Center for Theoretical Physics
SEOUL NATIONAL UNIVERSITY

Composite resonances at a multi-TeV muon collider

A study for the minimal composite Higgs model

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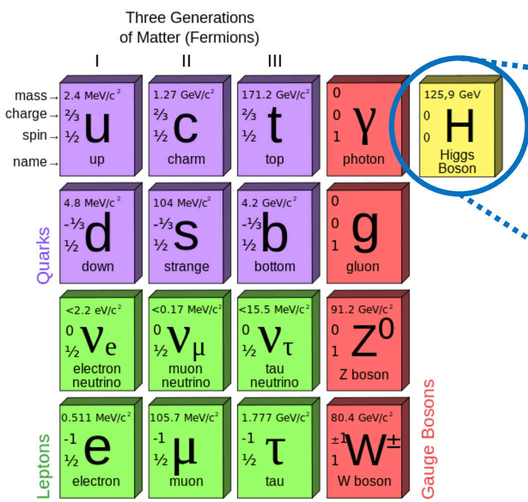
2020.12.1 @PITT PACC Workshop: Muon collider physics (remotely)

In collaboration with Da Liu and Lian-Tao Wang, in progress

The minimal composite Higgs model

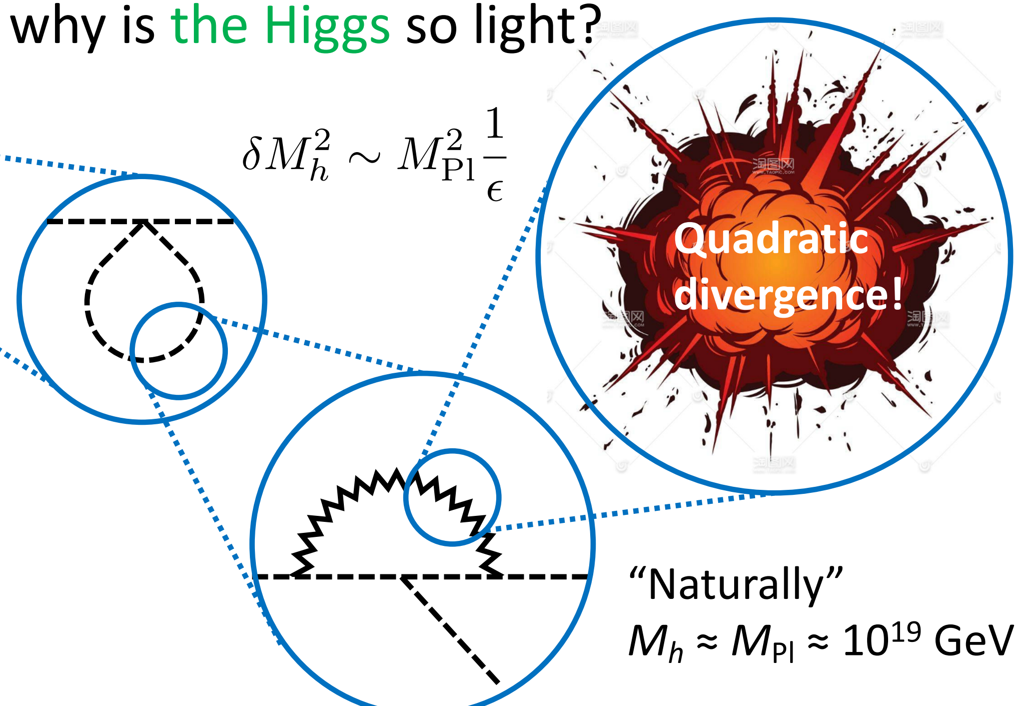
- Solving the hierarchy problem

The mass of an elementary scalar is sensitive to the high scale **new physics** correction; why is the Higgs so light?



The Standard Model

$$\delta M_h^2 \sim M_{\rm Pl}^2 \frac{1}{\epsilon}$$

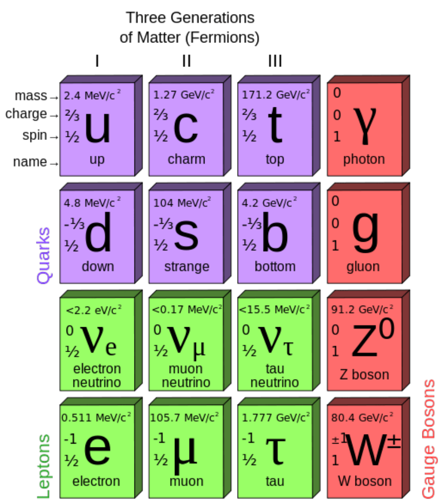


"Naturally"
$M_h \approx M_{\rm Pl} \approx 10^{19}$ GeV

The minimal composite Higgs model

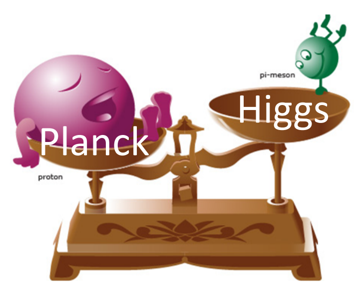
- Solving the hierarchy problem

If the Higgs is a composite Nambu-Goldstone boson (NGB) from spontaneous symmetry breaking of a strong interacting sector…

