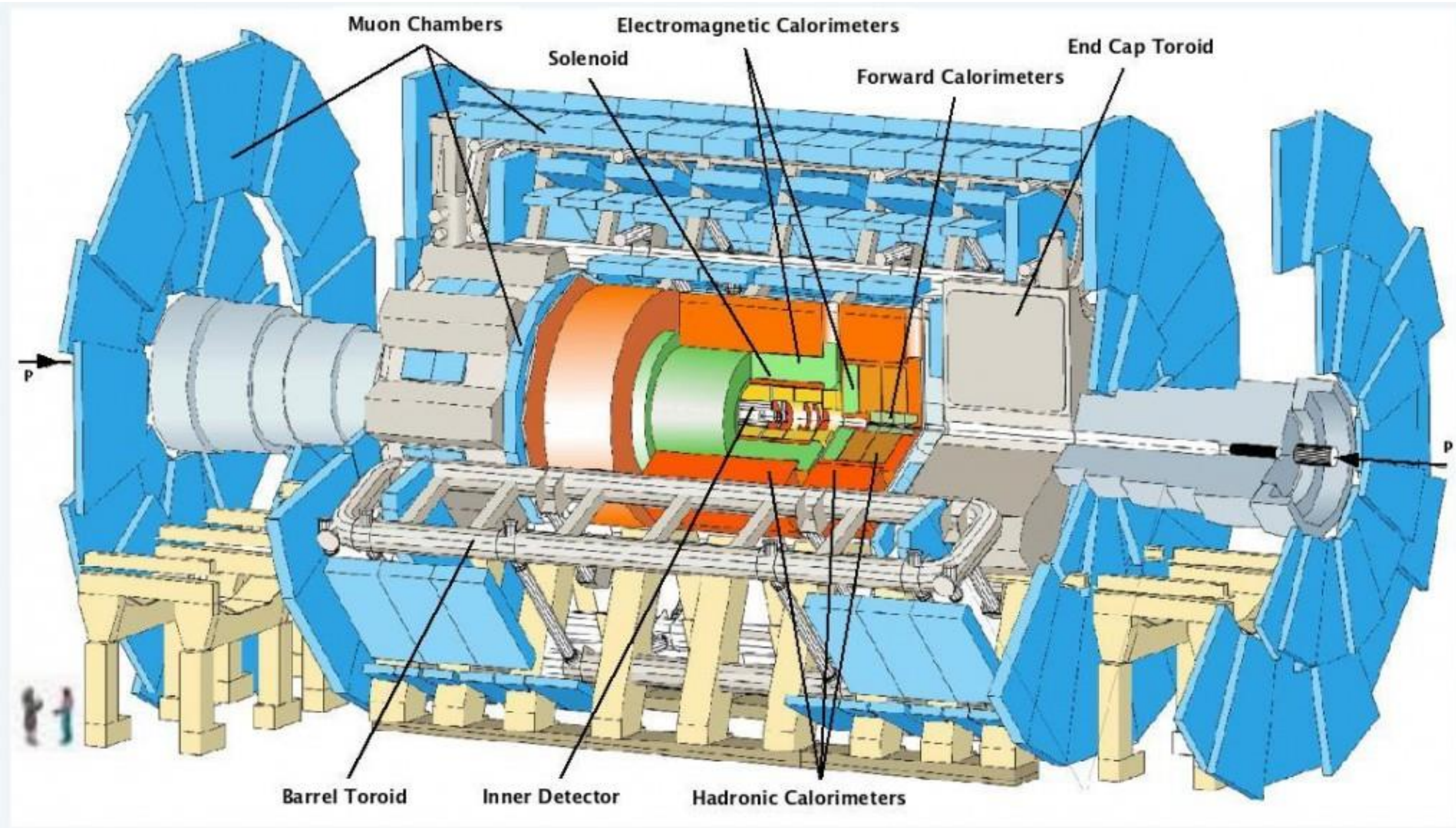
$$M_Q - M_{Q'} \sim (Q^2 - Q'^2) \times 166 \text{ MeV}$$

