The LHC Phenomenology of Vectorlike Confinement

Takemichi Okui

(Florida State University)

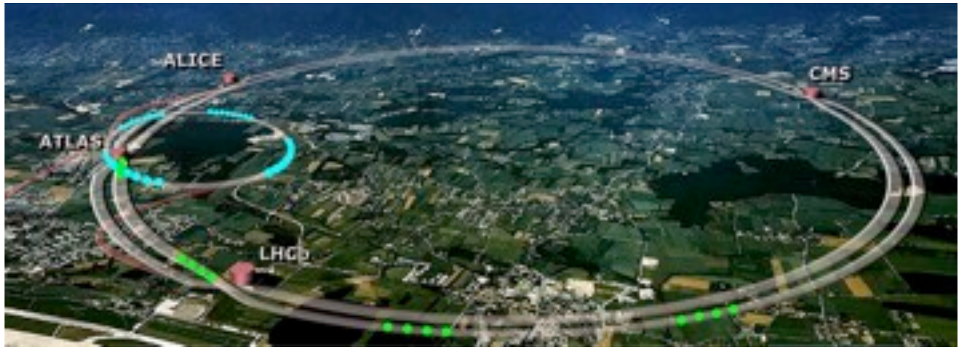
Based on work with C. Kilic (Rutgers) and R. Sundrum (Hopkins)

For details and references, see C.K & T.O, 1001.xxxx,
C.K., T.O & R.S., 0906.0577 (pub. in JHEP),
C.K., T.O & R.S., 0802.2568 (pub. in JHEP).

My worry...

The SM

Rich new physics?



Beautifully tested.
No signs of new physics at TeV.

tension!
$\Leftrightarrow$

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⇔

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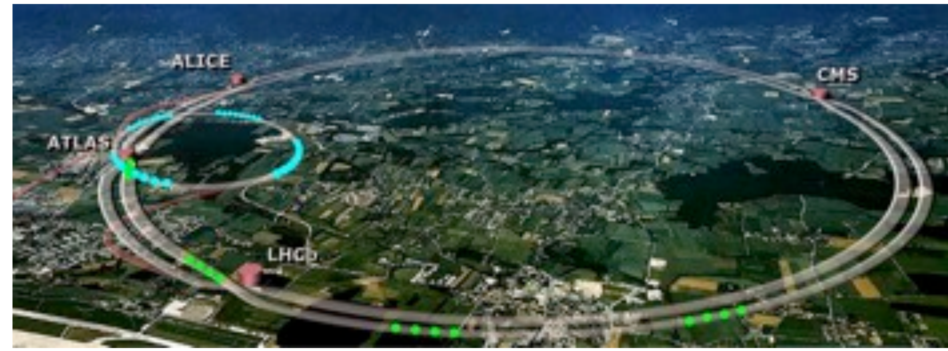
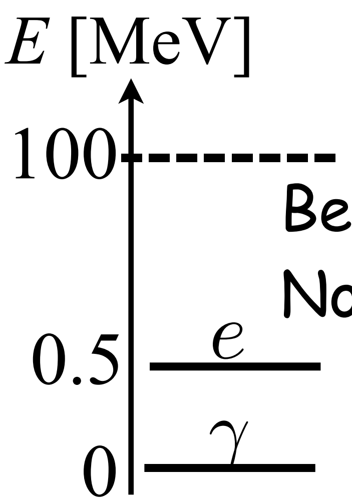


Encouraging (imaginary) "history"

"SM" @ $E <$ 100 MeV



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No signs of new physics

My worry...

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tension!
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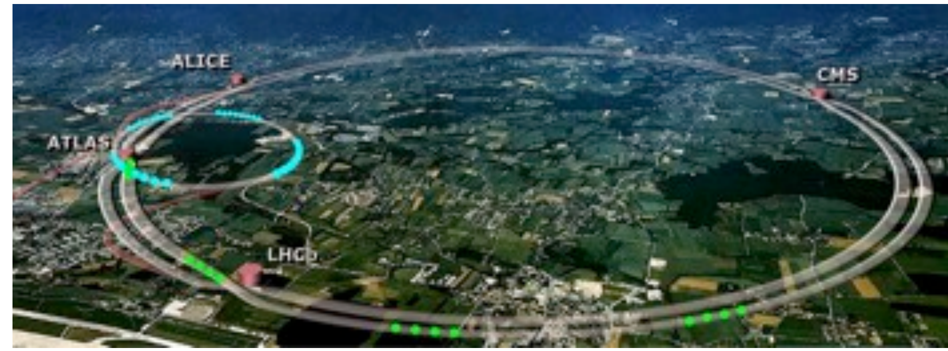

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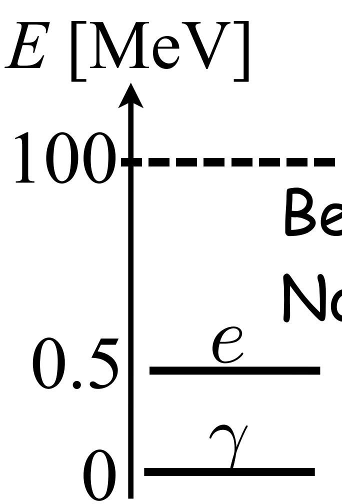
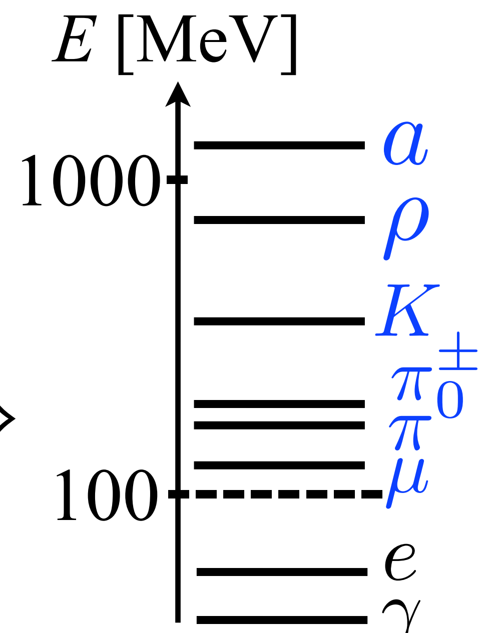


Beautifully tested
No signs of new physics $\Rightarrow$



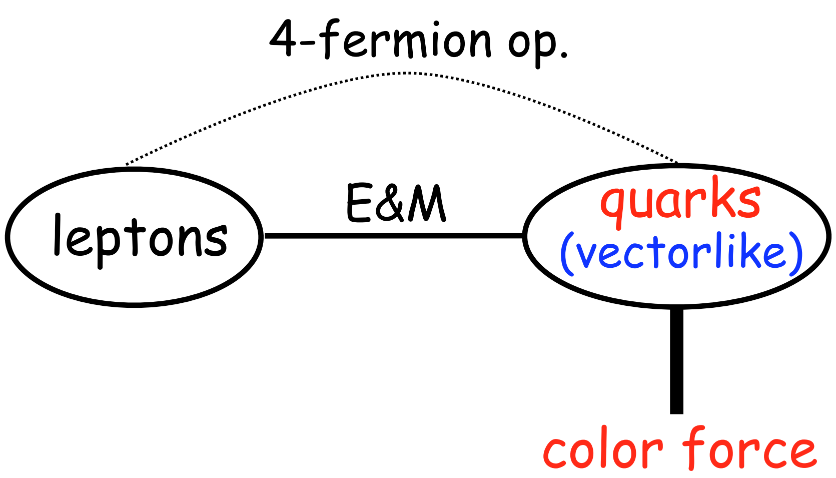
DRAMATIC new physics!!

T. OKUI (FSU)

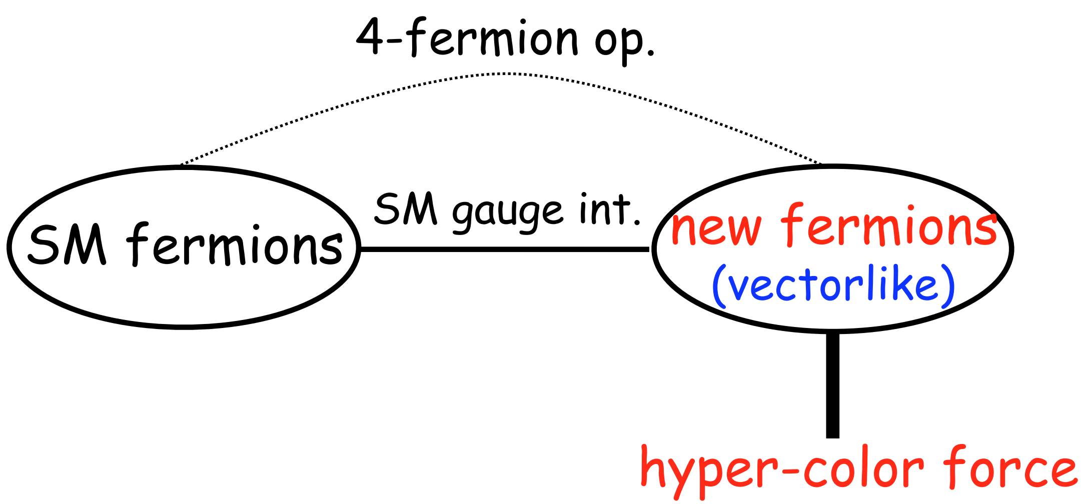
If Nature repeats itself at TeV...

- QED-QCD system -

(i.e. SM at GeV $< E \ll M_W$)



- Vectorlike Confinement at TeV -



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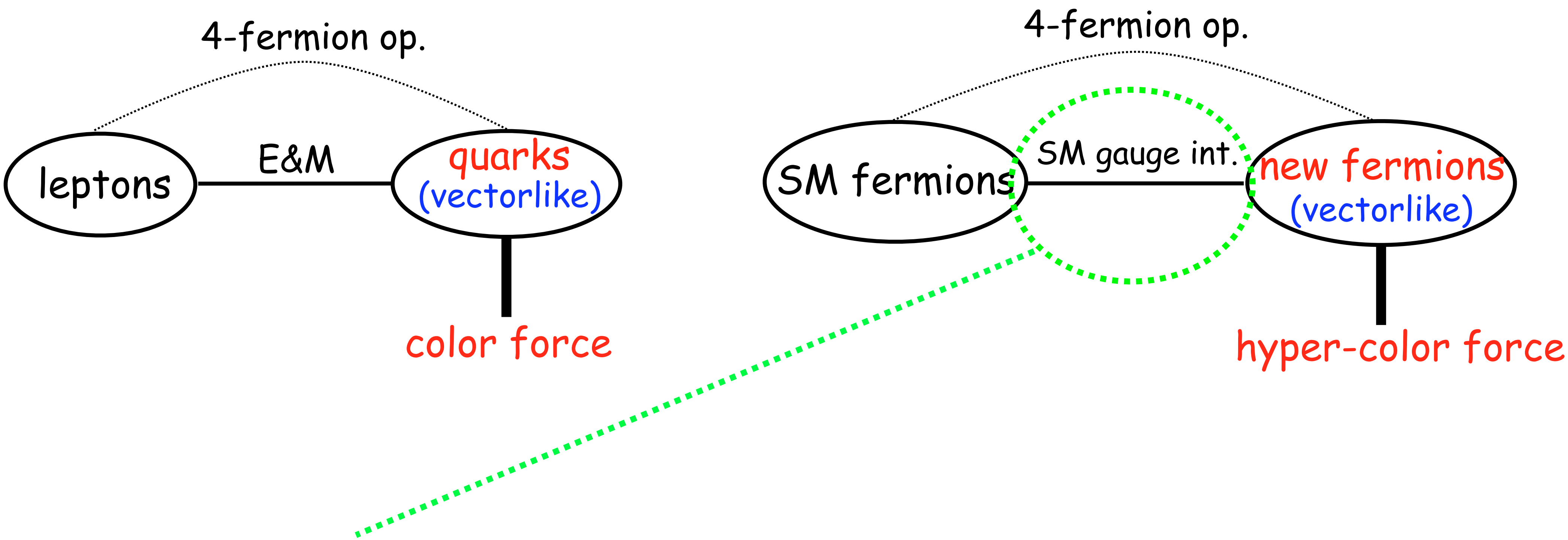

"Gauge Mediation"

Safe from flavor constraints

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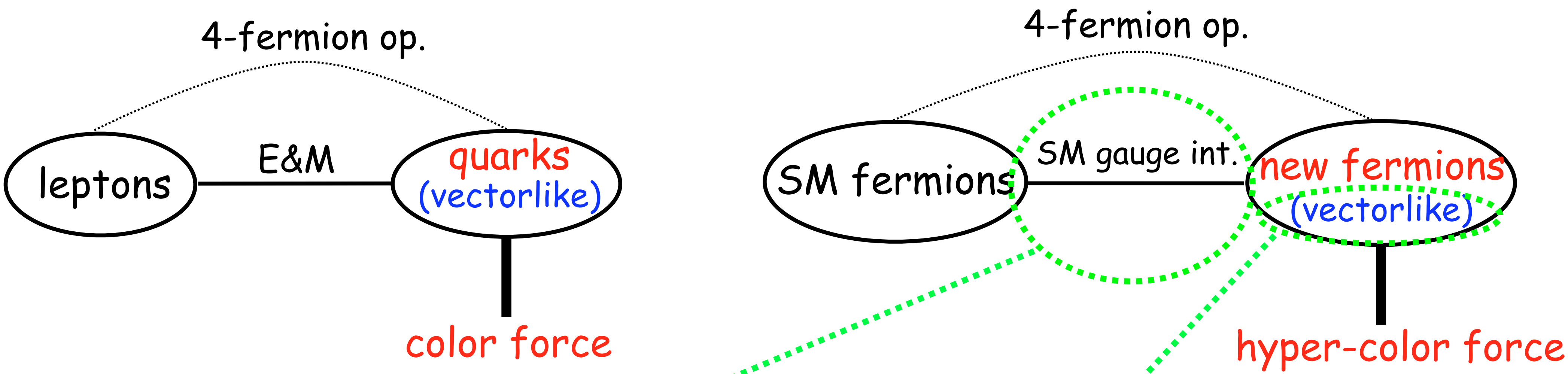

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Can have mass w/o EWSB

Safe from precision EW constraints

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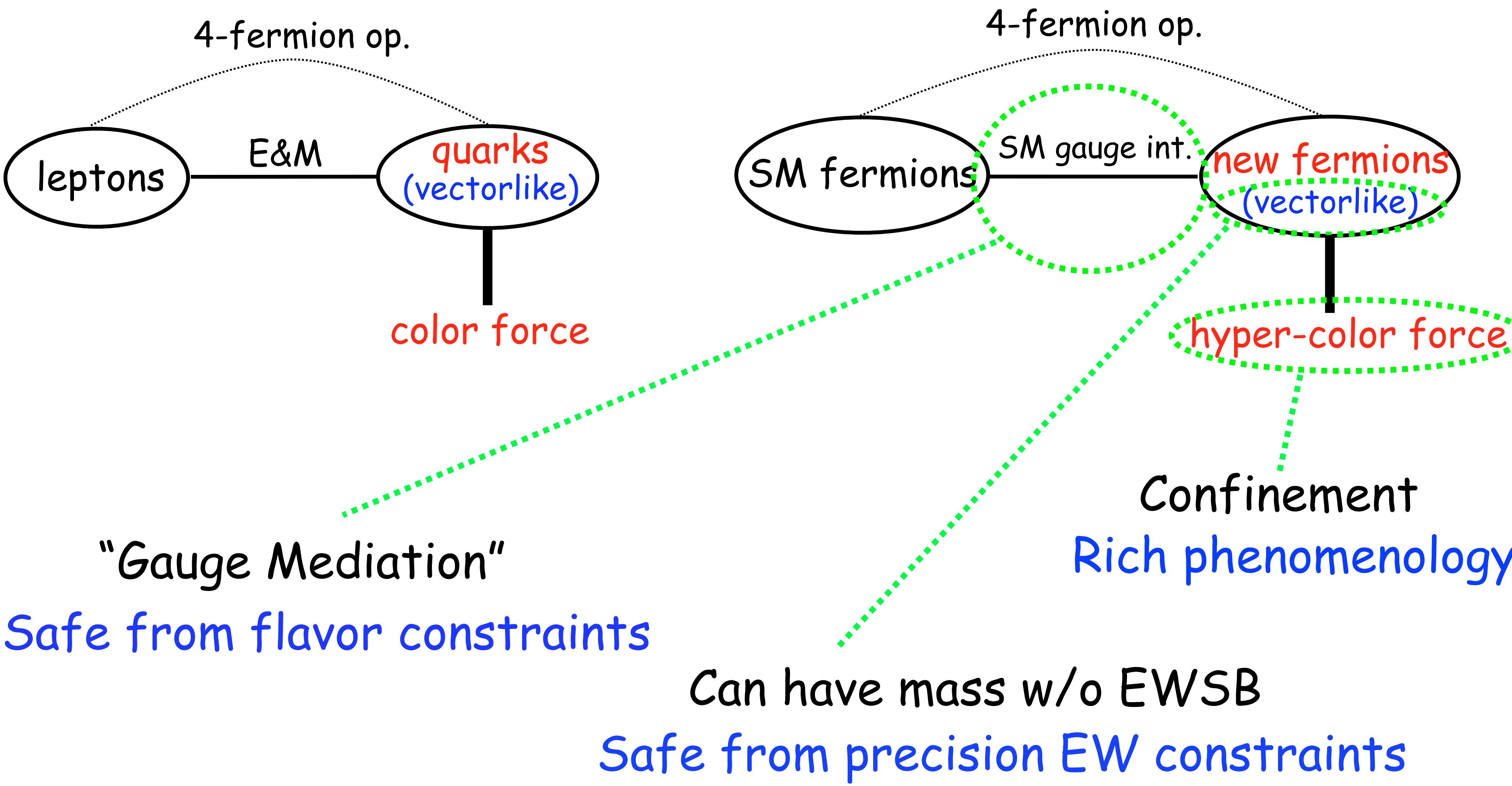