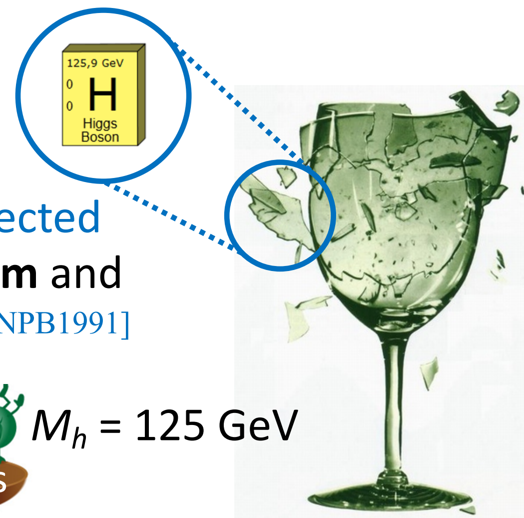


The elementary sector (SM without Higgs)

Then its mass is protected by **Goldstone theorem** and naturally light.[Kaplan, NPB1991]



M_h = 125 GeV



The composite sector (New strong dynamics)

- # The minimal composite Higgs model

The strong dynamics: SO(5)/SO(4) [Agashe *et al*, NPB2005]

Broken generators: 10 − 6 = 4: NGBs as the Higgs doublet

$$SO(5):\{\underbrace{\overbrace{T_L^a,\ T_R^a}^{SO(4)}}_{SU(2)_L\ \ SU(2)_R},\ \overbrace{\hat{T}^i}^{SO(5)/SO(4)}\}$$

a: 1,2,3;

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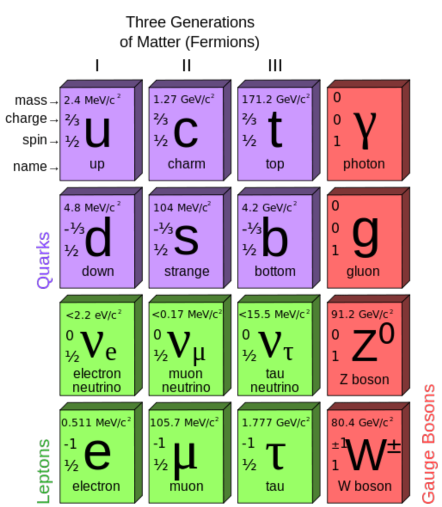
i: 1,…,4;

$$\boxed{H=\frac{1}{\sqrt{2}}\begin{pmatrix} h_2+ih_1 \\ h_4-ih_3 \end{pmatrix}}$$



The elementary sector
(SM without Higgs)

The composite sector
(New strong dynamics)

- # The minimal composite Higgs model

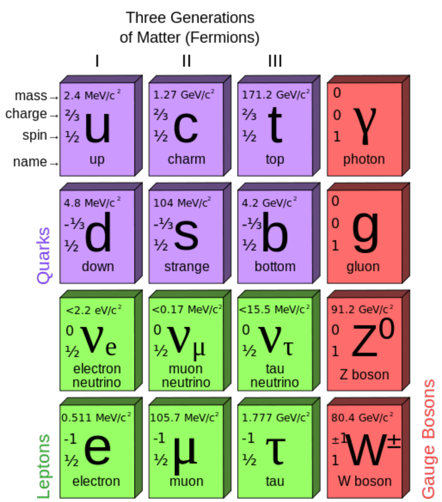
The strong dynamics: SO(5)/SO(4) [Agashe *et al*, NPB2005]

Broken generators: 10 − 6 = 4: pseudo-NGBs as the Higgs doublet

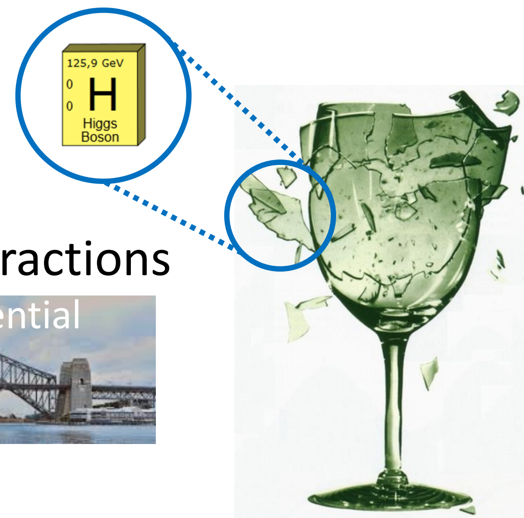
$$\mathcal{L}_{\rm MCHM} = \mathcal{L}_{\rm strong} + \mathcal{L}_{\rm SM} + \mathcal{J}_\mu^{a_L} W^\mu_{a_L} + \mathcal{J}_{Y\,\mu} B^\mu + y_L \bar q_L \mathcal{O}_R + y_R \bar u_R \mathcal{O}_L$$