$$M_{\pi^\pm} \sim 140 \text{ MeV}$$

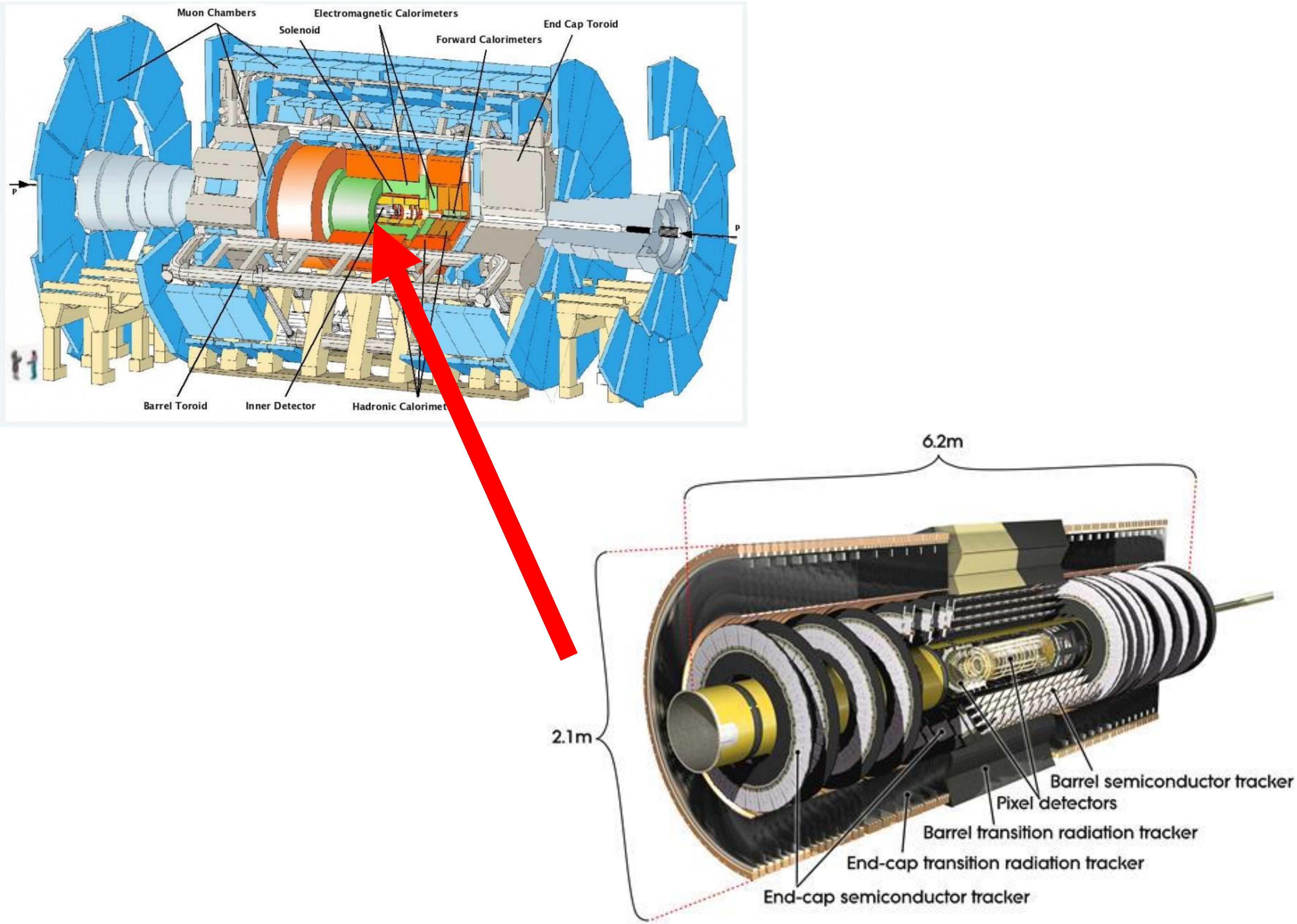
$$\tau(\chi^+ \to \chi^0 \pi^+) \sim \frac{44\,\text{cm}}{n^2-1} \sim 1 - 3 \text{ cm}$$