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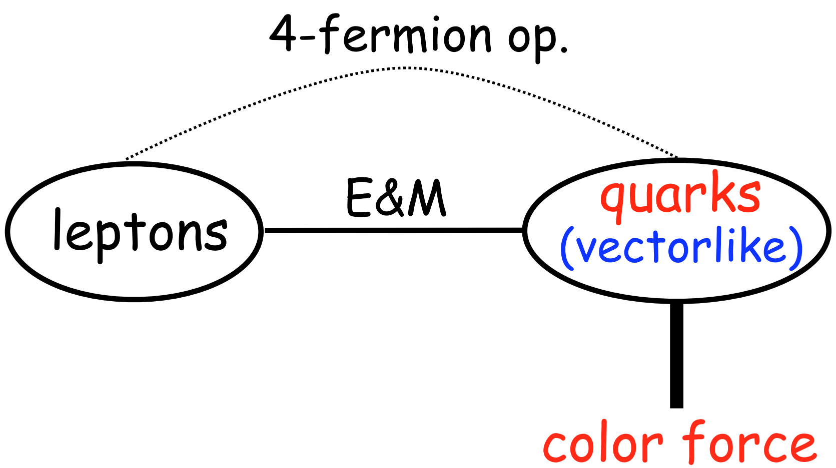
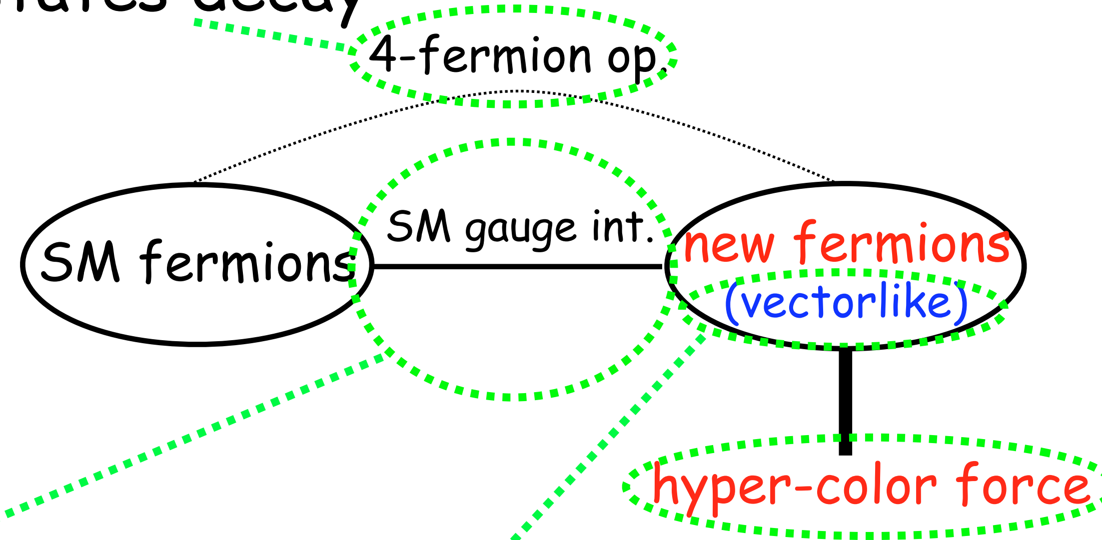


- Vectorlike Confinement at TeV -

Let stable bound states decay



Confinement

Rich phenomenology

"Gauge Mediation"

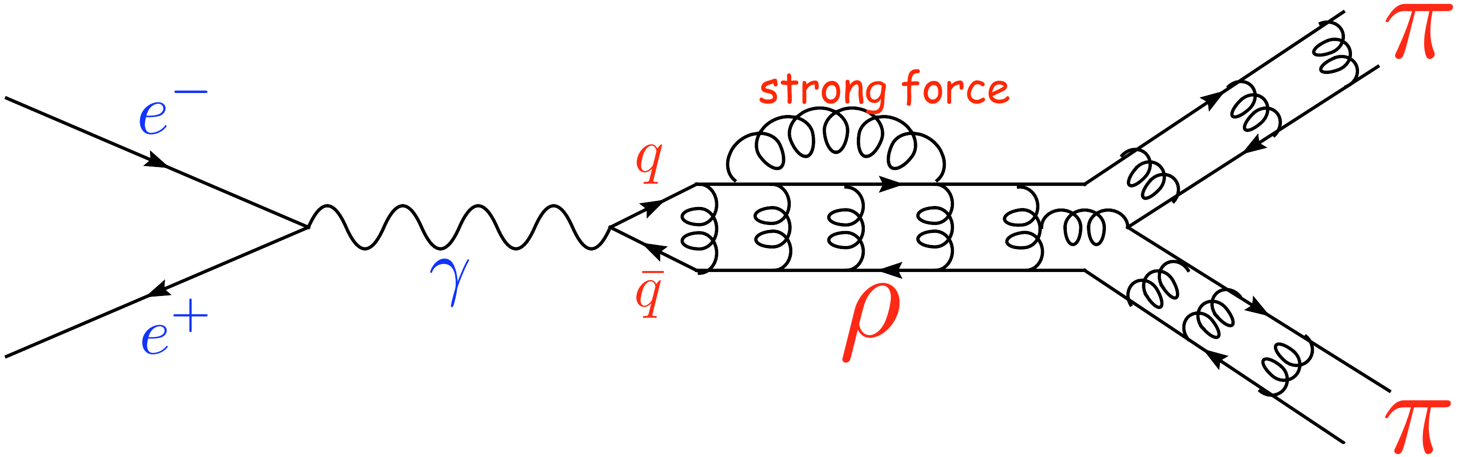
Safe from flavor constraints

Can have mass w/o EWSB

Safe from precision EW constraints

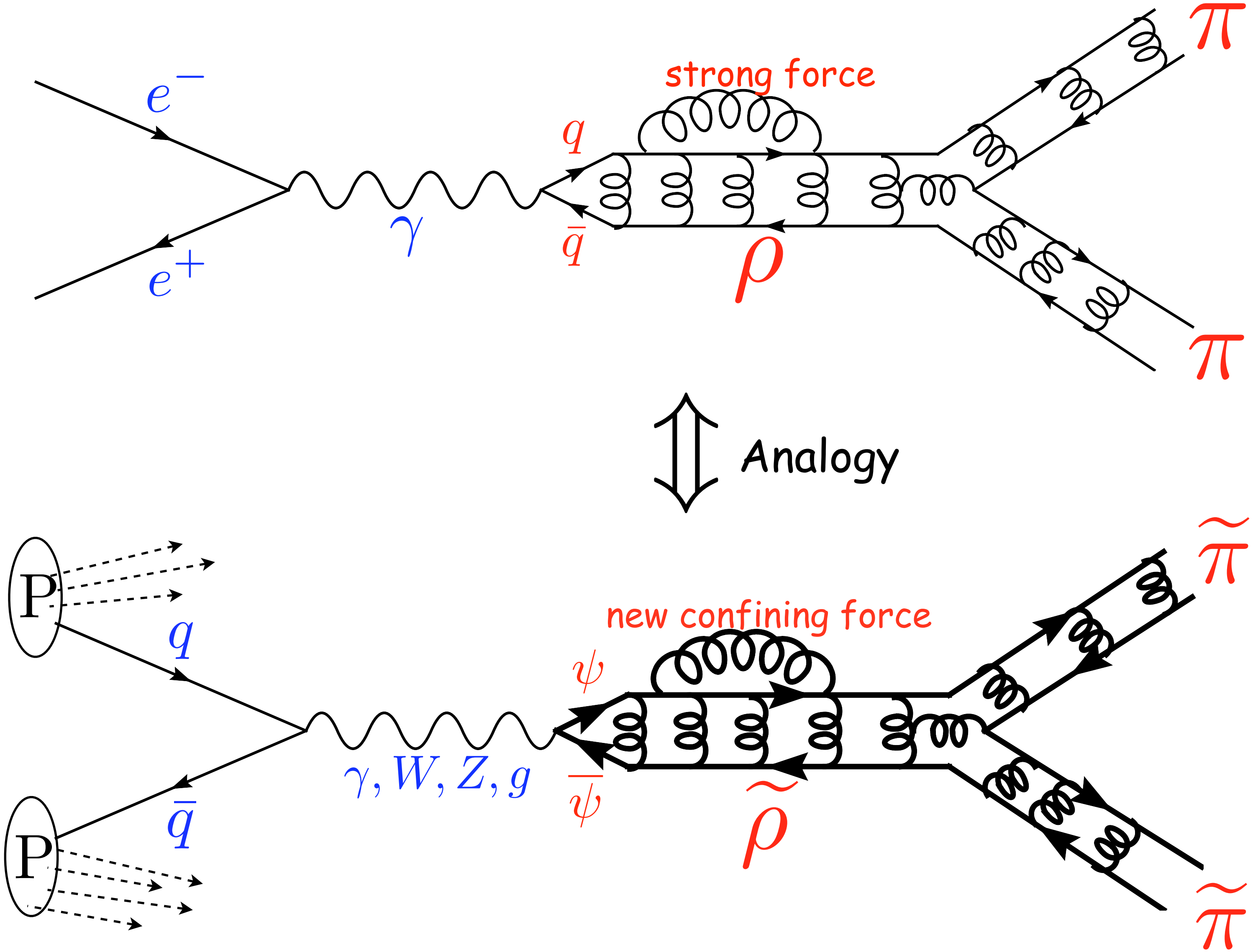
A very simple (yet pheno rich) possibility at TeV!

The Signature Process



$$\frac{\rho \to e^+e^-}{\rho \to \pi\pi} \sim 10^{-5}$$

The Signature Process



$$\frac{\rho \to e^+ e^-}{\rho \to \pi\pi} \sim 10^{-5}$$

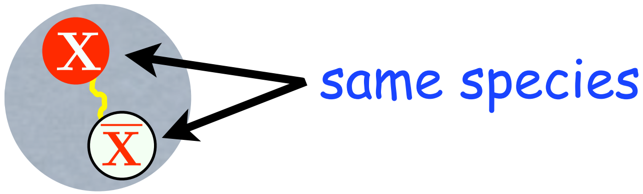
$$\simeq 100\ \%!$$

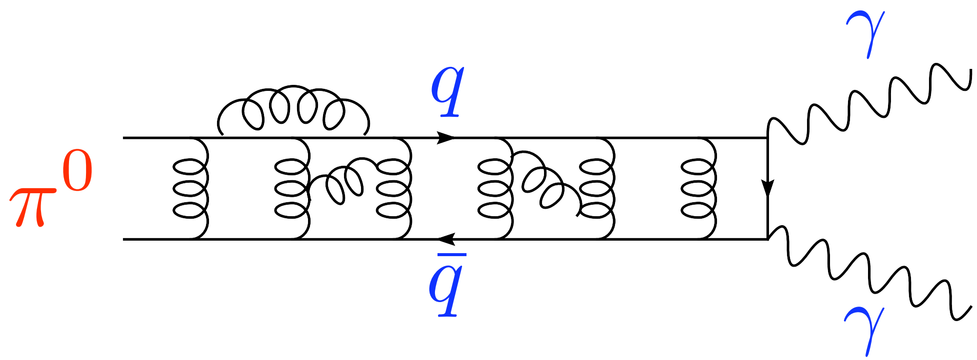
$$\mathrm{Br}(\rho \to f\bar{f}) < 1\%$$

How does $\tilde{\pi}$ decay?

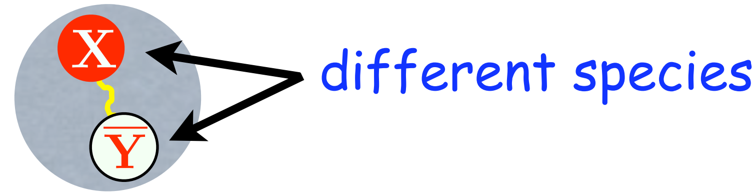
T. OKUI (FSU)

Two fates for $\tilde{\pi}$: Life can be short or long!





π^0 short-lived! $(c\tau \sim 10\,\mathrm{nm})$



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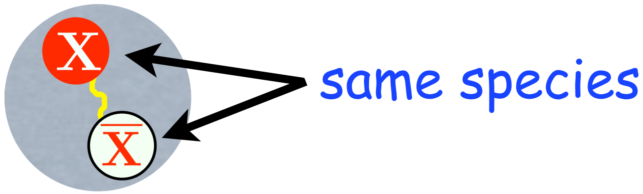

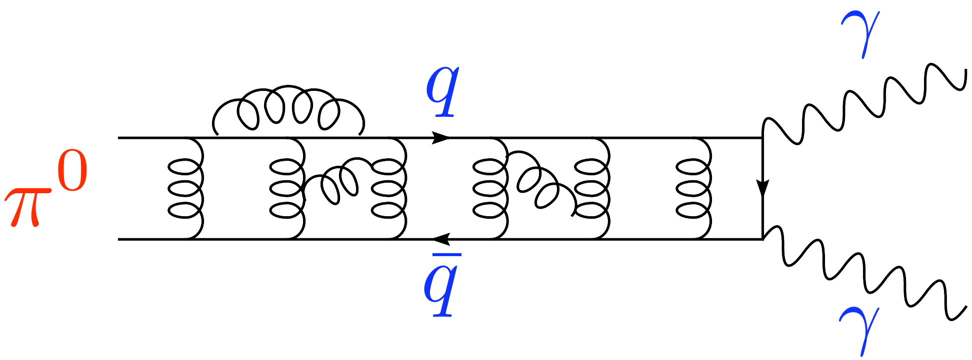

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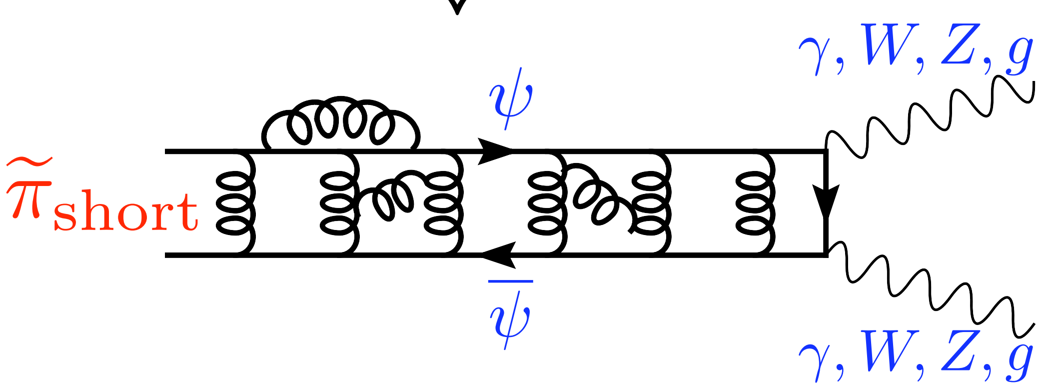
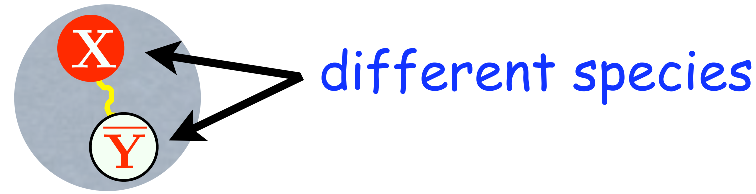
$\Updownarrow$ Analogy



Decays promptly!



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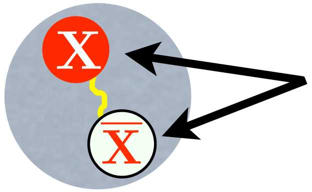
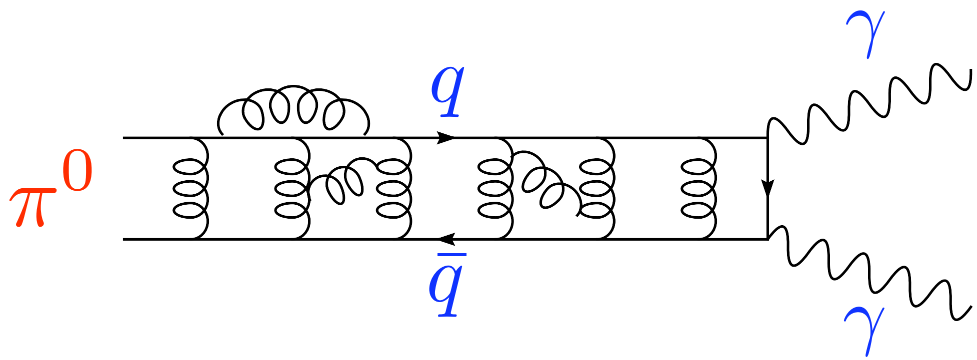


same species



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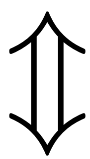
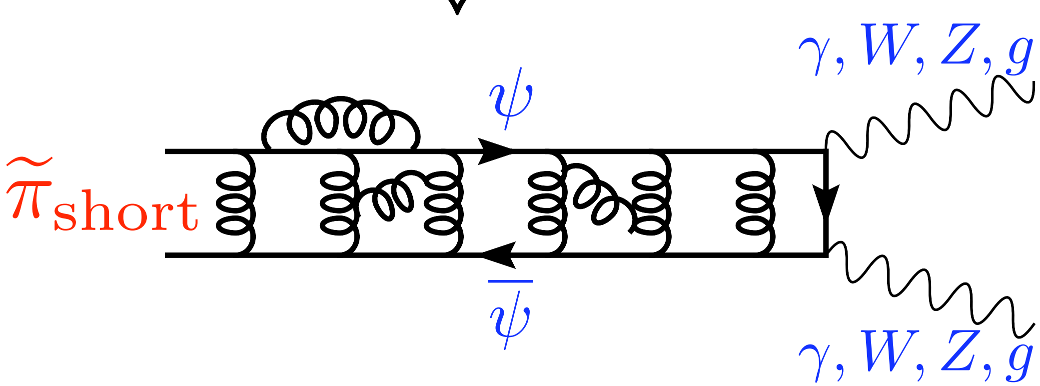


Analogy



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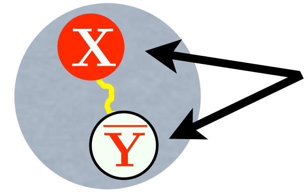
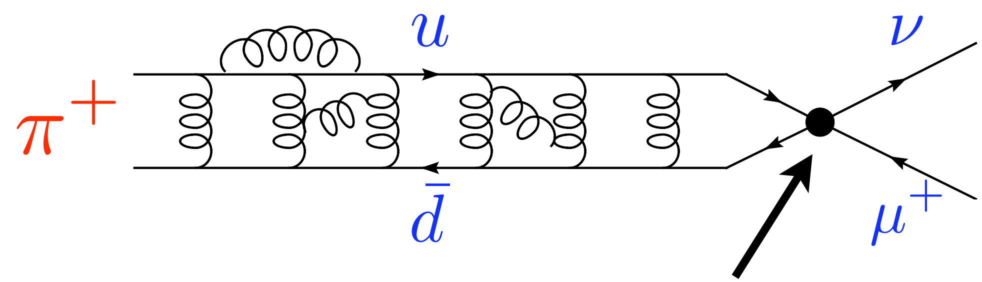


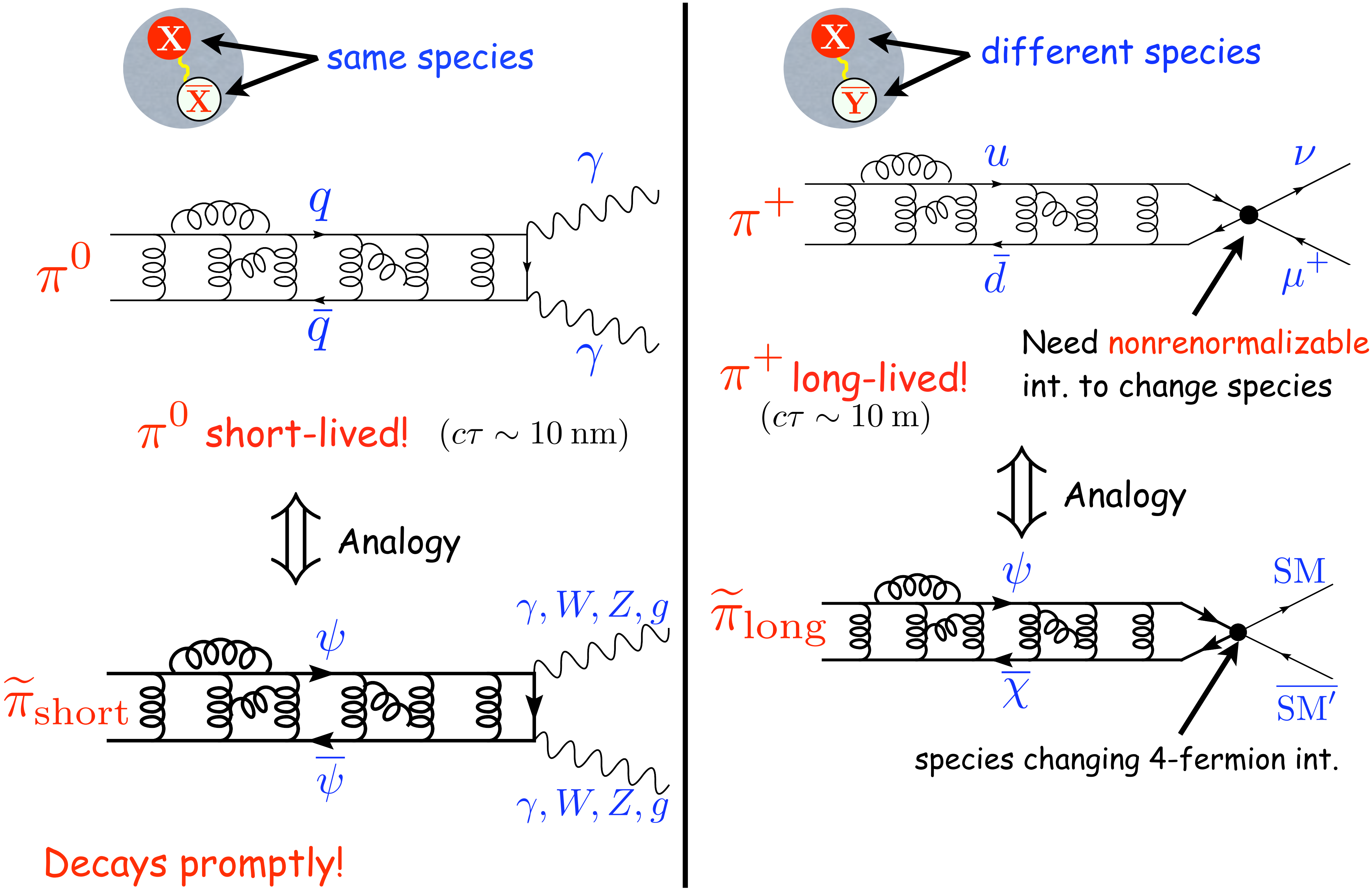
different species



Need nonrenormalizable int. to change species

π^+ long-lived! $(c\tau \sim 10\,\mathrm{m})$

Two fates for $\widetilde{\pi}$: Life can be short or long!