EW gauge coupling: Subgroup $SU(2)_L \times U(1)_Y$ gauged

Partial compositeness: q_L and t_R fill in the incomplete rep. of SO(5)



SO(5)-breaking Interactions



The elementary sector (SM without Higgs)

The composite sector (New strong dynamics)

- # The minimal composite Higgs model

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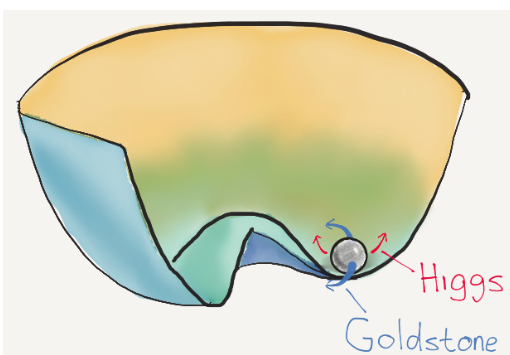
EW gauge coupling: Subgroup $SU(2)_L \times U(1)_Y$ gauged

Partial compositeness: q_L and u_R fill in the incomplete rep. of SO(5)

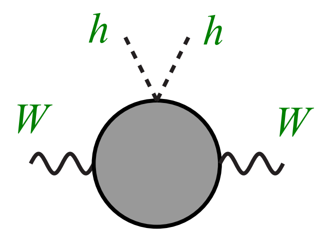
$$V_{\rm eff}(h) \approx \alpha \sin^2\frac{h}{f} - \beta \sin^2\frac{h}{f}\cos^2\frac{h}{f} \quad \xrightarrow{\text{EWSB}} \quad \sin^2\frac{\langle h\rangle}{f} = \frac{\beta-\alpha}{2\beta}$$

Higgs potential generated; EWSB triggered



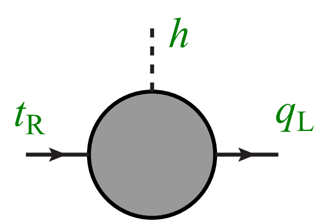
W and *Z* mass

$$\langle \mathcal{J}\mathcal{J}\rangle \sim g^2 f^2 \sin^2\frac{h}{f}$$



Top mass

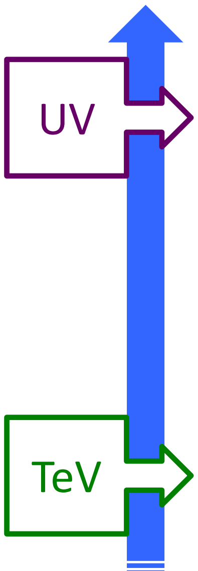
$$\langle \mathcal{O}_L \mathcal{O}_R\rangle \sim \frac{y_L y_R}{g_\rho} f \sin\frac{h}{f}$$



• Phenomenology of the composite Higgs model

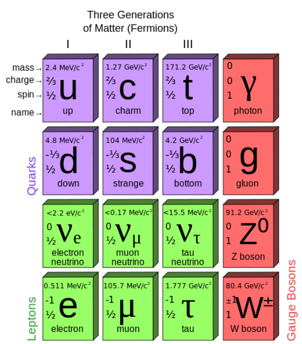
The strong dynamics: SO(5)/SO(4) [Agashe *et al*, NPB2005]

Broken generators: 10 – 6 = 4: pseudo-NGBs as the Higgs doublet

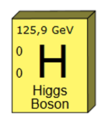


$$\mathcal{L}_{\rm MCHM} = \mathcal{L}_{\rm strong} + \mathcal{L}_{\rm SM} + \mathcal{J}_\mu^{a_L} W_{a_L}^\mu + \mathcal{J}_{Y\mu} B^\mu + y_L \bar{q}_L \mathcal{O}_R + y_R \bar{u}_R \mathcal{O}_L$$

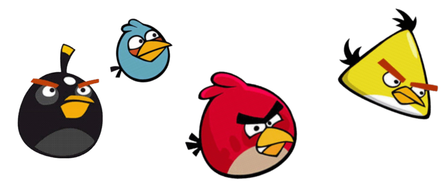
------ Nonperturbative confinement ------



Indirect



Direct signals



Vector resonances

$\langle 0|\mathcal{J}_\mu|\rho\rangle \sim \epsilon_\mu m_\rho f$

Top partners

$\langle 0|\mathcal{O}_{L,R}|\Psi\rangle \sim y_{L,R} m_\Psi f$

See Andrea Wulzer’s talk for the indirect search;

We focus on the direct search.