Example Process



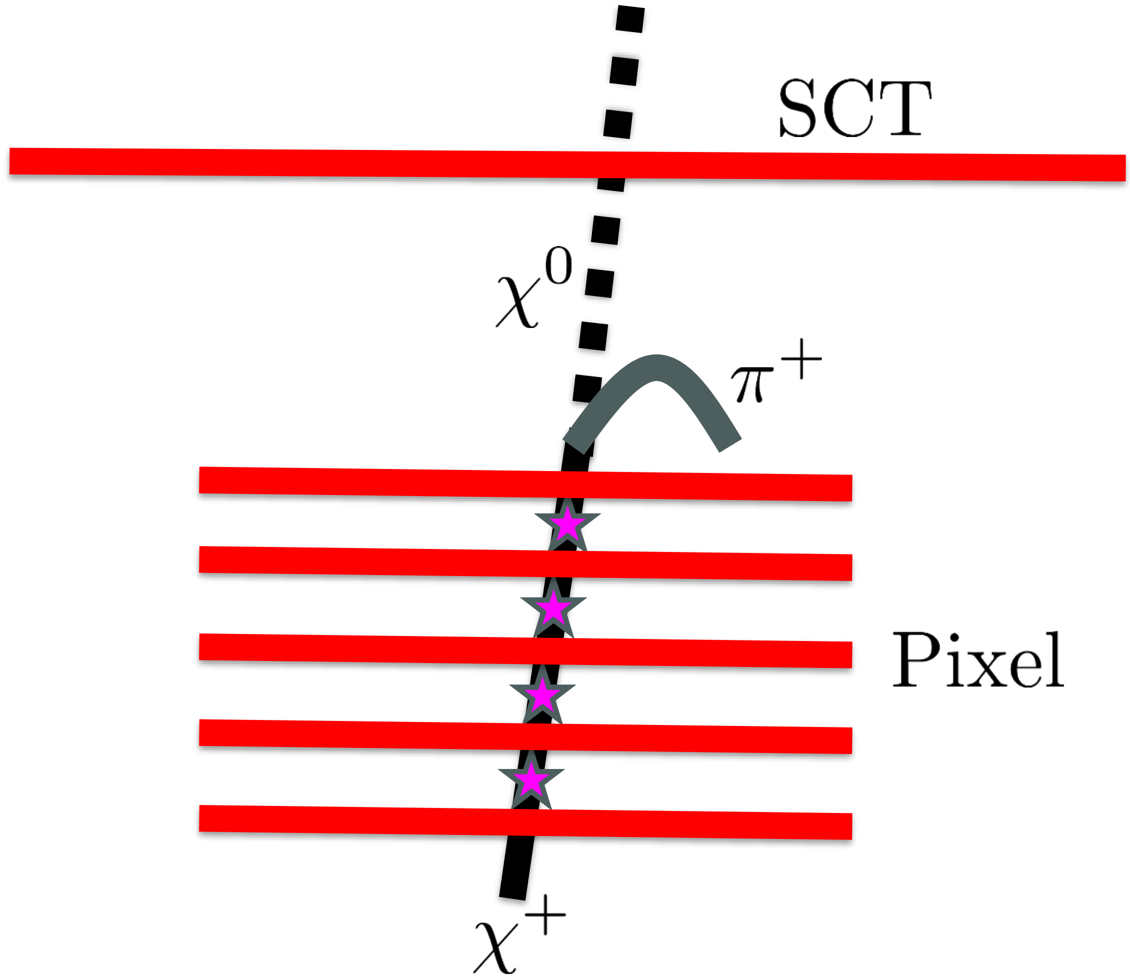


Muon Chambers
Electromagnetic Calorimeters
Solenoid
End Cap Toroid
Forward Calorimeters
P
P
Barrel Toroid
Inner Detector
Hadronic Calorimeters