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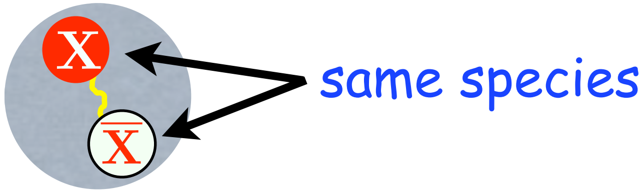

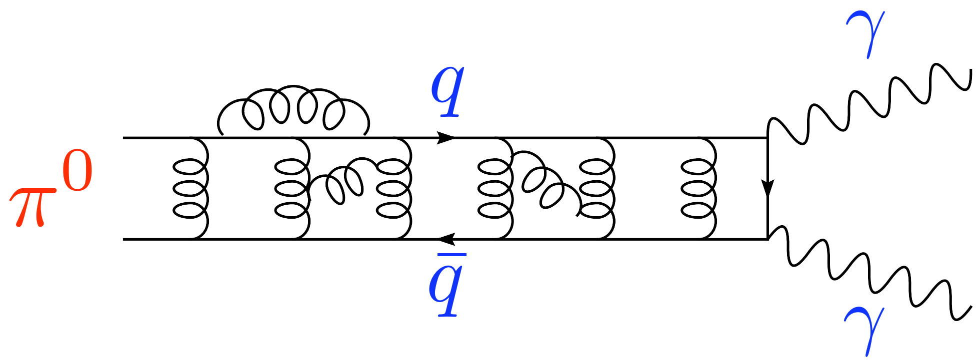

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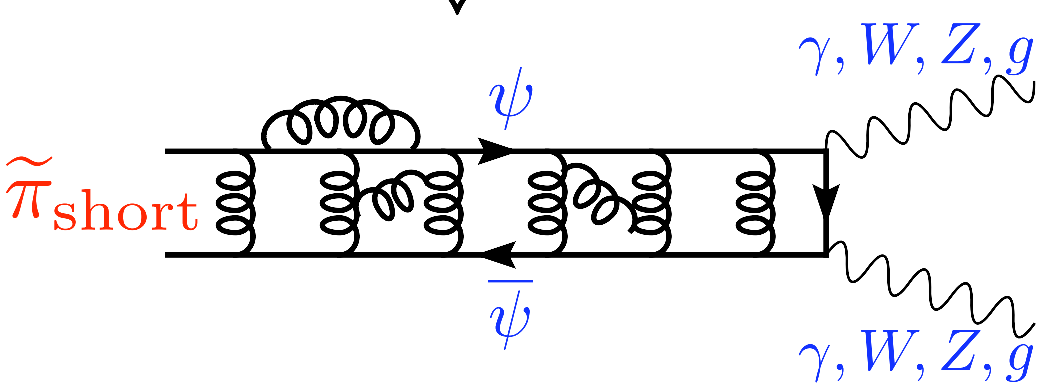

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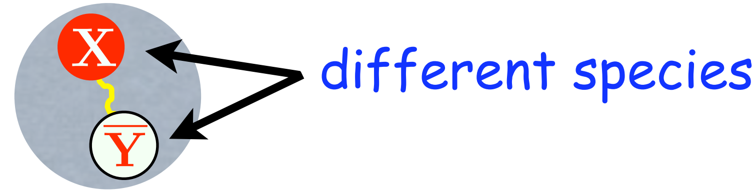

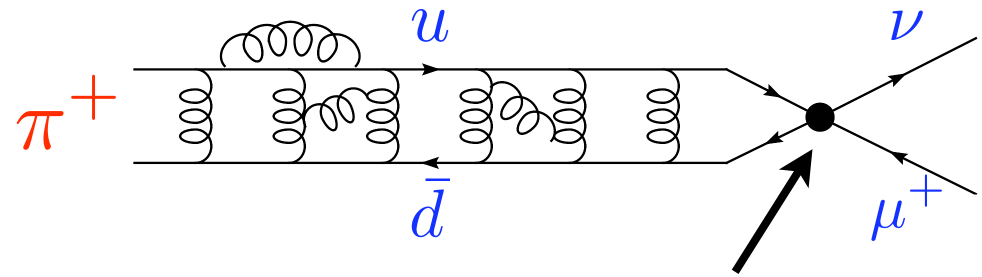

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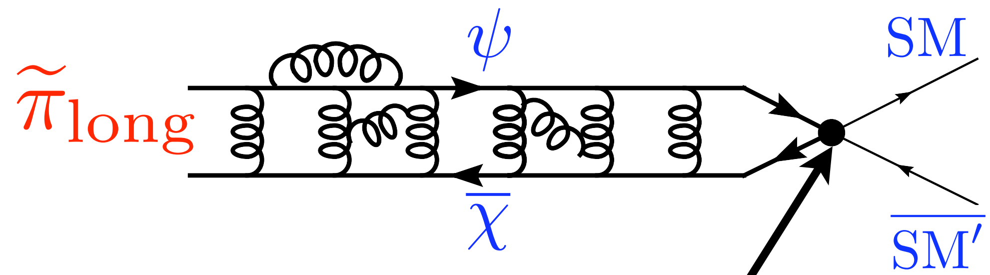


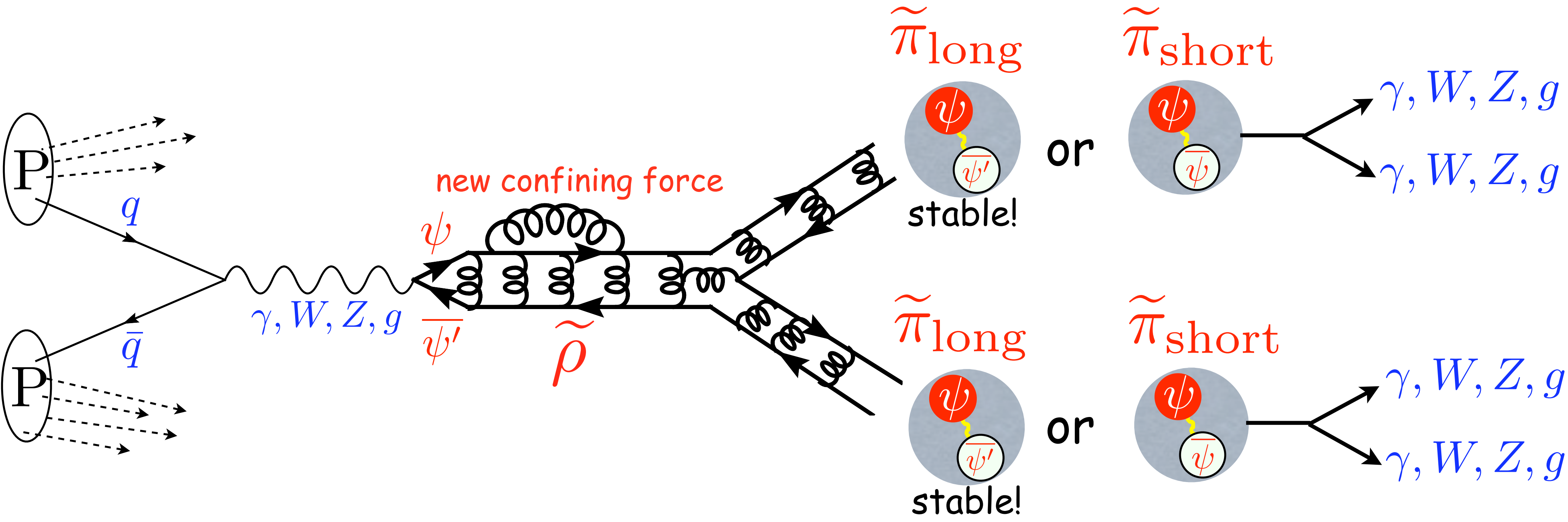
species changing 4-fermion int.

Absence of excessive flavor violations

$\Longrightarrow$ Stable on collider time scale!

T. OKUI (FSU)

Summary of Framework

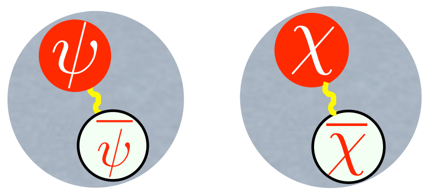


* Charged massive stable particles (CHAMPs)
* Colored massive stable particles (→ R-hadrons)
* Dark matter
* Multi-W, -Z, -photon productions
* Multi-jet productions
* (Displaced) leptoquarks, di-quarks, di-leptons

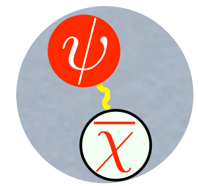
The Di-CHAMP Resonance Signal

The Di-CHAMP Resonance

2 species: ψ χ (Say, EW doublet and singlet w/o color)

$\widetilde{\pi}_{\rm short} =$ 

→ a pair of W, Z, γ

$\widetilde{\pi}_{\rm long} =$ 

Charged, massive & stable!

("CHAMP")

Existence very generic!

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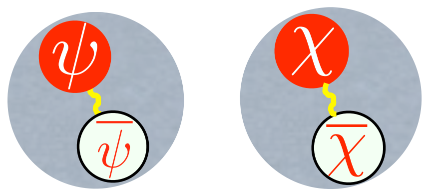
$\widetilde{\pi}_{\text{short}} =$ 

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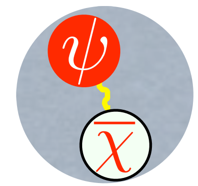
$\widetilde{\pi}_{\text{long}} =$ 

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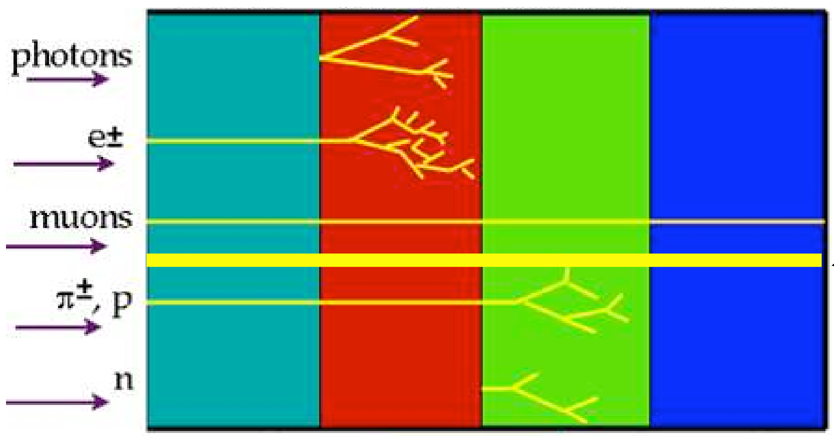
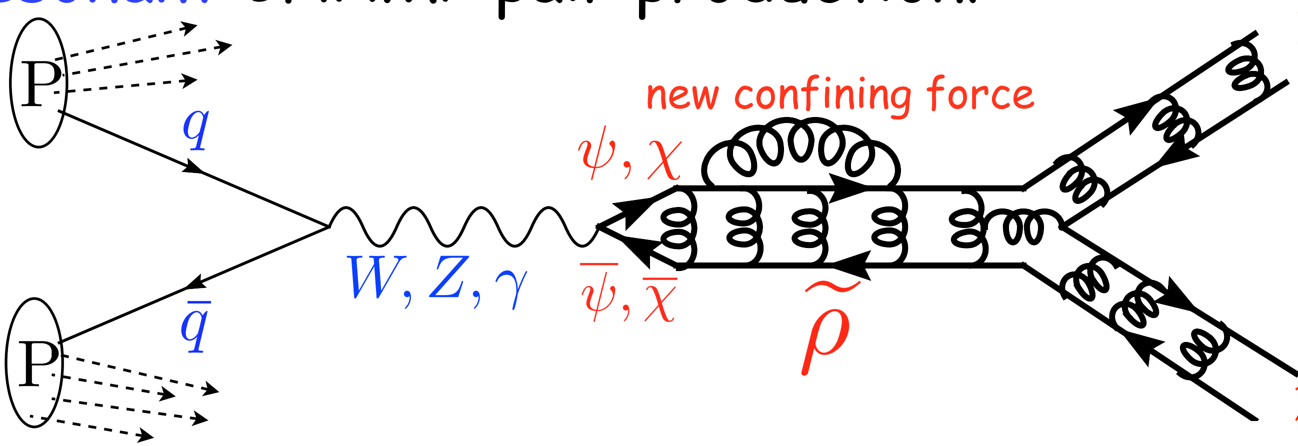


A CHAMP = a massive "muon"

Spectacular collider signal!

Resonant CHAMP pair production!

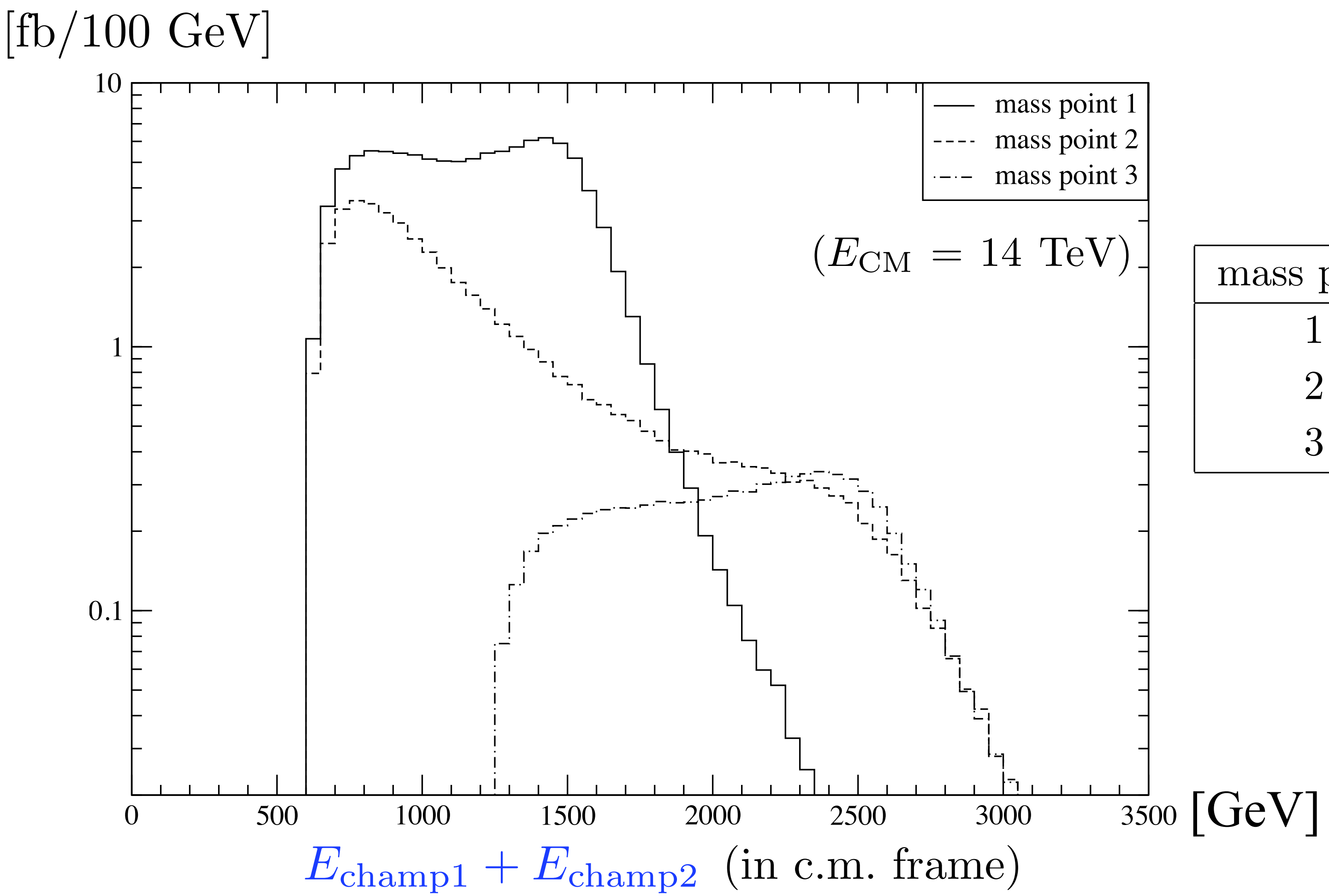


$\widetilde{\pi}_{\text{long}}$ CHAMP!

$\widetilde{\pi}_{\text{long}}$ CHAMP!