Resonances mass around 1-10 TeV, might be detected at current or future colliders! This talk: a multi-TeV muon collider

- The vector resonance

The $\rho^{\pm,0}$-resonance: (3,1) of SO(4) [same with W^a]:

SU(2)$_L$ gauge coupling

Order 1 parameter

$$\mathcal{J}^a_\mu W^\mu_a \to -a_\rho^2 f^2 g_\rho \rho^a_\mu \left(g_2 W^a_\mu - \frac{i}{f^2} H^\dagger \frac{\sigma^a}{2} \overleftrightarrow{D}_\mu H \right)$$

SO(5)/SO(4) decay constant

Strong dynamics coupling

$$\boxed{g_\rho \sim \frac{4\pi}{\sqrt{N}}}$$

ρ mass term & the ρ-W mixing angle

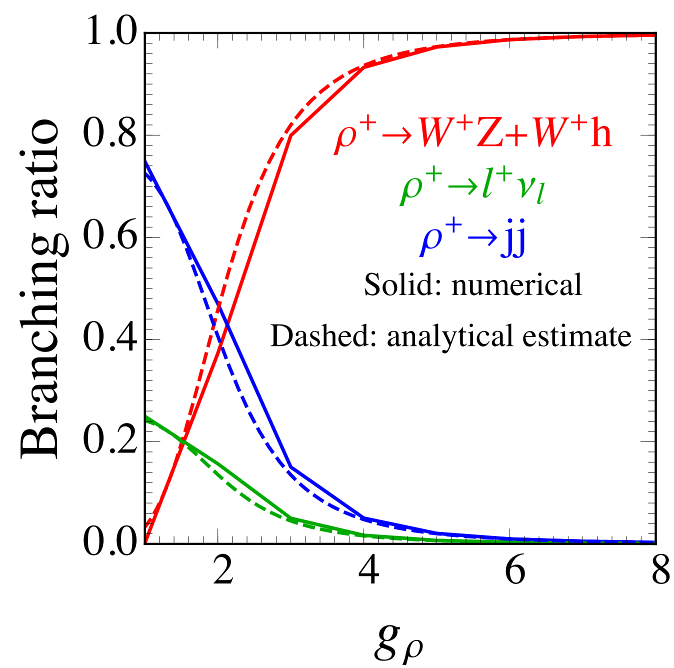
$$\boxed{\frac{1}{2}(a_\rho g_\rho f)^2 \rho^a_\mu \rho^\mu_a} \qquad \sin\theta \sim \frac{g_2}{\sqrt{g_\rho^2 + g_2^2}} \approx \frac{g_2}{g_\rho}$$

The ρ-elementary quark coupling

$$g_{\rho f_L \bar{f}_L^{(\prime)}} = g_2 \sin\theta \sim \frac{g_2^2}{g_\rho}$$

The ρ-Goldstone coupling

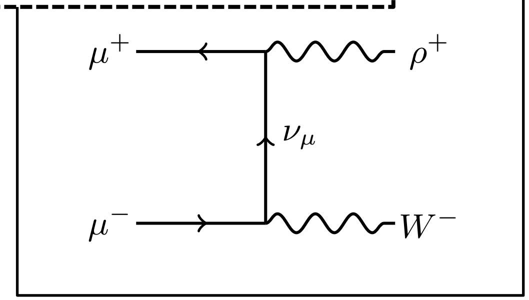
$$\sim g_\rho \rho^a_\mu H^\dagger \frac{\sigma^a}{2} i\overleftrightarrow{D}_\mu H$$



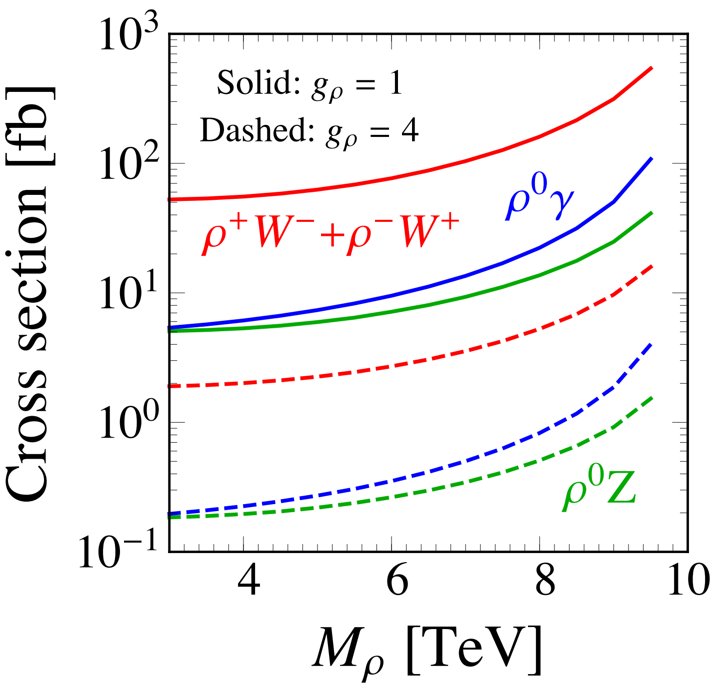
• The vector resonance

The production of $\rho^{\pm,0}$ at a multi-TeV muon collider:
The ρV associated production, with $V = W^{\pm}, Z, \gamma$.