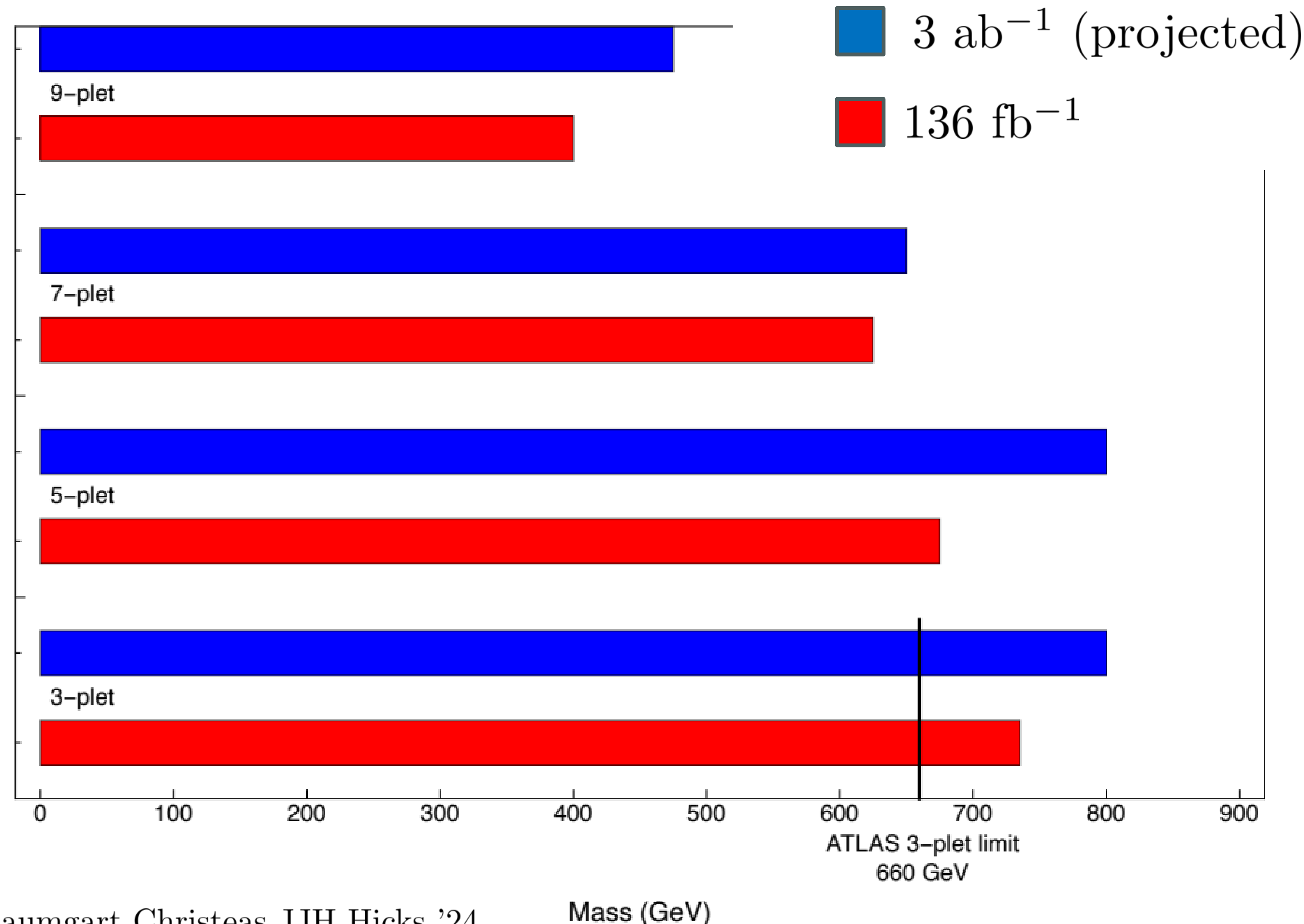


Muon Chambers
Electromagnetic Calorimeters
Solenoid
End Cap Toroid
Forward Calorimeters
P
P
Barrel Toroid
Inner Detector
Hadronic Calorimet
6.2m
2.1m
Barrel semiconductor tracker
Pixel detectors
Barrel transition radiation tracker
End-cap transition radiation tracker
End-cap semiconductor tracker