T. OKUI (FSU)

Can we see the parent $\tilde{\rho}$ resonance?



mass point	$m_{\tilde{\rho}}$ (TeV)	$m_{\tilde{\pi}}$ (GeV)
1	1.5	300
2	2.5	300
3	2.5	600

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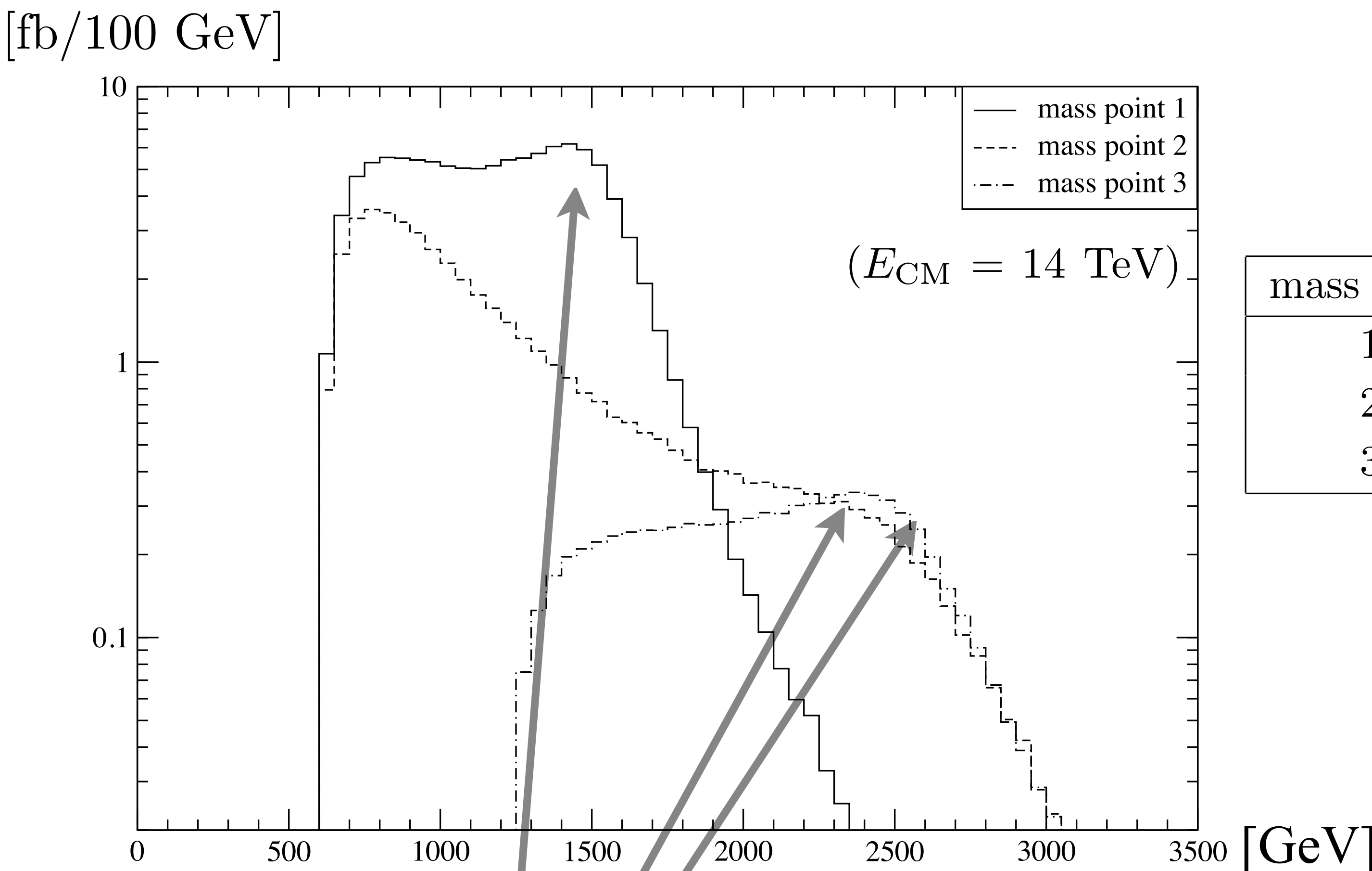

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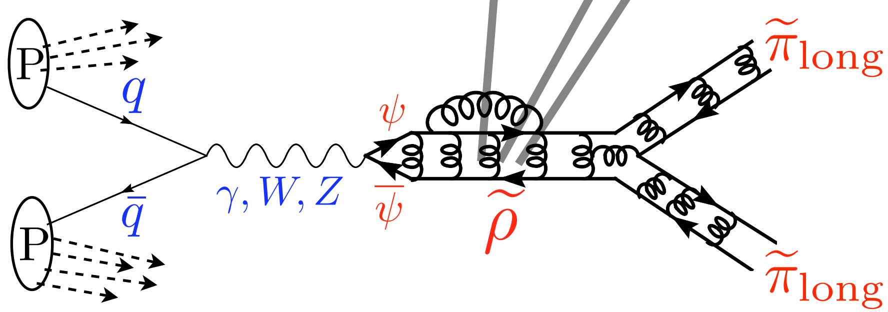

"Di-CHAMP" resonance!

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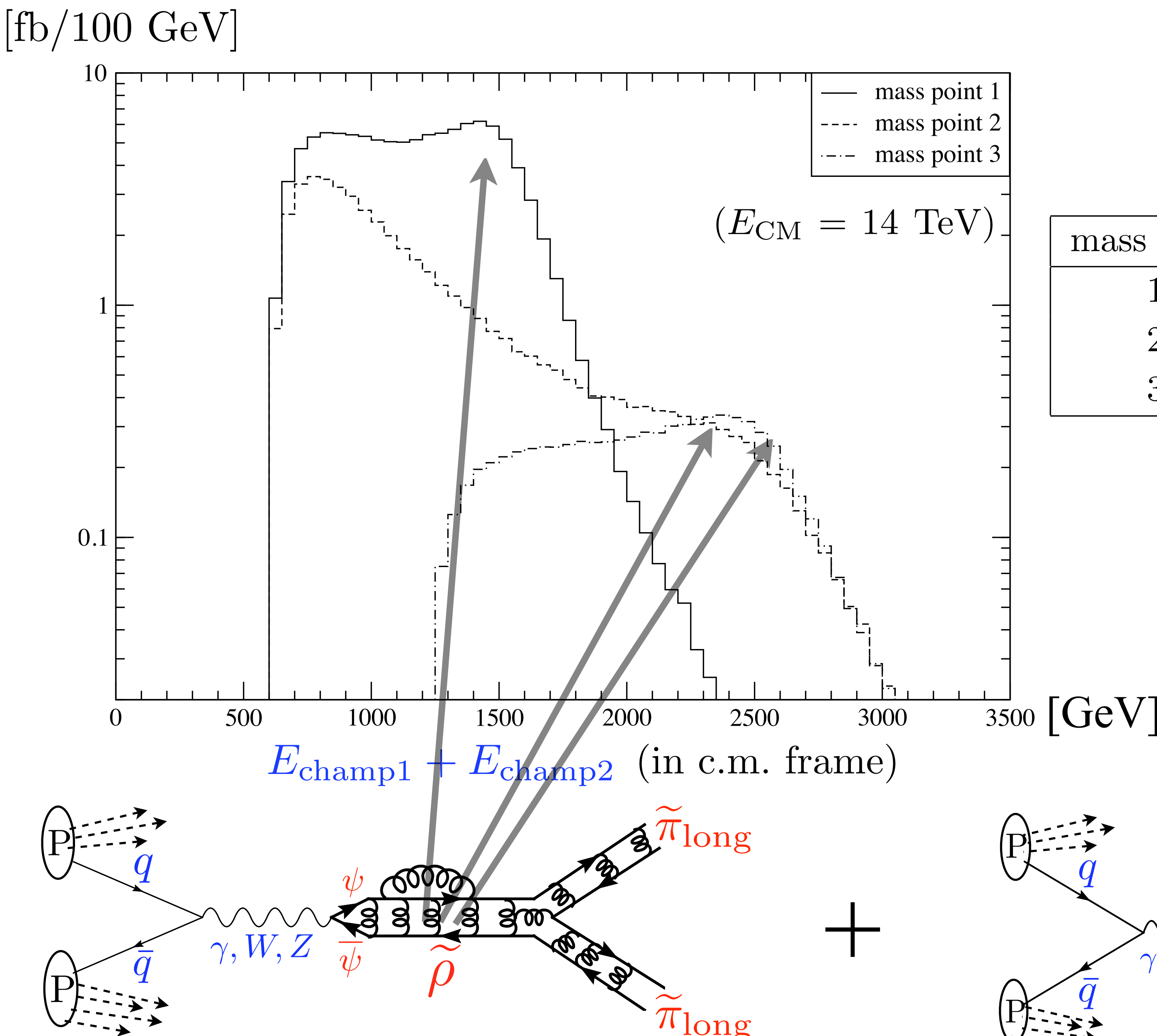

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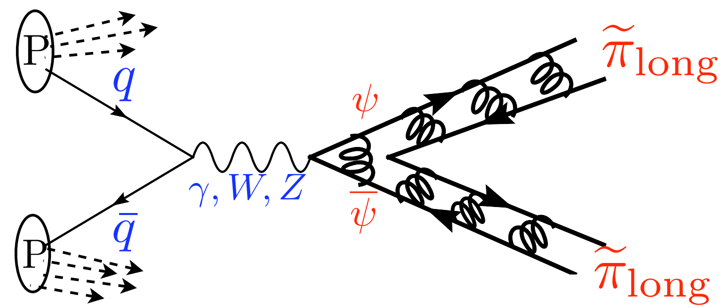
+



"Di-CHAMP" resonance!

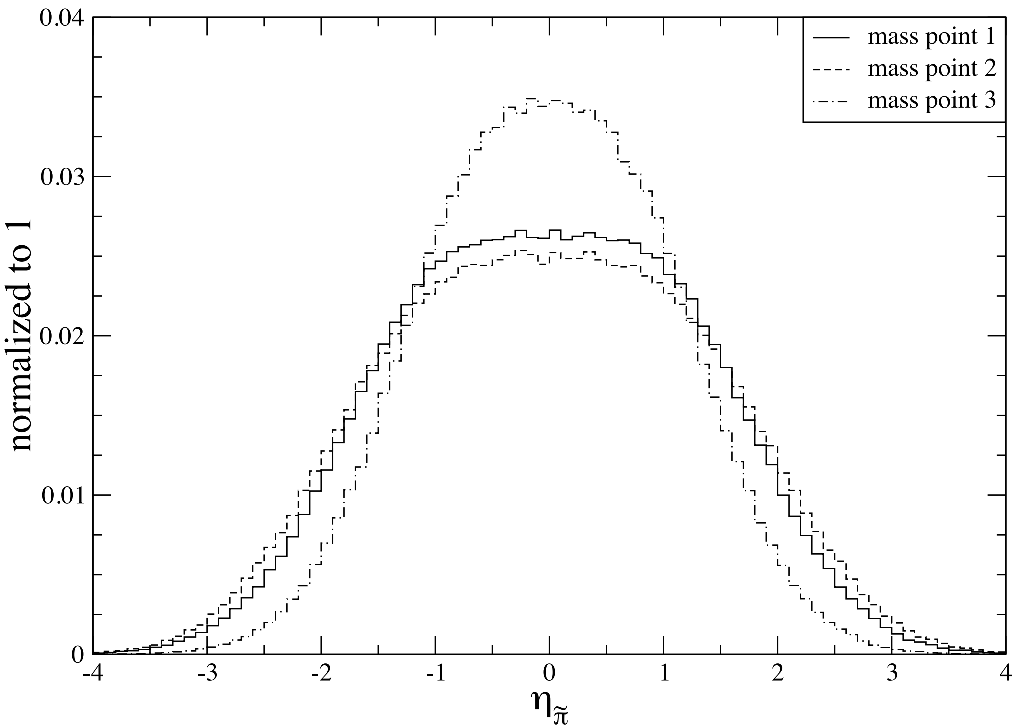
"Drell-Yan" CHAMP production

T. OKUI (FSU)

Can we trigger on the CHAMPs?

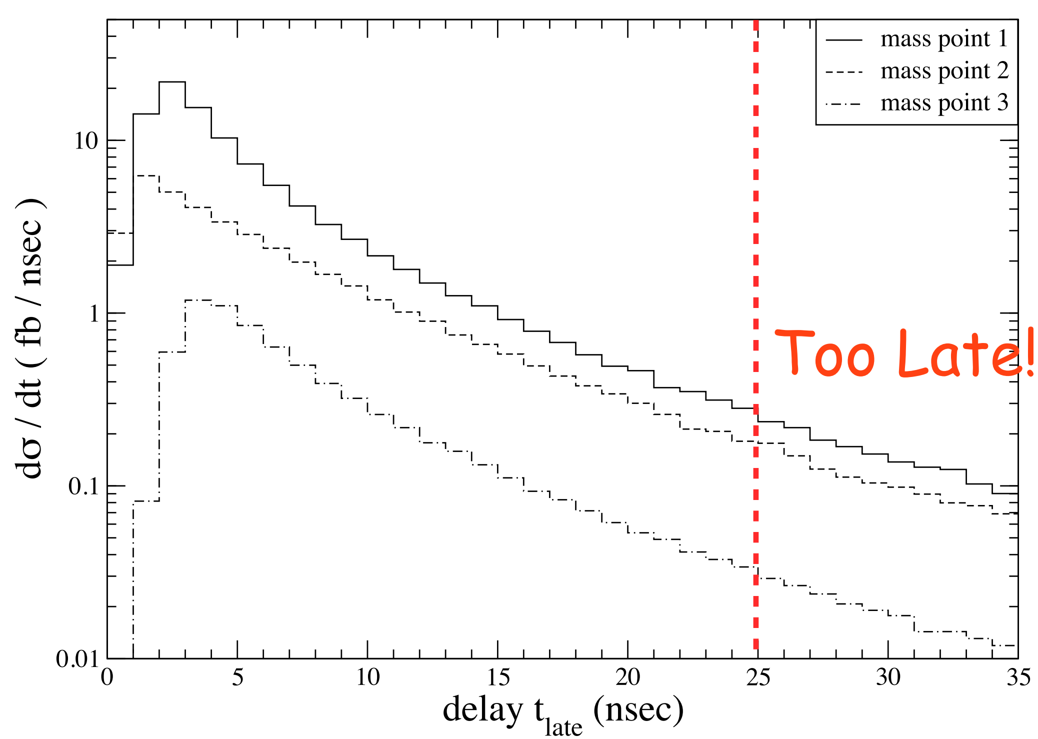
mass point	$m_{\tilde{\rho}}$ (TeV)	$m_{\tilde{\pi}}$ (GeV)
1	1.5	300
2	2.5	300
3	2.5	600

CHAMP pseudo-rapidity



Most events central

"Time lag" at muon chamber



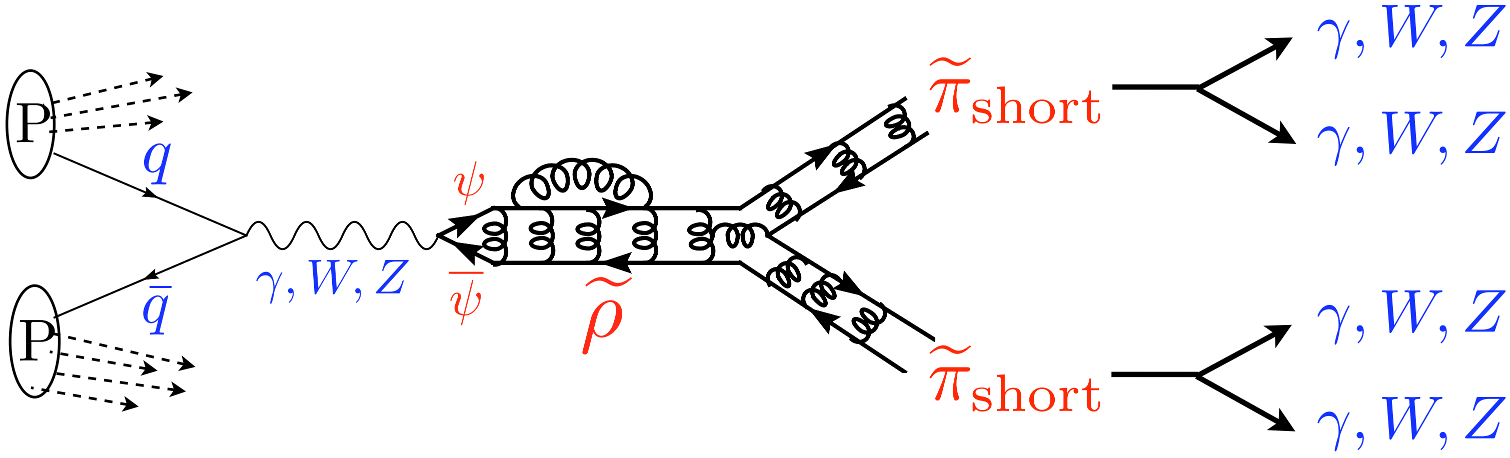
Most CHAMPs arrive in time

Trigger efficiency very high!

T. OKUI (FSU)

The Multi-photon Resonance Signal

Look at $\widetilde{\pi}_{\rm short}$ of the same model.