Diagram illustration



At a 10 TeV muon collider



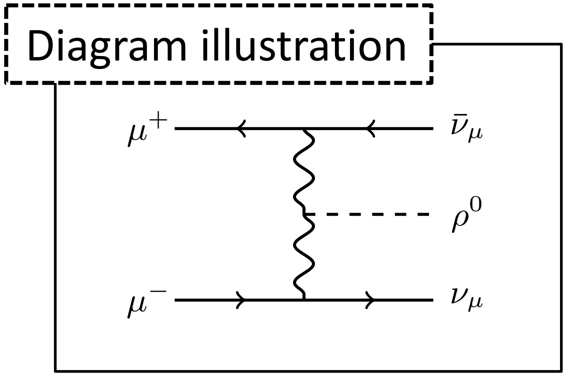
Features:

1. The ρW channel always dominates;
2. Rate proportional to g_ρ^{-2};

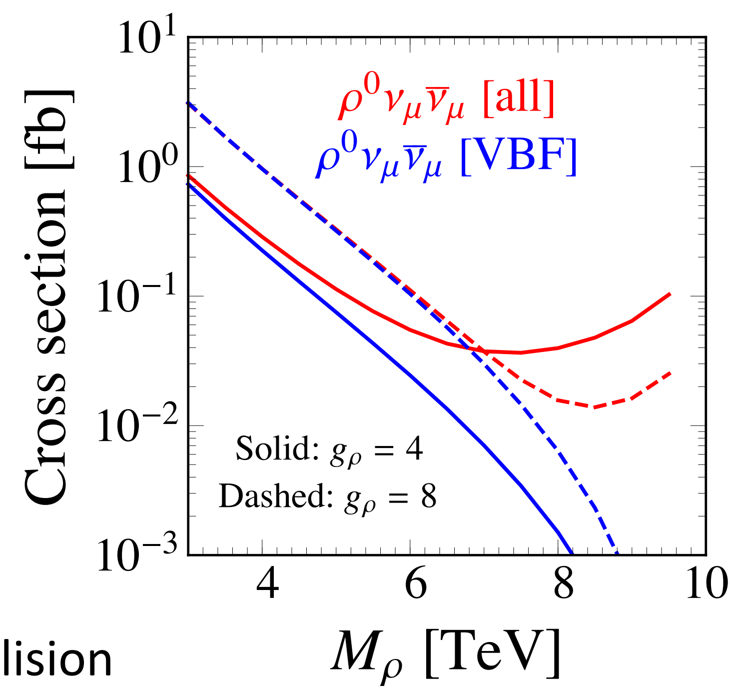
3. Rate increases when M_ρ is close to the collision energy: the t-channel light fermion on-shell

• The vector resonance

The production of $\rho^{\pm,0}$ at a multi-TeV muon collider:
The vector boson fusion (VBF).



At a 10 TeV muon collider



Features:

1. The ρV channel "pollutes" VBF, and it's hard to separate:

$$\mu^+\mu^- \to \rho^0 Z \to \rho^0 \nu_\mu \bar{\nu}_\mu$$

2. For large g_ρ, VBF dominates, however for M_ρ close to the collision energy, ρV always dominates.

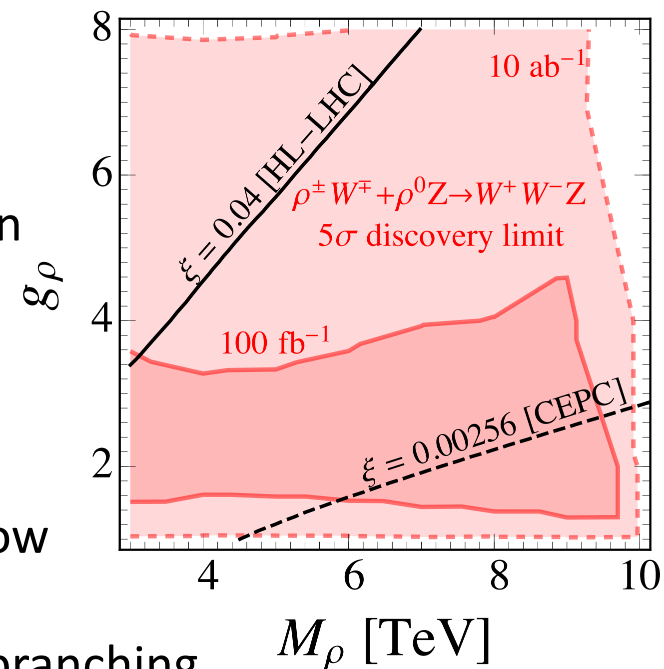
- # The vector resonance

Estimating the reach in the $\rho W + \rho Z$ => W^+W^-Z channel

Setup:

1. The $V = W^{\pm}$ and Z in the final state not decay;
2. Require $p_T(V) > 500$ GeV and treat V as a fat-jet [tagging efficiency 60% and mis-tag rate 5%];
3. Require 3 fat-jet, and the combination of any 2 of them within the mass window $[M_\rho \pm \Gamma_\rho]$.