Disappearing Tracks (ATLAS)



*SCT = Semiconductor Tracker



Baumgart Christeas JJH Hicks '24

Improved Searches

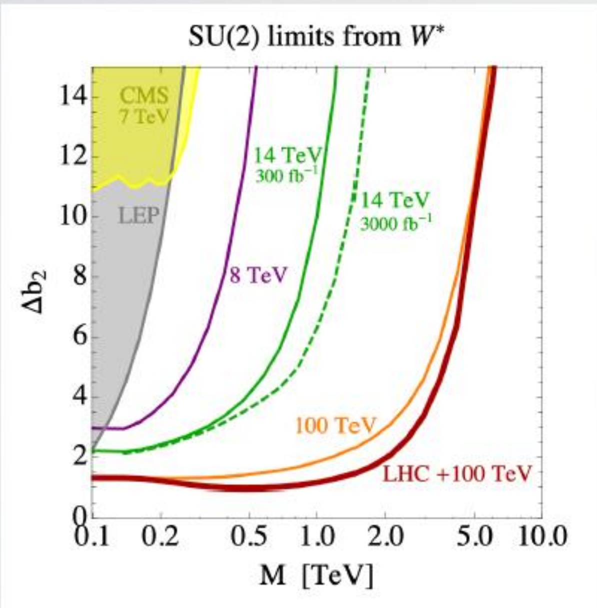
Higher Luminosity LHC won't help that much...

Direct / Indirect DM Detection

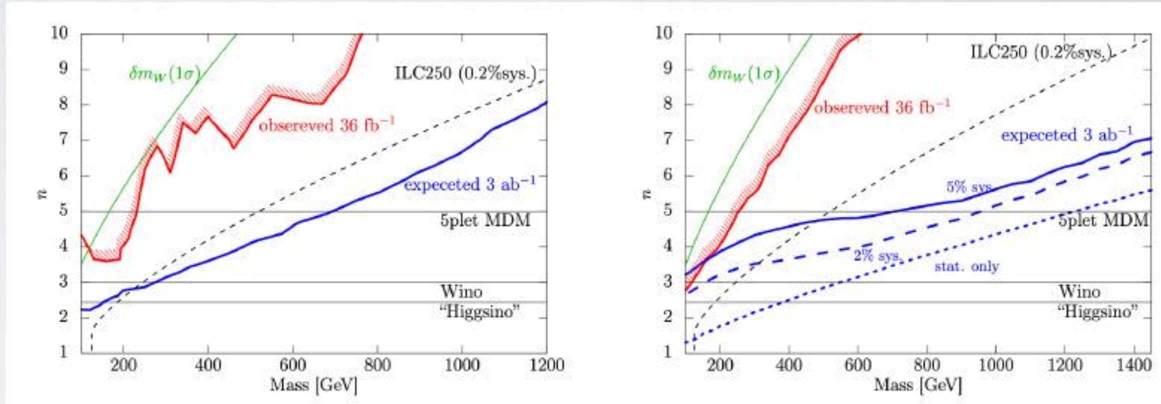
"Precision" α_2 Measurements?

Muon Collider / FCC?

FUTURE LIMITS



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

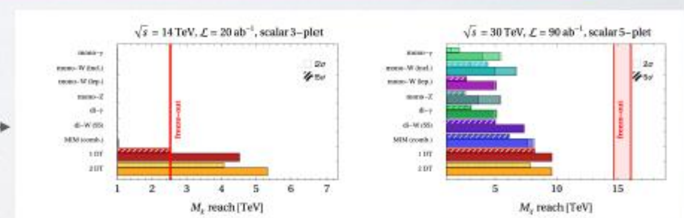


(a) Fitting based search (b) MC based search

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

Stringent future constraints from modified Drell-Yan

2107.09688: S. Bottaro et al.
μ-collider →



(Courtesy of M. Baumgart)

Summary / Future

What Was This Talk About?

- Strings $\cap$ "just n-plet" $= \{\}$ (very likely)
- Recast wino limits for $n = 5, 7, 9$

- No-go theorem for perturbative strings?
- Other "string-killer" scenarios?