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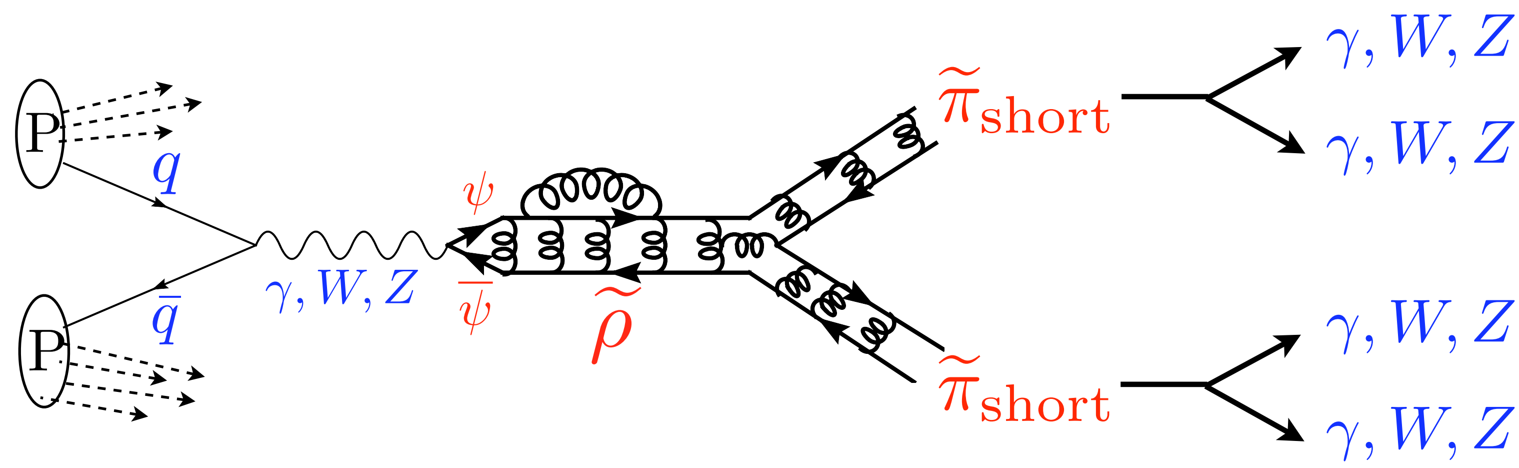
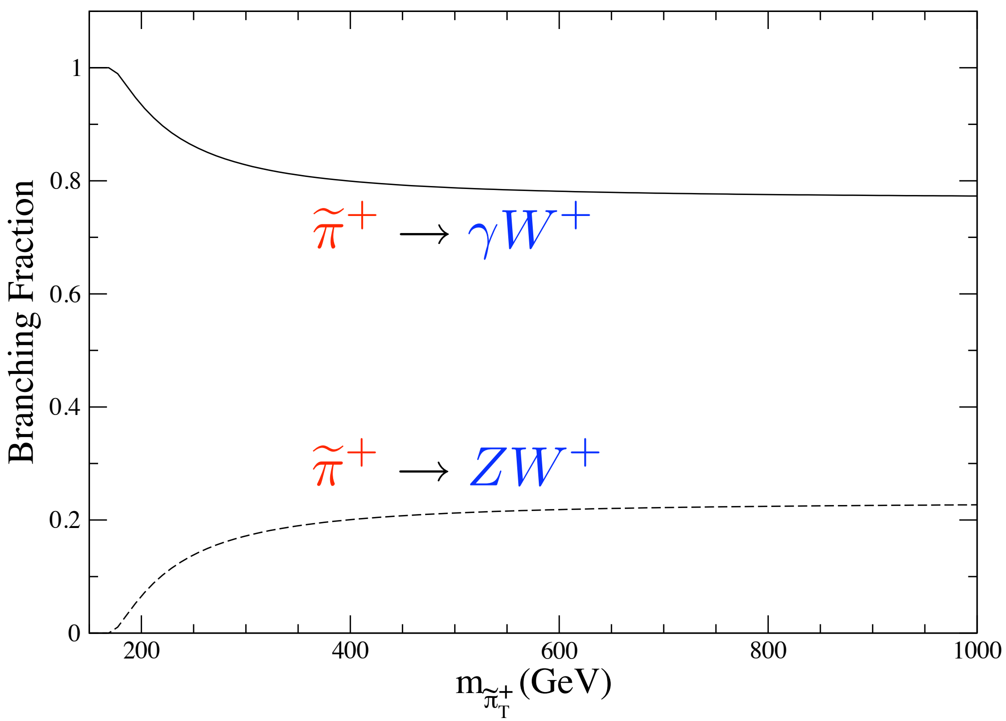
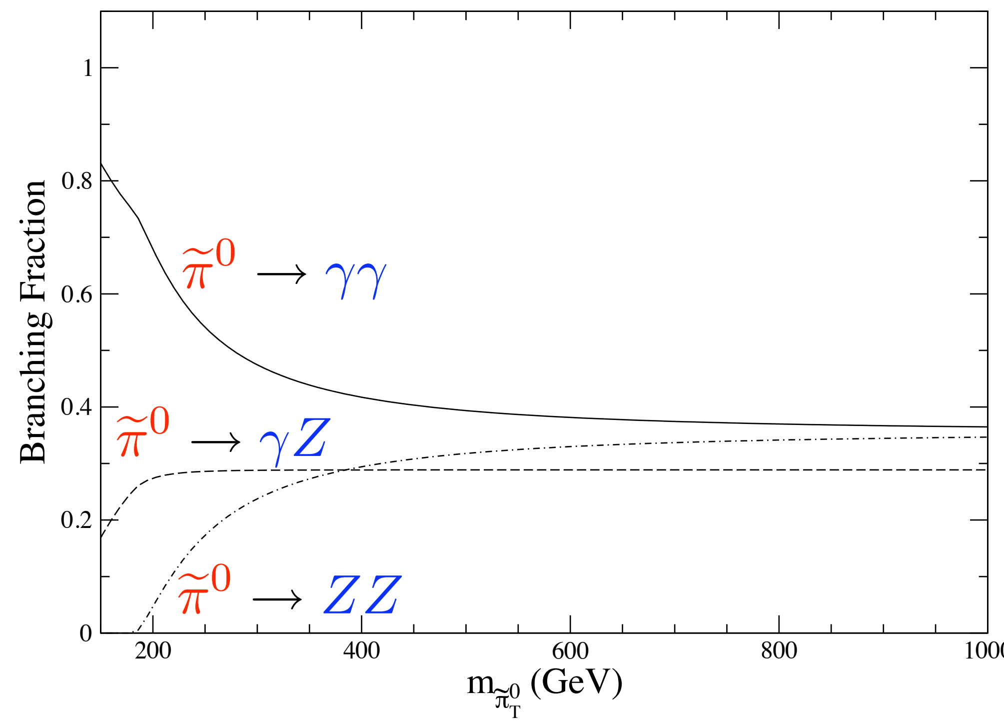
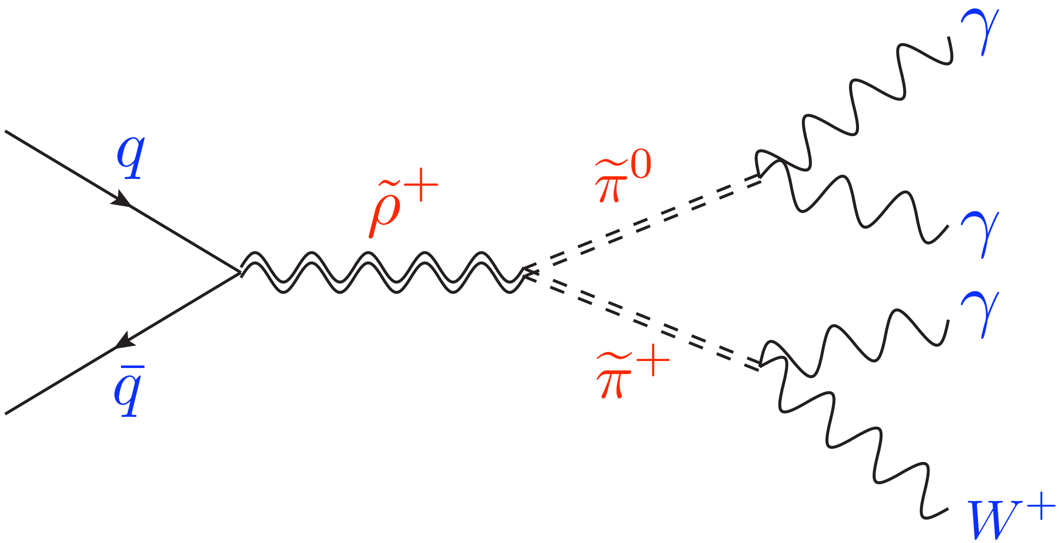






Lots of photons!

Can we reconstruct $\tilde{\rho}$ and $\widetilde{\pi}$?



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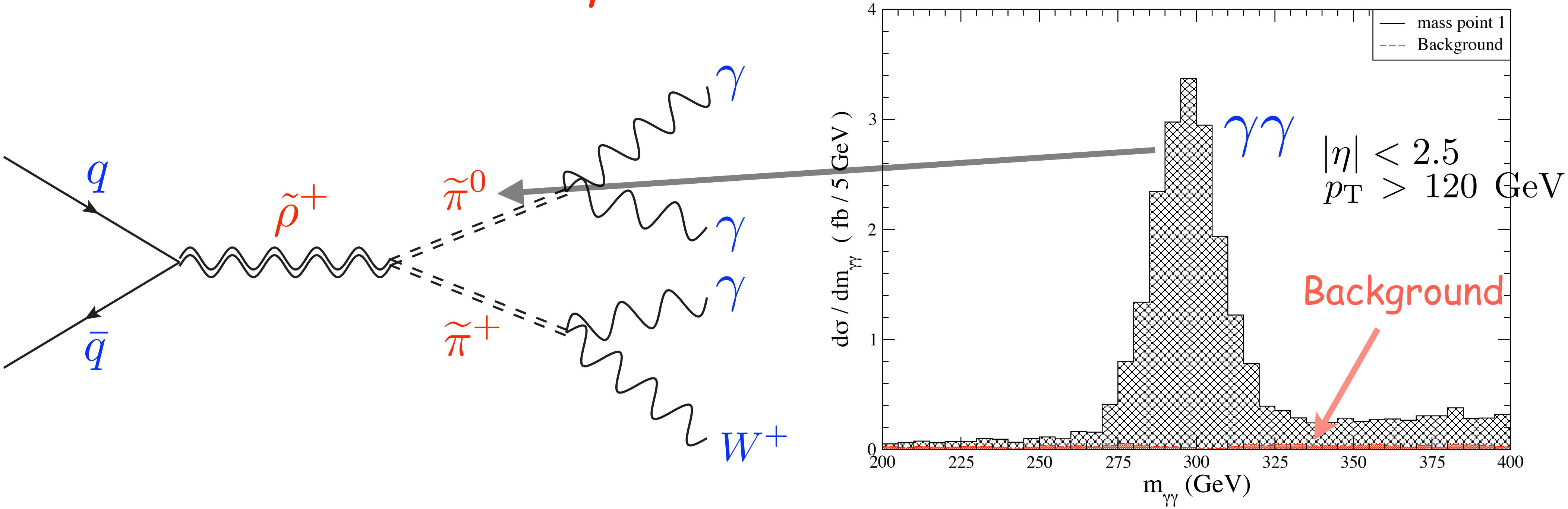

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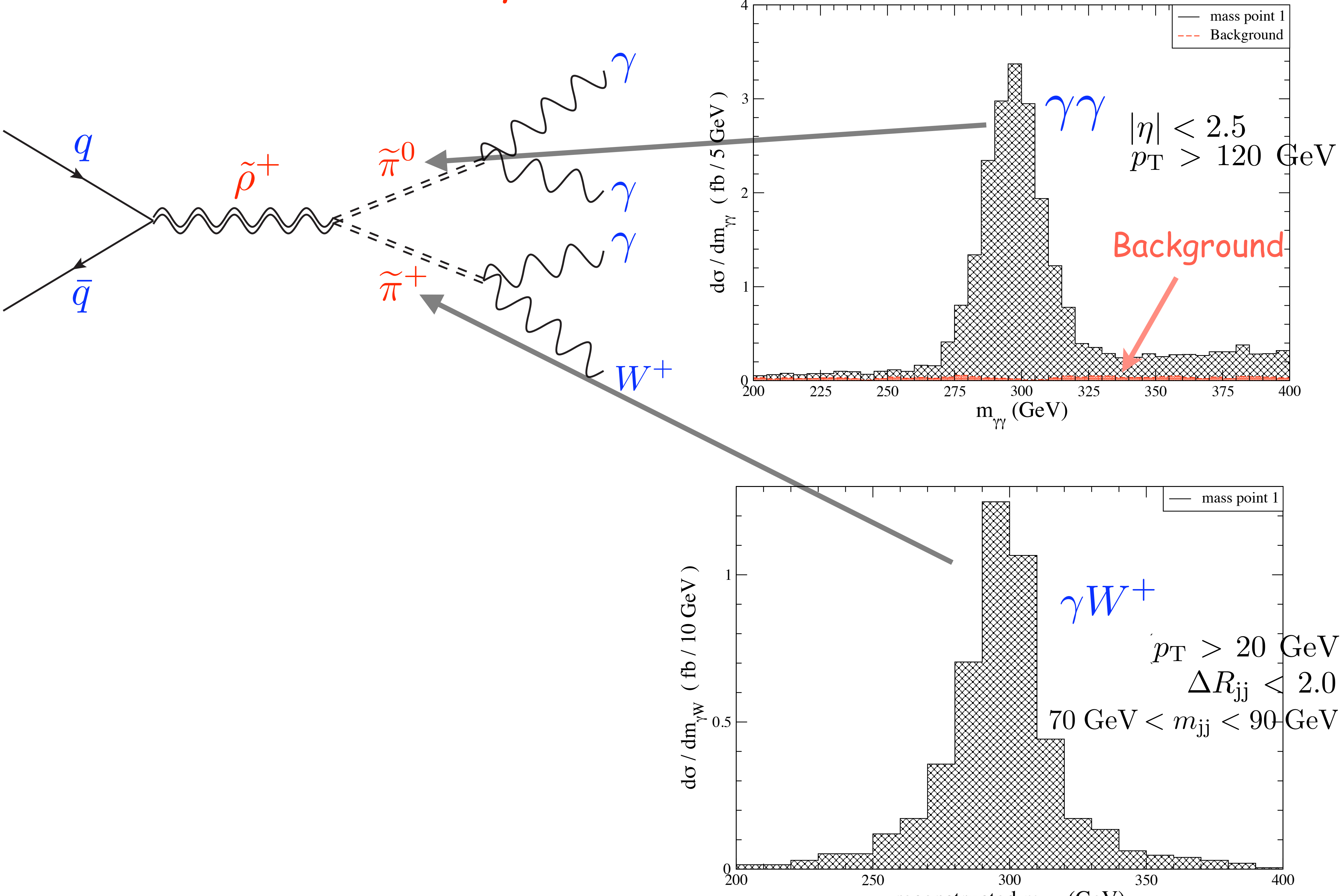

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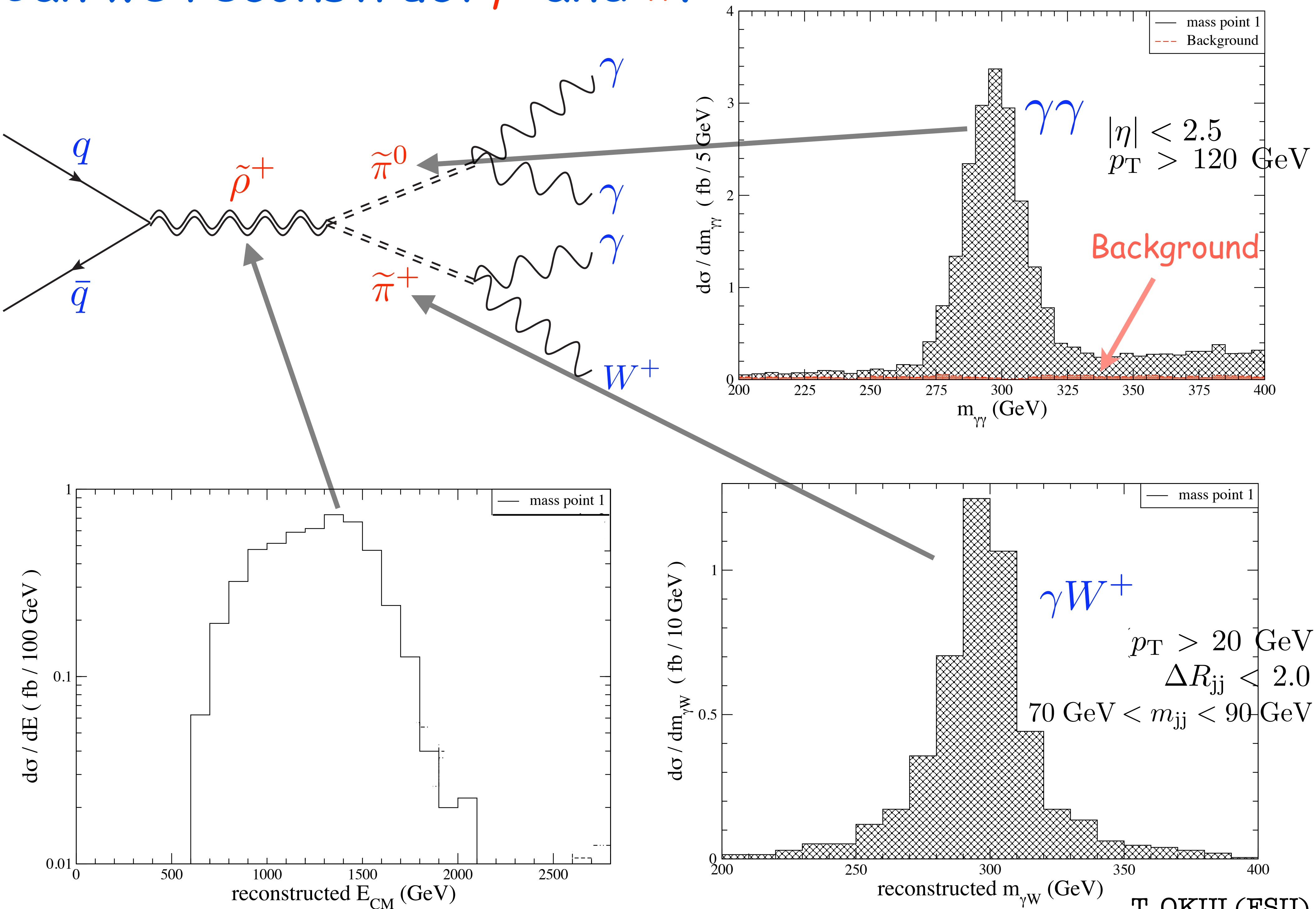
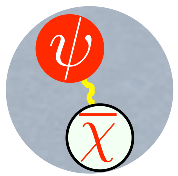


T. OKUI (FSU)

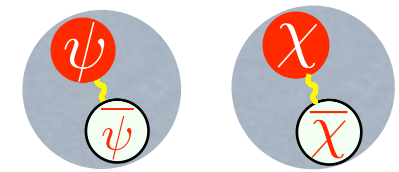
The Di- and Tetra-R-hadron Signals

The Di- and Tetra-R-hadrons

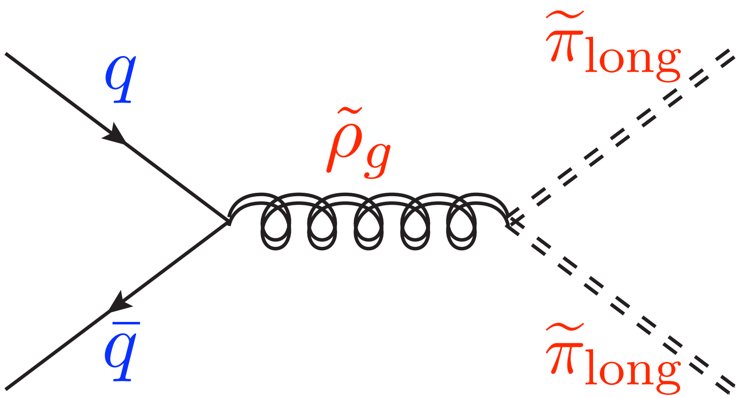
2 species: ψ χ (Say, color triplet and singlet w/ hypercharge)

$\widetilde{\pi}_{\rm long} =$ 

Colored, massive & stable!
(→"R hadron")

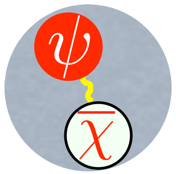
$\widetilde{\pi}_{\rm short} =$ 

$\longrightarrow gg\ (\simeq 99\%)\,,\, g\gamma\,,\, gZ$



The Di- and Tetra-R-hadrons

2 species: ψ χ (Say, color triplet and singlet w/ hypercharge)