At a 10 TeV muon collider



Results:

1. The large g_ρ region suffers from the low production rate;
2. The small g_ρ region suffers from low branching ratio to $W^{\pm}Z$ or W^+W^-;
3. ($\xi = v^2 / f^2$ constrained by EW measurements)

- The top partners

The *Ψ*-resonance: $(2,2)_{2/3}$ of SO(4) x $U(1)_X$

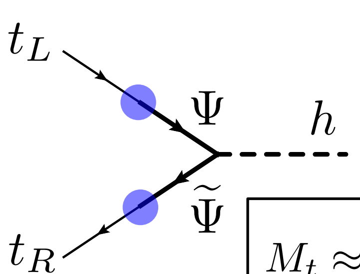
Decomposed to 2 vector-like-quark doublets Q_X and Q under $SU(2)_L$ x $U(1)_Y$

$$(\mathbf{2},\mathbf{2}) \to \mathbf{2}_{7/6} \oplus \mathbf{2}_{1/6}$$
$$\Psi_{(\mathbf{2},\mathbf{2})} \to \begin{pmatrix} X_{5/3} \\ X_{2/3} \end{pmatrix} \oplus \begin{pmatrix} T \\ B \end{pmatrix}$$

SM 3rd-generation quarks in 5 of SO(5)

Mixing parameter

$$y_L \bar{q}_L^{\mathbf{5}} \mathcal{O}_R \to y_L f \bar{q}_L Q + y_L f \left(1 - \cos\frac{\sqrt{2}|H|}{f}\right) \frac{1}{2|H|^2} (\bar{q}_L \widetilde{H})(H^\dagger Q_X - \widetilde{H}^\dagger Q);$$
$$y_R \bar{t}_R^{\mathbf{5}} \mathcal{O}_L \to -\frac{y_R f}{\sqrt{2}|H|} \sin\frac{\sqrt{2}|H|}{f} (\bar{t}_R H^\dagger Q_X - \bar{t}_R \widetilde{H}^\dagger Q)$$



$$M_t \approx \frac{y_L y_R f}{\sqrt{M_\Psi^2 + y_L^2 f^2}} \frac{v}{\sqrt{2}}$$

Goldstone equivalence theorem:

Br(T –> tZ) ≈ Br(T –> th) ≈ 50%

Br($X_{2/3}$ –> tZ) ≈ Br($X_{2/3}$ –> th) ≈ 50%

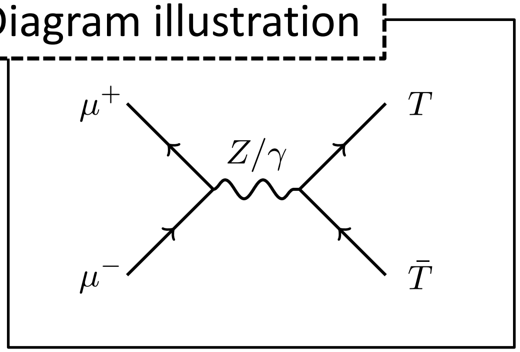
Br(B –> tW^-) ≈ 100%

Br($X_{5/3}$ –> tW^+) = 100%

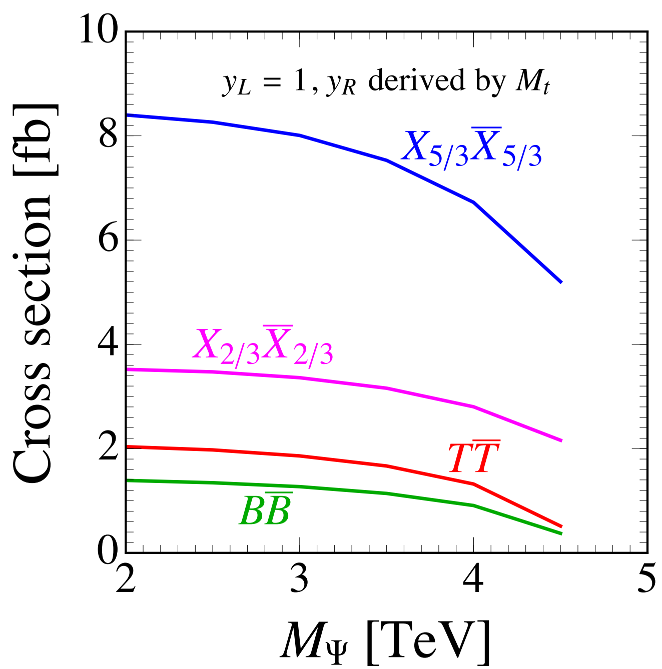
- # The top partners

The production of top partners at a multi-TeV muon collider:
The pair production: Drell-Yan process

Diagram illustration



At a 10 TeV muon collider



Features:

1. The charge 5/3 top partner has the largest rate;

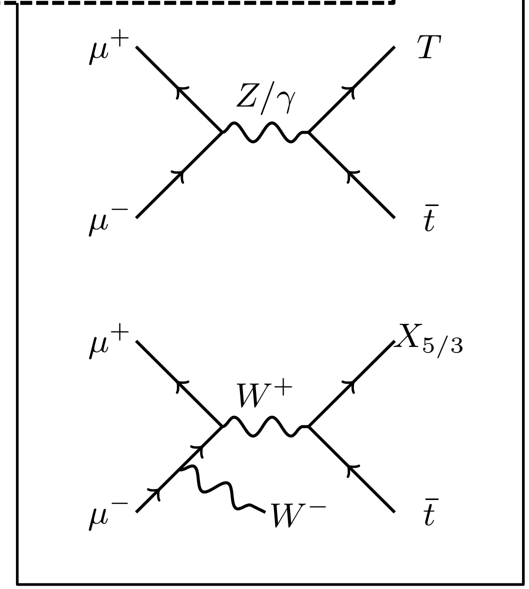
2. Partly due to the lightness of $X_{5/3}$ because it doesn't mix with SM particles. Other top partners are heavier.

- # The top partners

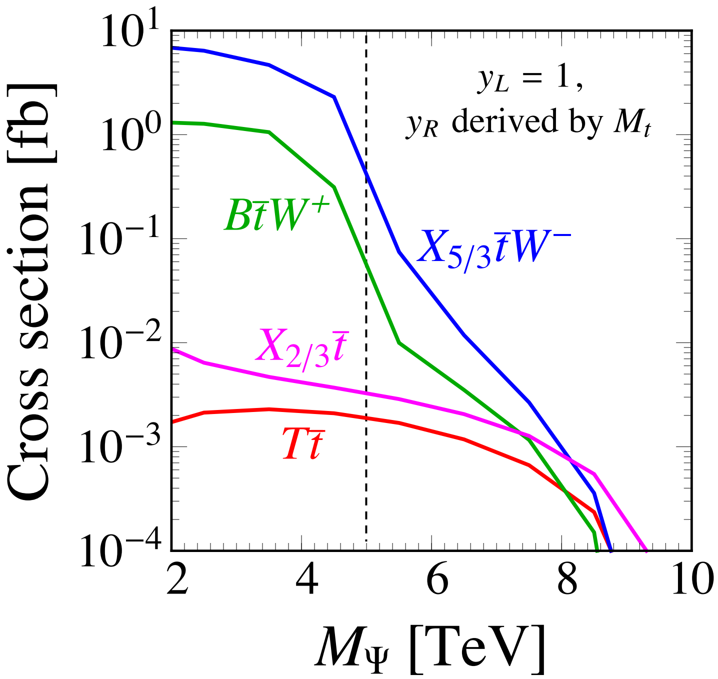
The production of top partners at a multi-TeV muon collider:

The "DY-like" single production

Diagram illustration



At a 10 TeV muon collider



Features:

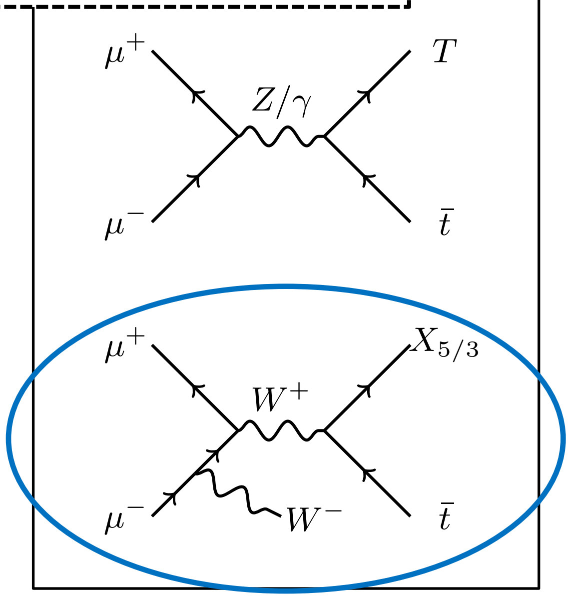
1. The charge 5/3 top partner again acquires the largest rate;
2. For M_ψ < 5 TeV the $X_{5/3}tW$ channel receives pair production contribution.