$\widetilde{\pi}_{\rm long} =$ 

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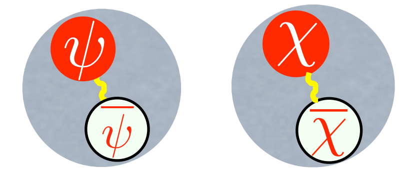
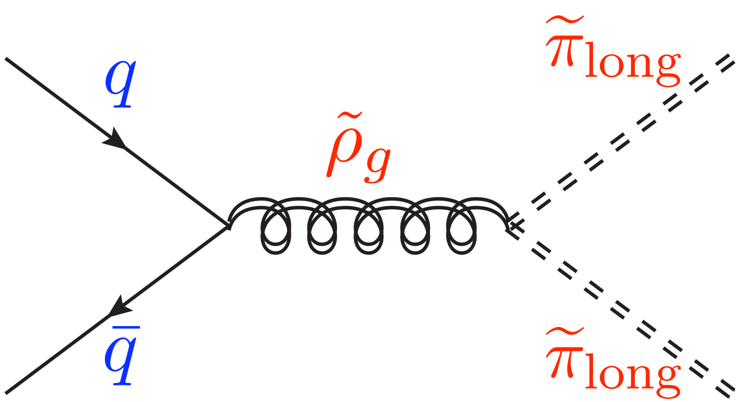
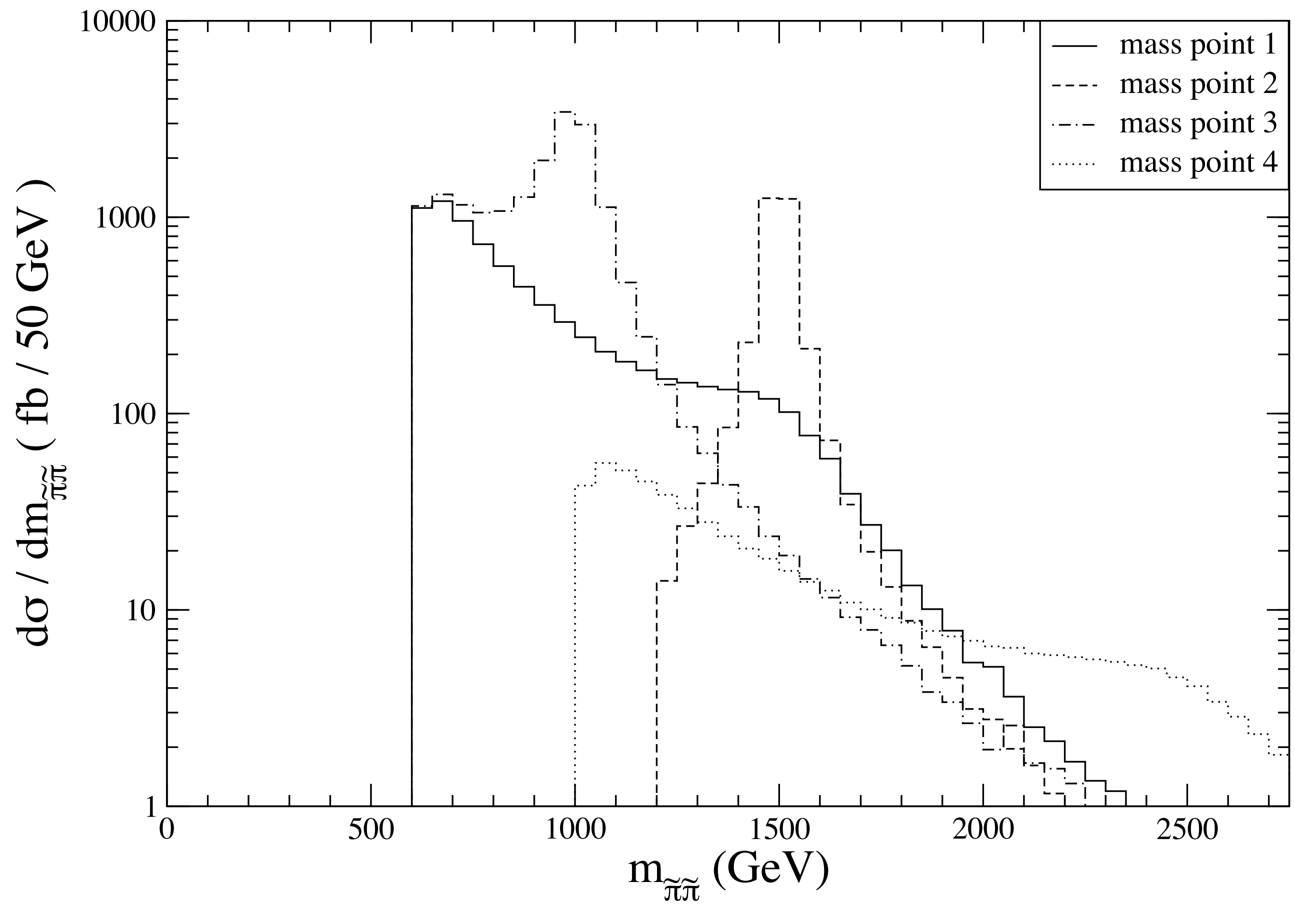
$\widetilde{\pi}_{\rm short} =$ 

$\longrightarrow gg\ (\simeq 99\%)\,,\, g\gamma\,,\, gZ$



mass point	$m_{\tilde{\rho}}$ (TeV)	$m_{\tilde{\pi}}$ (GeV)
1	1.5	300
2	1.5	600
3	1.0	300
4	2.5	500

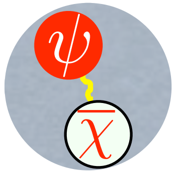


Di-R-hadron rate >> Di-CHAMP rate!

T. OKUI (FSU)

The Di- and Tetra-R-hadrons

2 species: ψ χ (Say, color triplet and singlet w/ hypercharge)

$\widetilde{\pi}_{\rm long} =$  Colored, massive & stable!

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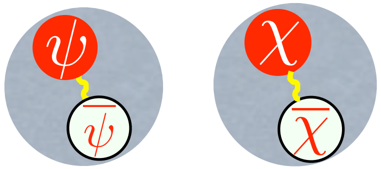
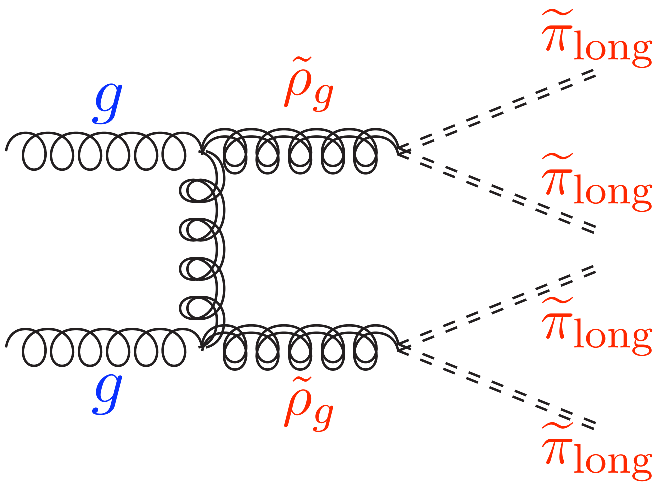
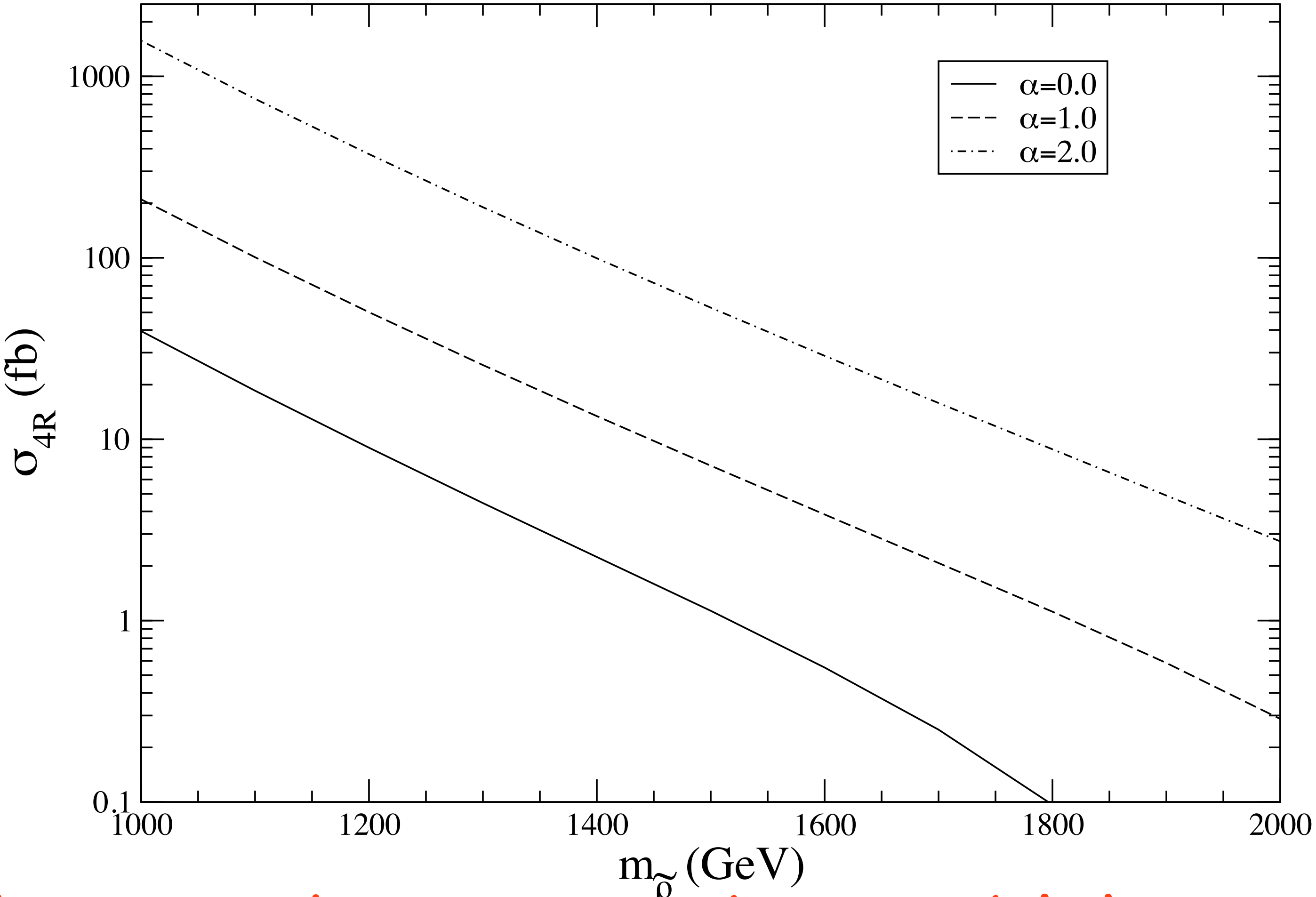
$\widetilde{\pi}_{\rm short} =$ 

$\longrightarrow gg\ (\simeq 99\%)\,,\, g\gamma\,,\, gZ$





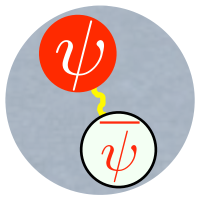
Even FOUR R-hadron production can be sizable!

T. OKUI (FSU)

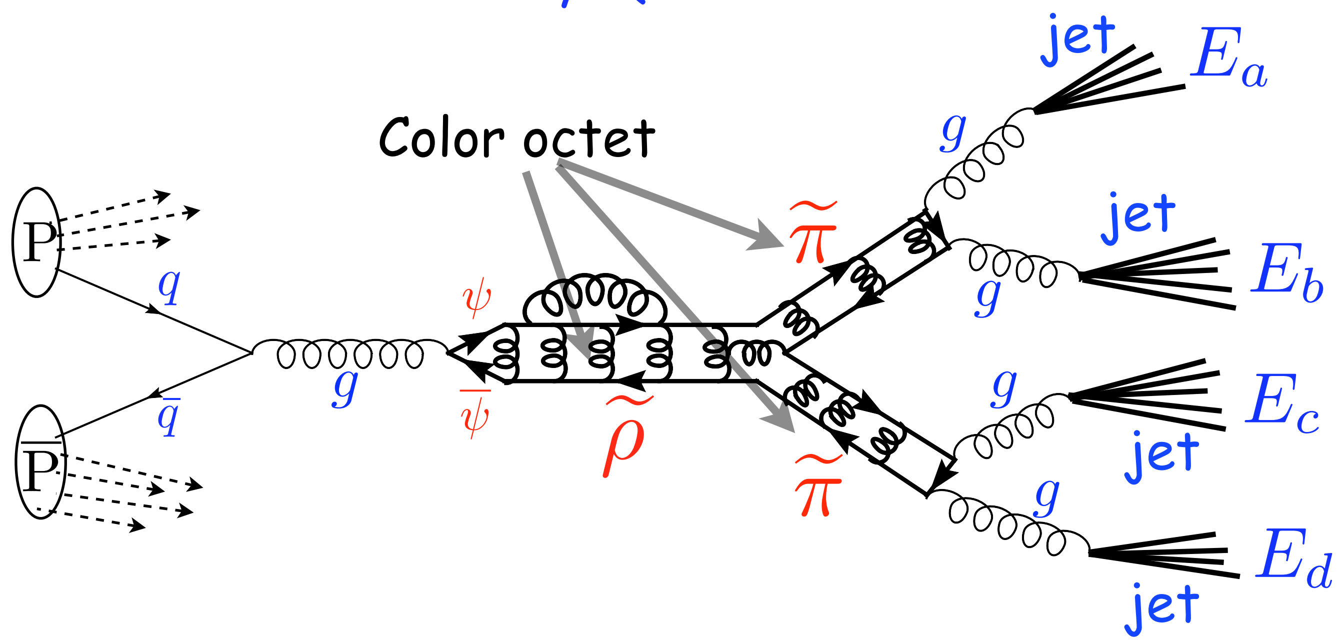
The Multi-jet Resonance Signal at the Tevatron

Multijet Resonances at Tevatron

Only one species: ψ w/ no electroweak int. Only QCD int.

$\widetilde{\pi}_{\rm short} =$ 

No $\widetilde{\pi}_{\rm long}$



Multijet Resonances at Tevatron

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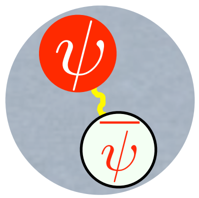
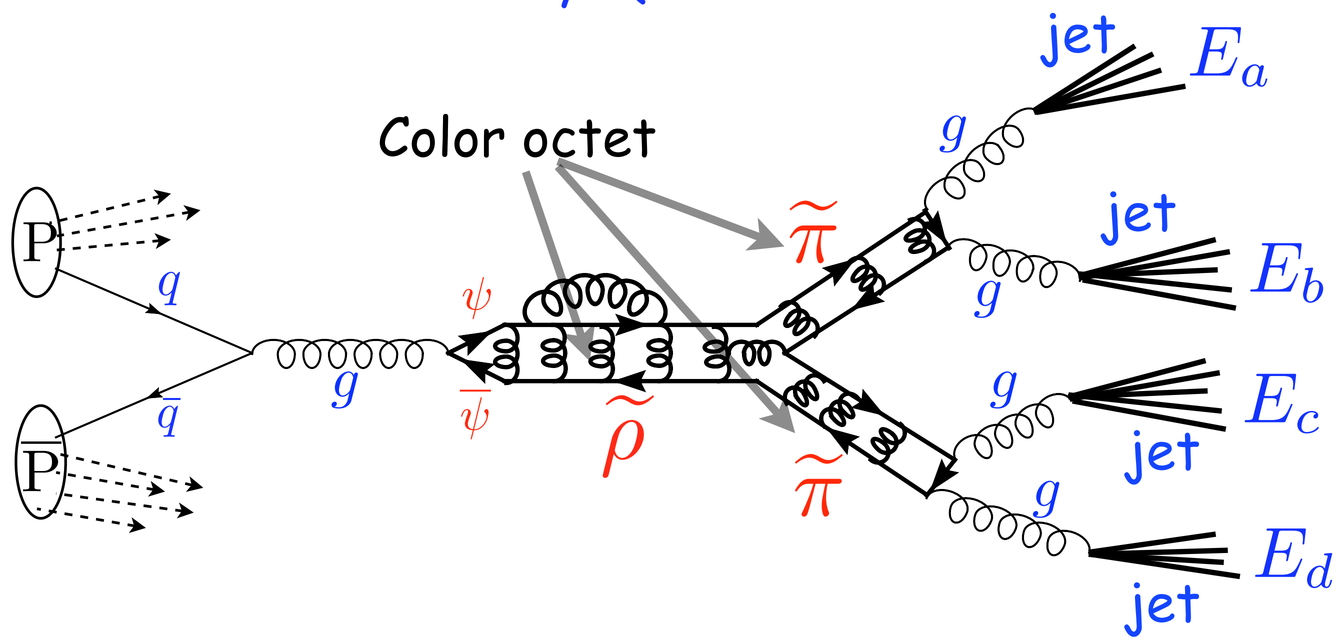
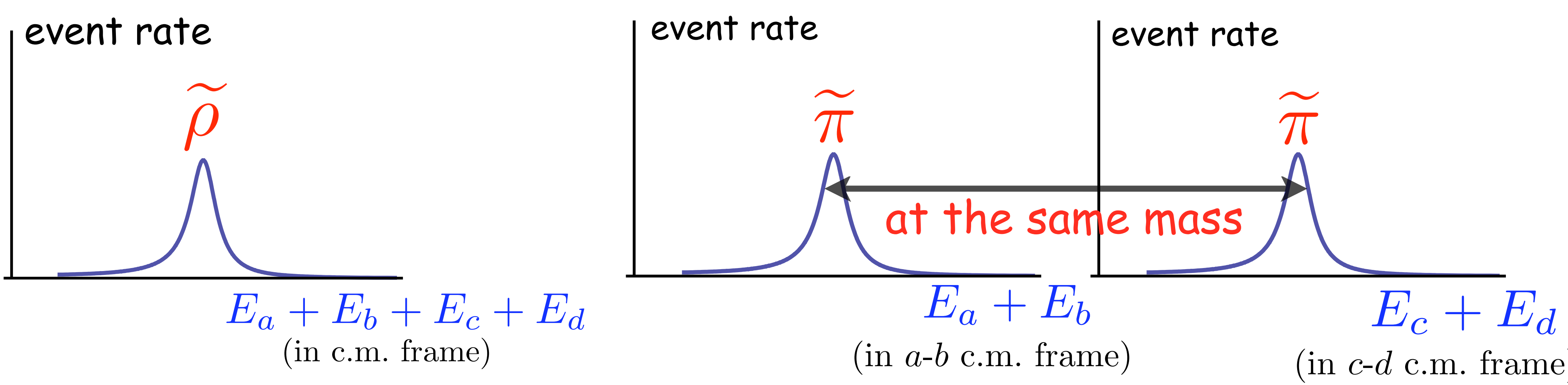
$\widetilde{\pi}_{\text{short}} =$ 

No $\widetilde{\pi}_{\text{long}}$



Kinematical features:



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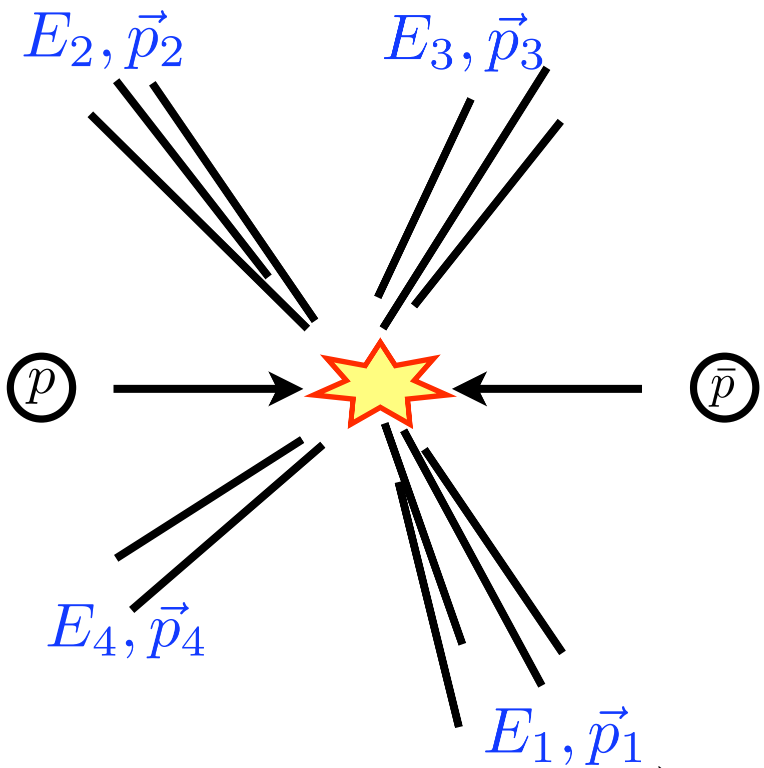
Observables and Cuts for the Tevatron Multijet Model



$(p_{\rm T1} > p_{\rm T2} > p_{\rm T3} > p_{\rm T4})$

$(p_{\rm T} \equiv |\vec{p}_{\perp\,\rm beam}|)$

(1) To pick out the $\widetilde{\rho}$

$$m_{\rm 4j} \equiv E_1 + E_2 + E_3 + E_4 \quad \text{(in c.m. frame)}$$

(2) To pick out the two $\widetilde{\pi}$'s

(i) choose 2 pairs ij and kl

(ii) calculate

$$m_{ij} \equiv E_i + E_j \quad \text{(in } i\text{-}j \text{ c.m. frame)}$$

and similarly m_{kl}

(iii) minimize $\Delta m \equiv |m_{ij} - m_{kl}|$

(iv) keep event **only if**

$$\Delta m < 25 \text{ GeV}$$

(v) take average

$$\langle m_{\rm 2j} \rangle \equiv (m_{ij} + m_{kl})\,/2$$

(3) Signal: $p_{\rm T1} \sim p_{\rm T2} \sim p_{\rm T3} \sim p_{\rm T4}$

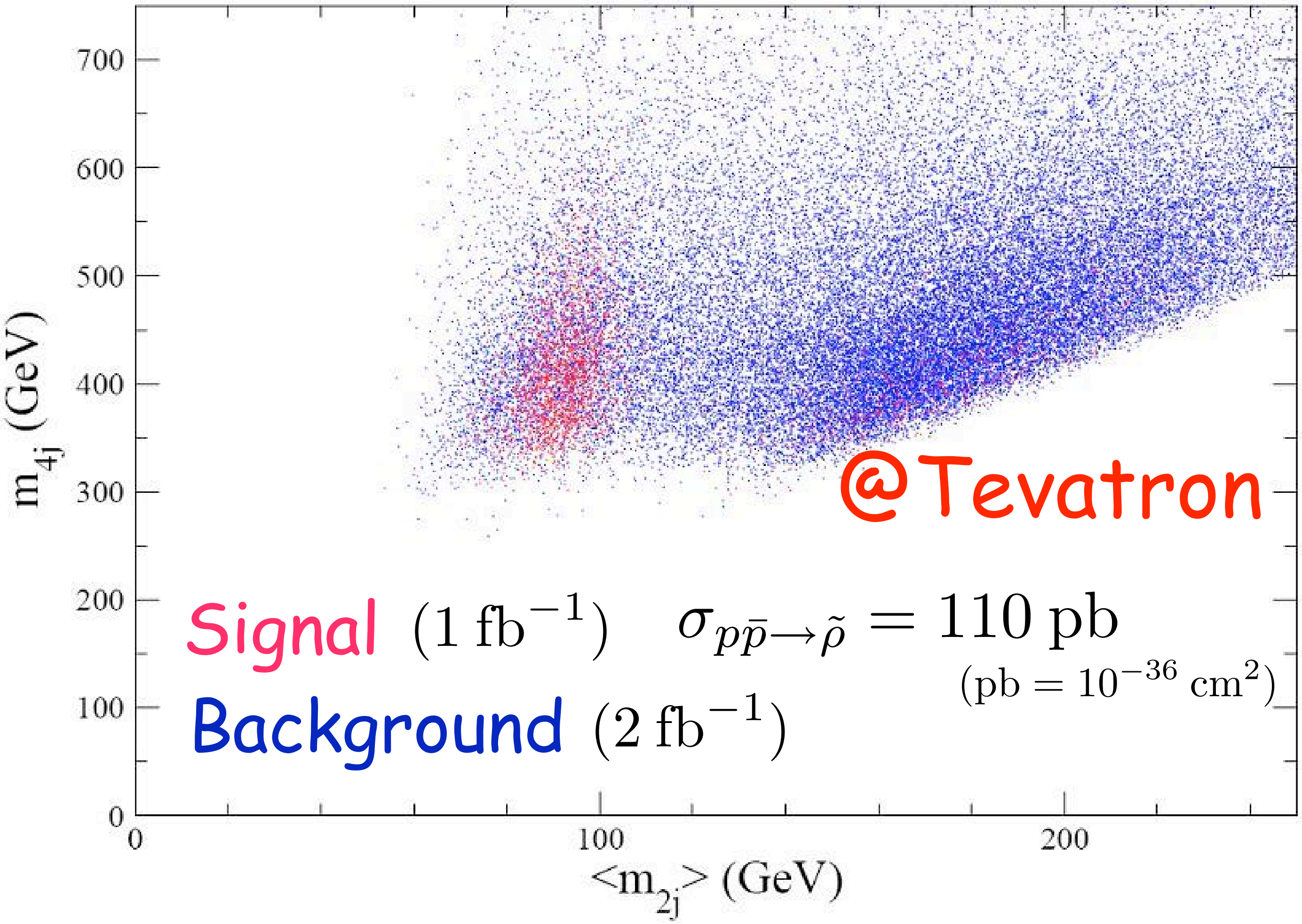
Backgrounds: $p_{\rm T1} \gg p_{\rm T2} \gg p_{\rm T3} \gg p_{\rm T4}$

so keep event **only if** $p_{{\rm T}i} > p_{\rm cutoff}$ for all 4 jets

T. OKUI (FSU)

Discovery potential for : $m_{\tilde{\rho}} = 350\ \text{GeV}$

$(m_{\tilde{\pi}} = 100\ \text{GeV})$



$p_{Ti} > p_{\text{cutoff}} = 40\ \text{GeV}$

$\underset{ij,\,kl}{\text{Min}} |m_{ij} - m_{kl}| < 25\ \text{GeV}$

$p_{T1} > 120\ \text{GeV}$

(CDF single-jet trigger: $p_{T1} > 100\ \text{GeV}$)

Signal: $2.7\ \text{pb}$ passing selection criteria

Background: $21\ \text{pb}$ passing criteria

Discovery potential for : $m_{\tilde{\rho}} = 350\ \text{GeV}$

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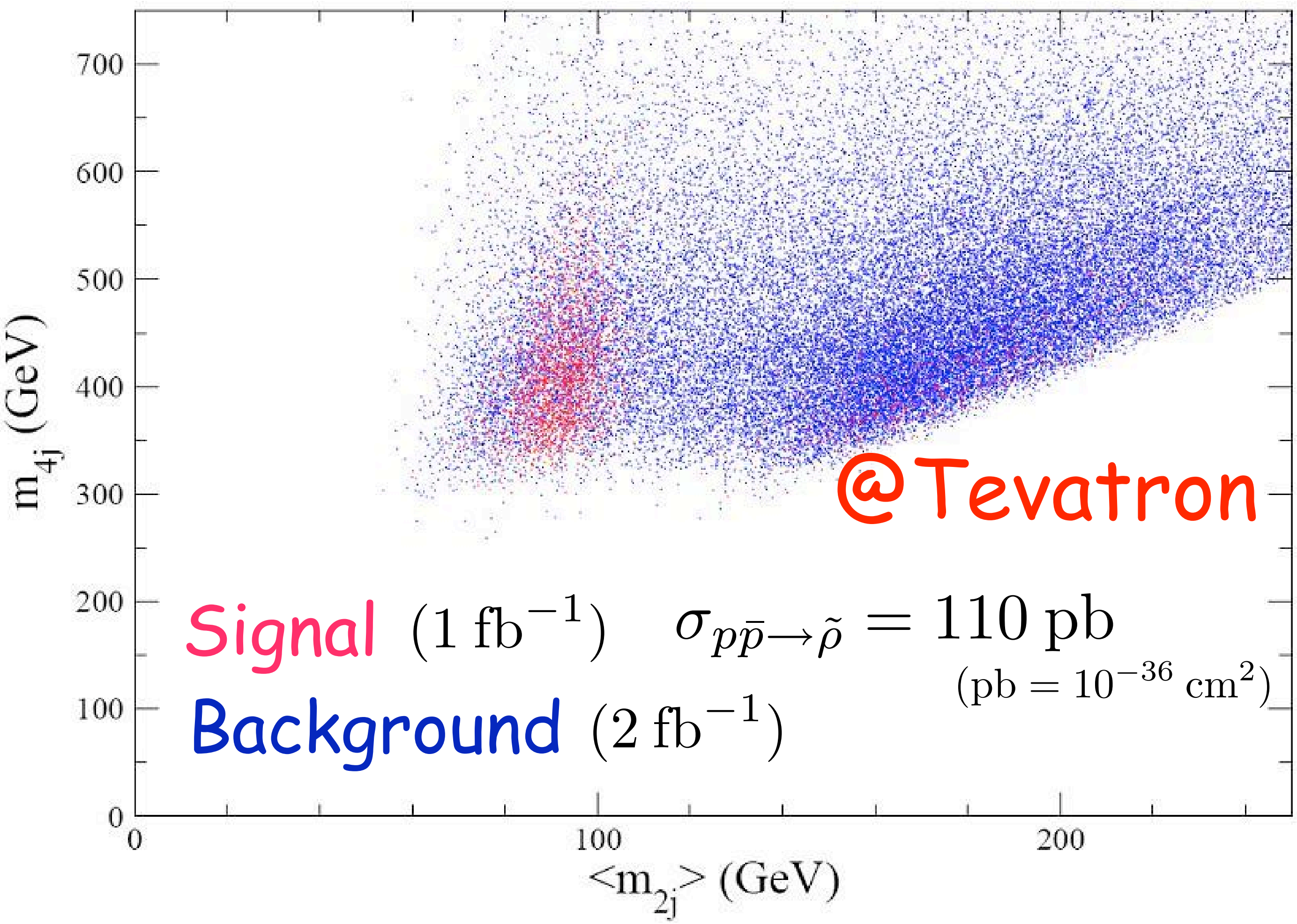

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(CDF single-jet trigger: $p_{T1} > 100\ \text{GeV}$)

Signal: $2.7\ \text{pb}$ passing selection criteria

Background: $21\ \text{pb}$ passing criteria

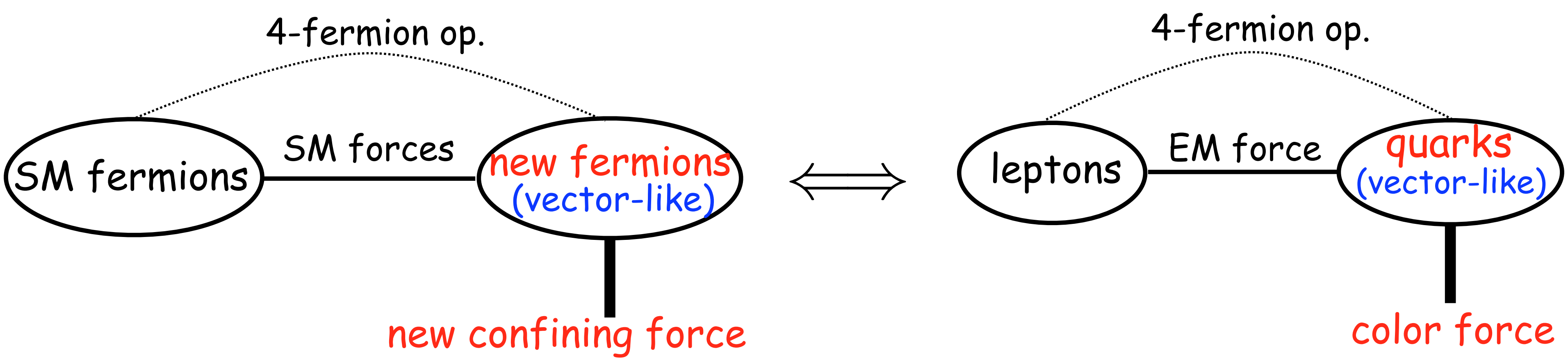
$$\sqrt{\sum_{\text{bins}} \left(\frac{S}{\sqrt{B}}\right)^2} = 32\ !$$

Discoverable in existing Tevatron data!

T. OKUI (FSU)

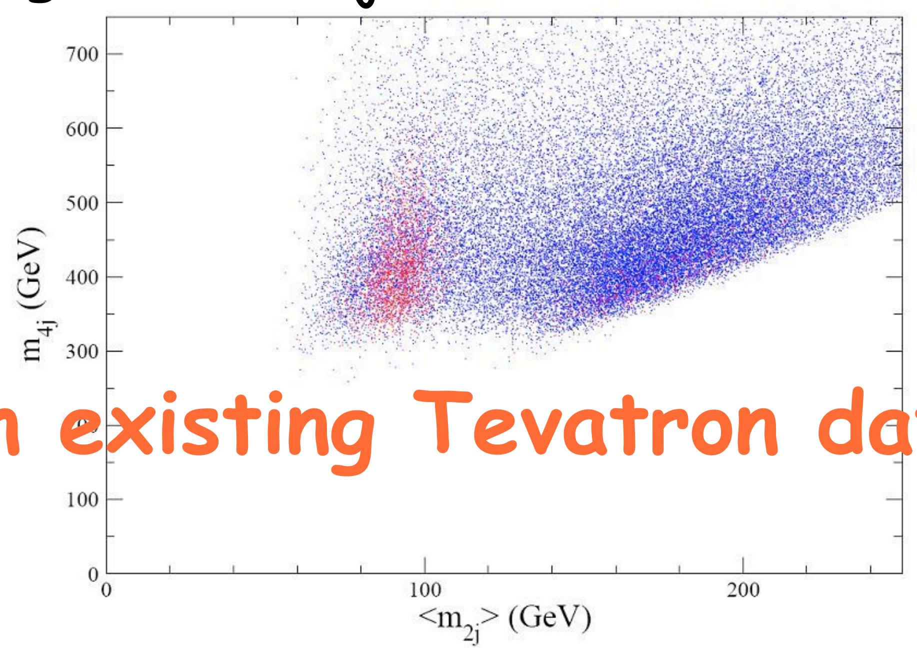
Conclusions

A broad class of simple extensions of the SM:



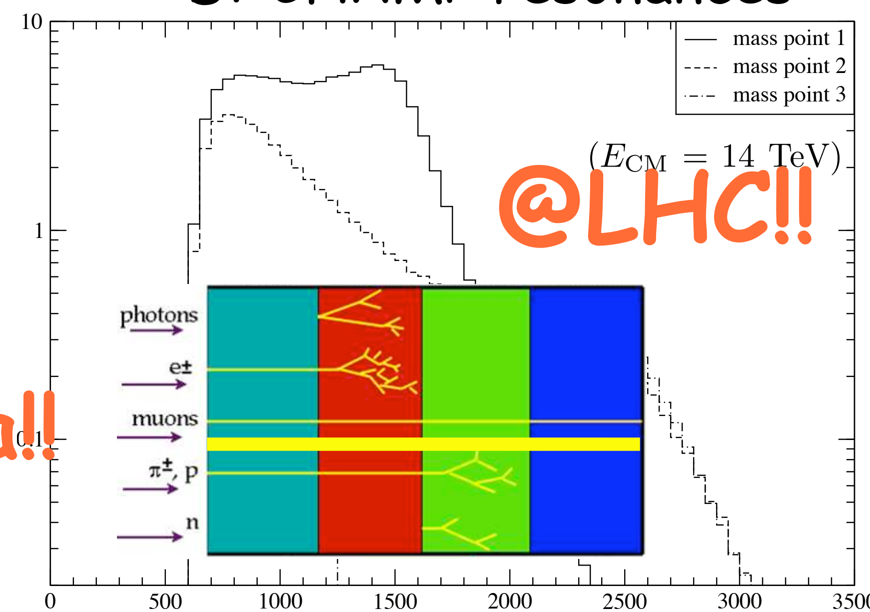
* can robustly evade all existing precision constraints
* can lead to extremely rich collider phenomenology

e.g. Multi-jets resonances



In existing Tevatron data!!

Di-CHAMP resonances



@LHC!!