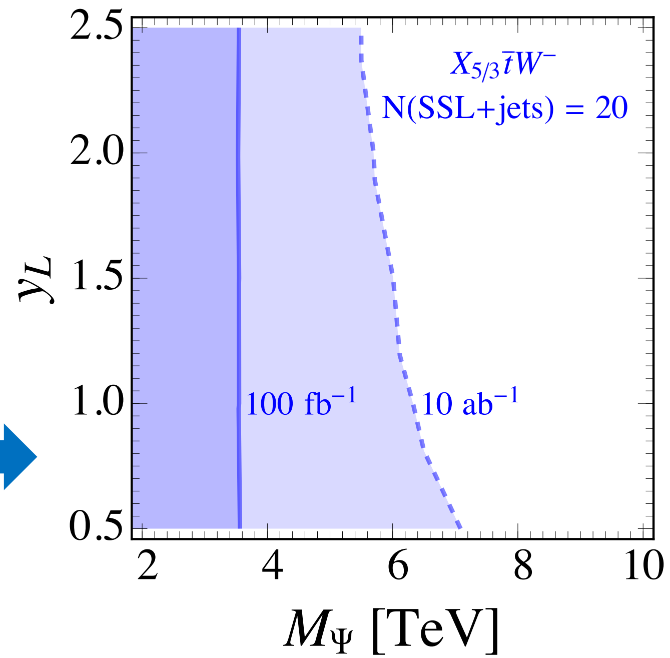
• The top partners

The production of top partners at a multi-TeV muon collider:
The same-sign di-lepton (SSL) signal

At a 10 TeV muon collider

Diagram illustration





Results:

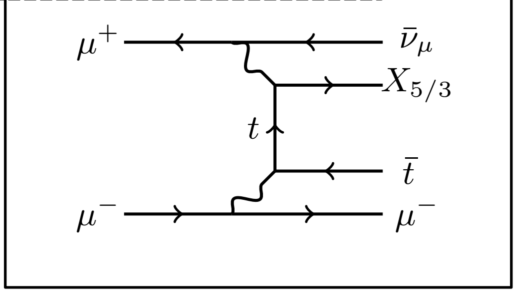
1. The contours for N(SSL+jets) = 20 as an estimate for the muon collider reach;
2. For $M_\psi < 5$ TeV the pair contribution dominates.

The top partners

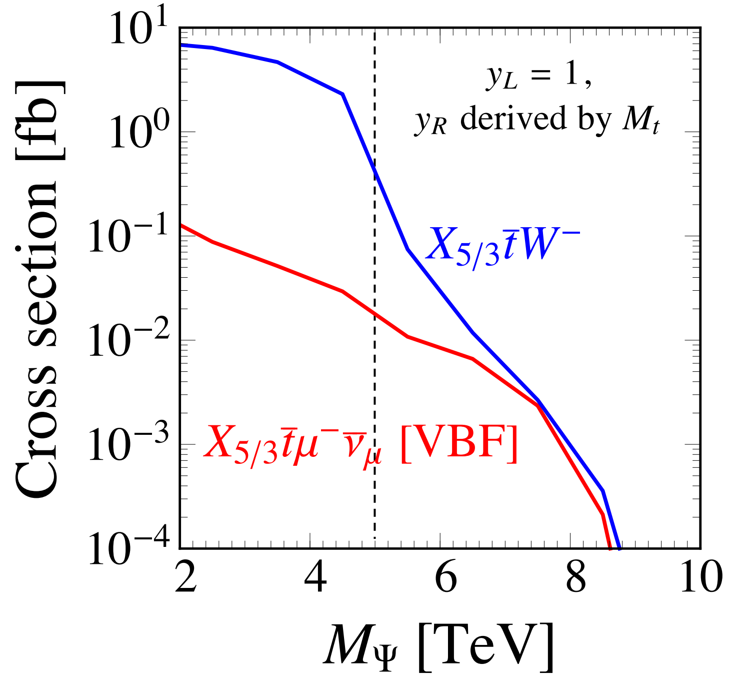
The production of top partners at a multi-TeV muon collider:

The VBF single production

Diagram illustration



At a 10 TeV muon collider



Setup:

By [VBF] we remove the $M(\mu\nu)$ from the *W*-pole.

Features:

For large M_ψ it is comparable with the Dell-Yan-like process.

Summary & discussions

The phenomenology of the minimal composite Higgs model at a multi-TeV muon collider is investigated.

1. The vector resonances: ρV associated production or VBF, and the former usually dominates;
2. The top partners: Drell-Yan pair produced or single (DY-like or VBF), and the $X_{5/3}$ channel always dominates;

Future directions (in progress):

1. The di-lepton decay channel of ρ;
2. Interplay between ρ and top partners;
3. The results at a 30 TeV muon collider;
4. …

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Looking forward to a muon collider!

Thank you!