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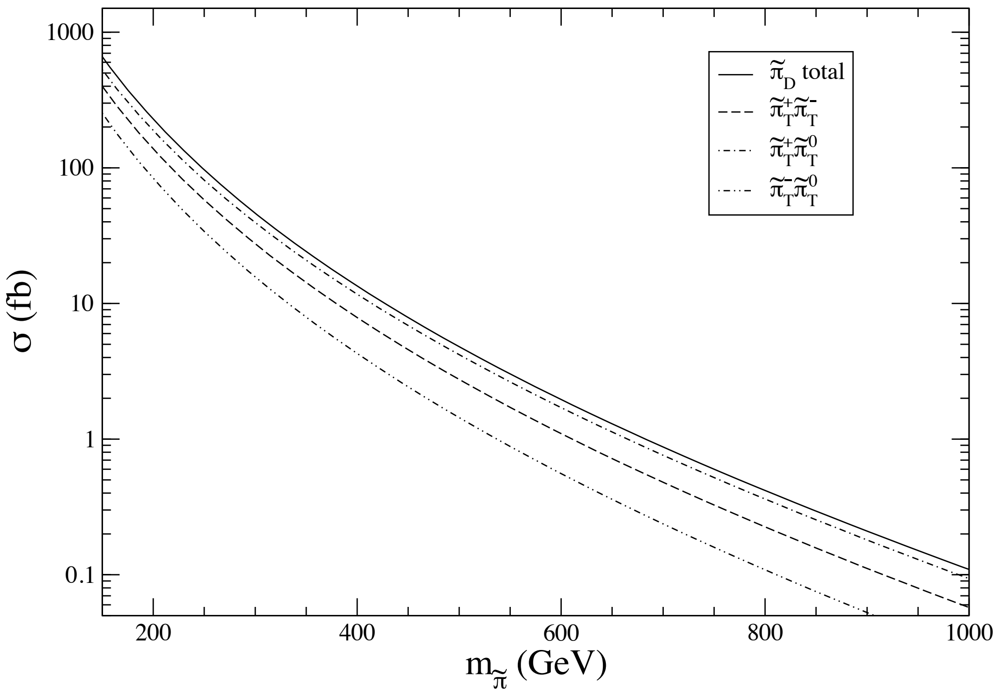
Backup slides

The Di-CHAMP/Multi-photon Benchmark



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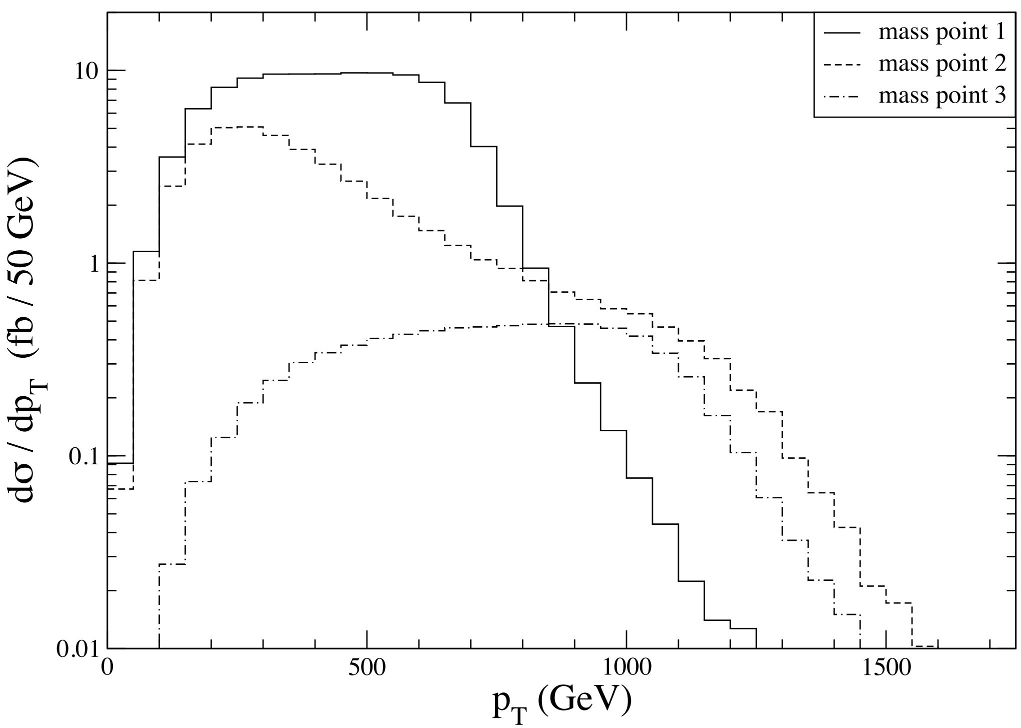

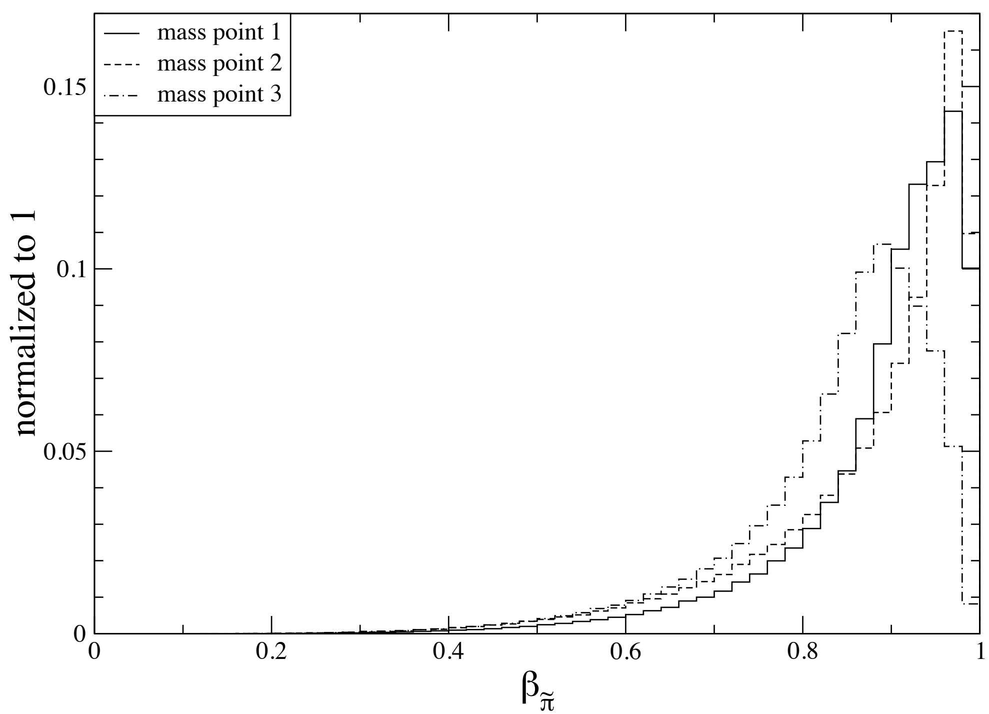

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The Di-CHAMP/Multi-photon Benchmark

	$\mathrm{SU}(3)_{\mathrm{HC}}$	$\mathrm{SU}(3)_{\mathrm{C}}$	$\mathrm{SU}(2)_{\mathrm{L}}$	$\mathrm{U}(1)_{\mathrm{Y}}$
ψ_1	**3**	**1**	**1**	-1
ψ_2	**3**	**1**	**2**	$1/2$

N=F=3, exactly like QCD!
→ Calculable!

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} - \frac{1}{4} H^a_{\mu\nu} H^{a\mu\nu} + \overline{\psi}_1 i \not{D} \psi_1 - m_1 \overline{\psi}_1 \psi_1 + \overline{\psi}_2 i \not{D} \psi_2 - m_2 \overline{\psi}_2 \psi_2 + \frac{\theta_H}{4} \epsilon^{\mu\nu\rho\sigma} H^a_{\mu\nu} H^a_{\rho\sigma}$$

	Color	Charge	Mass	Decays to
$\tilde{\pi}^0_{\mathrm{T}}$	–	0	m_{T}	W^+W^-, ZZ, $Z\gamma$, $\gamma\gamma$
$\tilde{\pi}^\pm_{\mathrm{T}}$	–	± 1	$m_{\mathrm{T}} + \delta m_{\mathrm{T}}$	$W^\pm Z$, $W^\pm\gamma$
$\tilde{\pi}^\pm_{\mathrm{D}}$	–	± 1	m_{D}	–
$\tilde{\pi}^{\pm\pm}_{\mathrm{D}}$	–	± 2	$m_{\mathrm{D}} + \delta m_{\mathrm{D}}$	$\tilde{\pi}^\pm_{\mathrm{D}} W^{\pm *}$
$\tilde{\pi}_{\mathrm{S}}$	–	0	m_{S}	$\gamma\gamma$, $(\gamma Z, ZZ)$

$$m^2_{\mathrm{T}} = \frac{3a m^2_{\tilde{\rho}}}{16\pi^2} \cdot 2g_2^2 + 6b m_{\tilde{\rho}} m_2 \,,$$

$$m^2_{\mathrm{D}} = \frac{3a m^2_{\tilde{\rho}}}{16\pi^2} \left(\frac{3}{4} g_2^2 + \frac{9}{4} g_1^2 \right) + 3b m_{\tilde{\rho}} (m_2 + m_1) \,,$$

$$m^2_{\mathrm{S}} = 2b m_{\tilde{\rho}} (m_2 + 2m_1) \,,$$

$$\mathcal{L}_{\tilde{\pi}_{\mathrm{D}}\ \mathrm{decay}} = \frac{c_{ij}}{M^2} J^\mu_{5\mathrm{D}}\, e^{\mathrm{T}}_{Ri} \mathcal{C} \gamma_\mu \ell_{Lj} \qquad J^\mu_{5\mathrm{D}} = \overline{\psi}_1 \gamma^\mu \gamma_5 \psi_2$$

T. OKUI (FSU)

The R-hadron Benchmark

	$\mathrm{SU(3)_{HC}}$	$\mathrm{SU(3)_C}$	$\mathrm{SU(2)_L}$	$\mathrm{U(1)_Y}$
ψ_1	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	1
ψ_3	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	$-1/3$

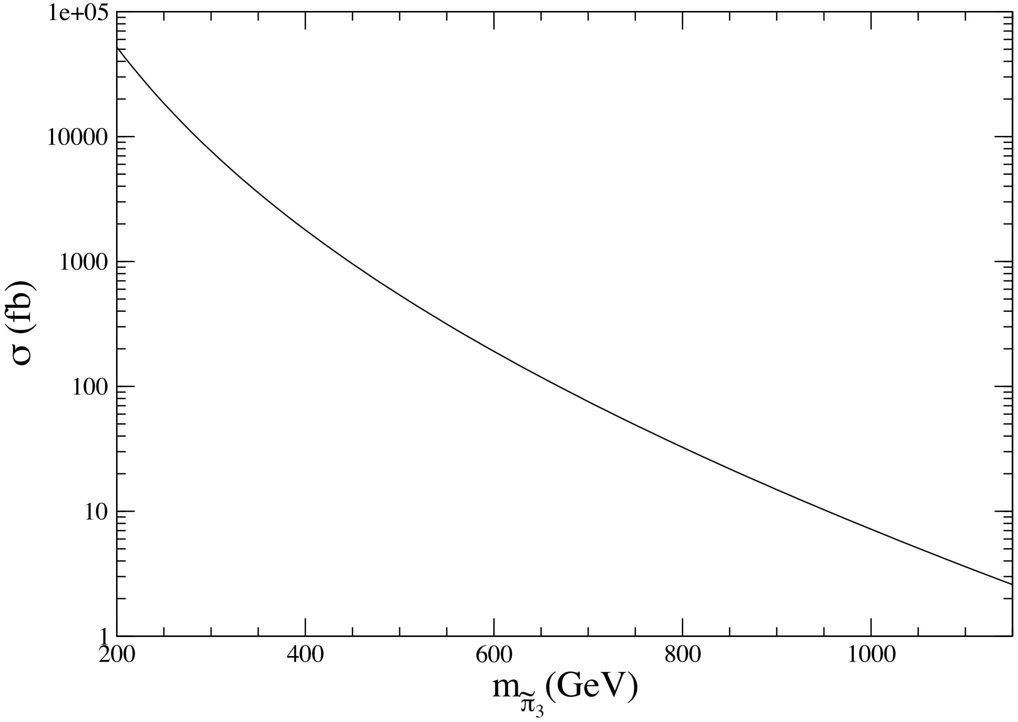
$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} - \frac{1}{4} H^a_{\mu\nu} H^{a\mu\nu} + \overline{\psi}_1 i \not{D} \psi_1 - m_1 \overline{\psi}_1 \psi_1 + \overline{\psi}_3 i \not{D} \psi_3 - m_3 \overline{\psi}_3 \psi_3 + \frac{\theta_H}{4} \epsilon^{\mu\nu\rho\sigma} H^a_{\mu\nu} H^a_{\rho\sigma}$$

	Color	Charge	Mass	Decays to
$\tilde{\pi}_8$	$\mathbf{8}$	0	$m_{\tilde{\pi}_8}$	$gg \gg gZ,\, g\gamma$
$\tilde{\pi}_3$	$\mathbf{3}$	$-4/3$	$m_{\tilde{\pi}_3}$	collider stable
$\tilde{\pi}_1$	$\mathbf{1}$	0	$m_{\tilde{\pi}_1}$	$gg \gg \gamma\gamma \gg \gamma Z,\, ZZ$

$$\begin{aligned} m^2_{\tilde{\pi}_8} &= \frac{3am^2_{\tilde{\rho}}}{16\pi^2} \cdot 3g_3^2 + 6bm_{\tilde{\rho}} m_3 \,, \\ m^2_{\tilde{\pi}_3} &= \frac{3am^2_{\tilde{\rho}}}{16\pi^2} \left(\frac{4}{3} g_3^2 + \frac{16}{9} g_1^2 \right) + 3bm_{\tilde{\rho}}(m_3 + m_1) \,, \\ m^2_{\tilde{\pi}_1} &= \frac{3b}{2} m_{\tilde{\rho}} (m_3 + 3m_1) \,, \end{aligned}$$

$$\mathcal{L}_{\tilde{\pi}_3 \text{ decay}} = \frac{c_{ij}}{M^2} P_3 \, d^{\mathrm{T}}_{Ri} \mathcal{C} e_{Rj} \qquad P_3 = \overline{\psi}_1 \gamma_5 \psi_3$$

The R-hadron Benchmark



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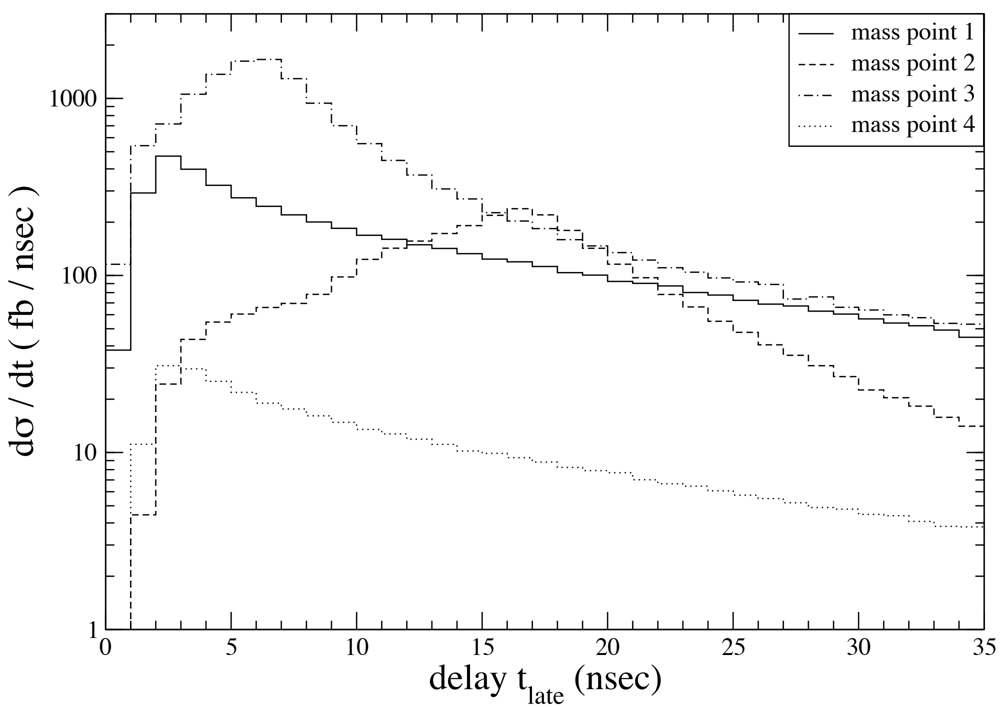
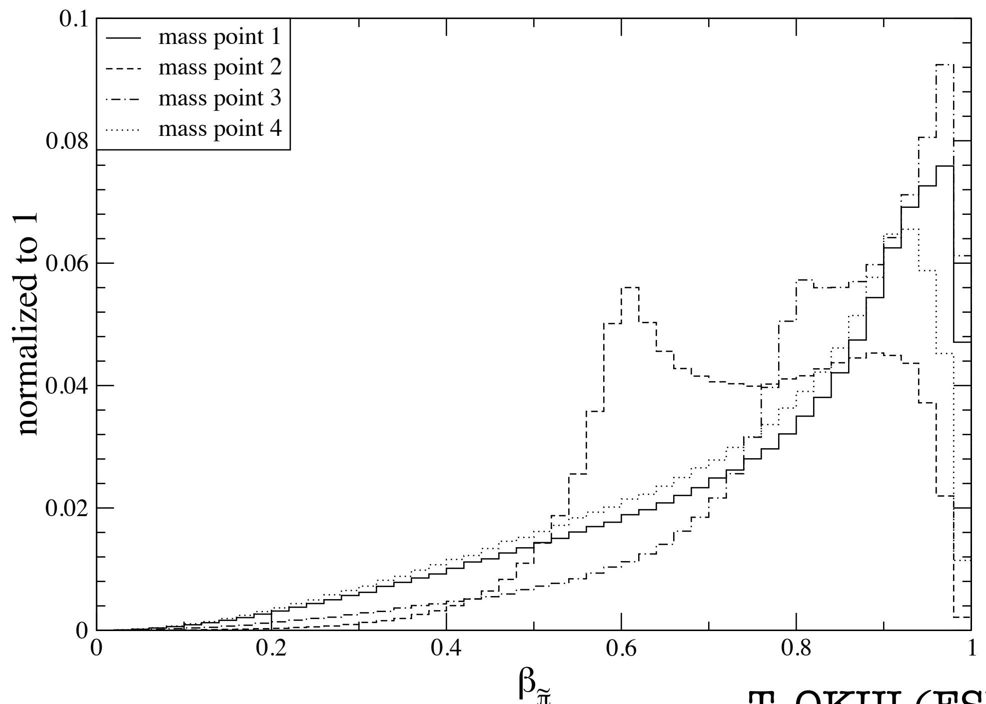




T. OKUI (FSU)

The Tevatron Multijet Model

Literally copy the QED-QCD system:

$(u, d, s) \sim (\mathbf{3}, \mathbf{3})$ under $\mathrm{SU}(3)_{\mathrm{color}} \times \mathrm{SU}(3)_{\mathrm{flavor}}$

(Take $m_{u,d,s} \to 0$ limit) $\cup$

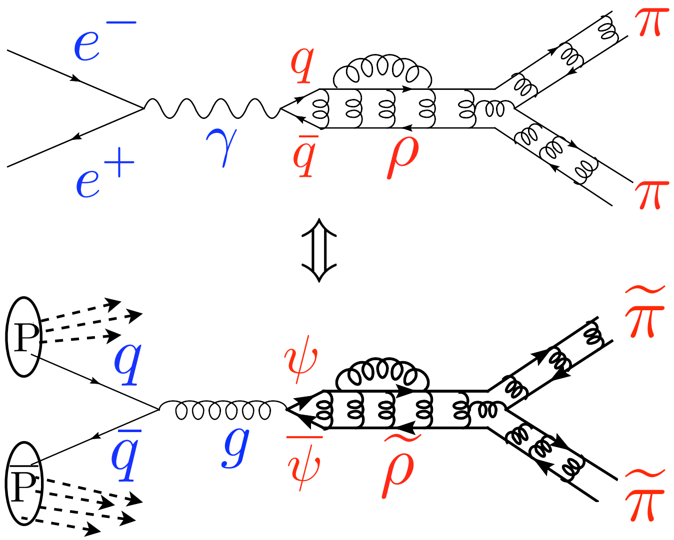
$\mathrm{U}(1)_{\mathrm{E\&M}}$

$\Updownarrow$ "dictionary"

$\psi \sim (\mathbf{3}, \mathbf{3})$ under $\mathrm{SU}(3)_{\mathrm{new}} \times \mathrm{SU}(3)_{\mathrm{flavor}}$

$(m_\psi = 0)$ $||$

$\mathrm{SU}(3)_{\mathrm{color}}$



Then, we can "analog compute" everything!

$\Gamma_{\rho^0 \to e^+ e^-}$ $\longrightarrow$ $\widetilde{\rho}$-q-$\bar{q}$ coupling

$\Gamma_{\rho^0 \to \pi^+ \pi^-}$ $\longrightarrow$ $\widetilde{\rho}$-$\widetilde{\pi}$-$\widetilde{\pi}$ coupling

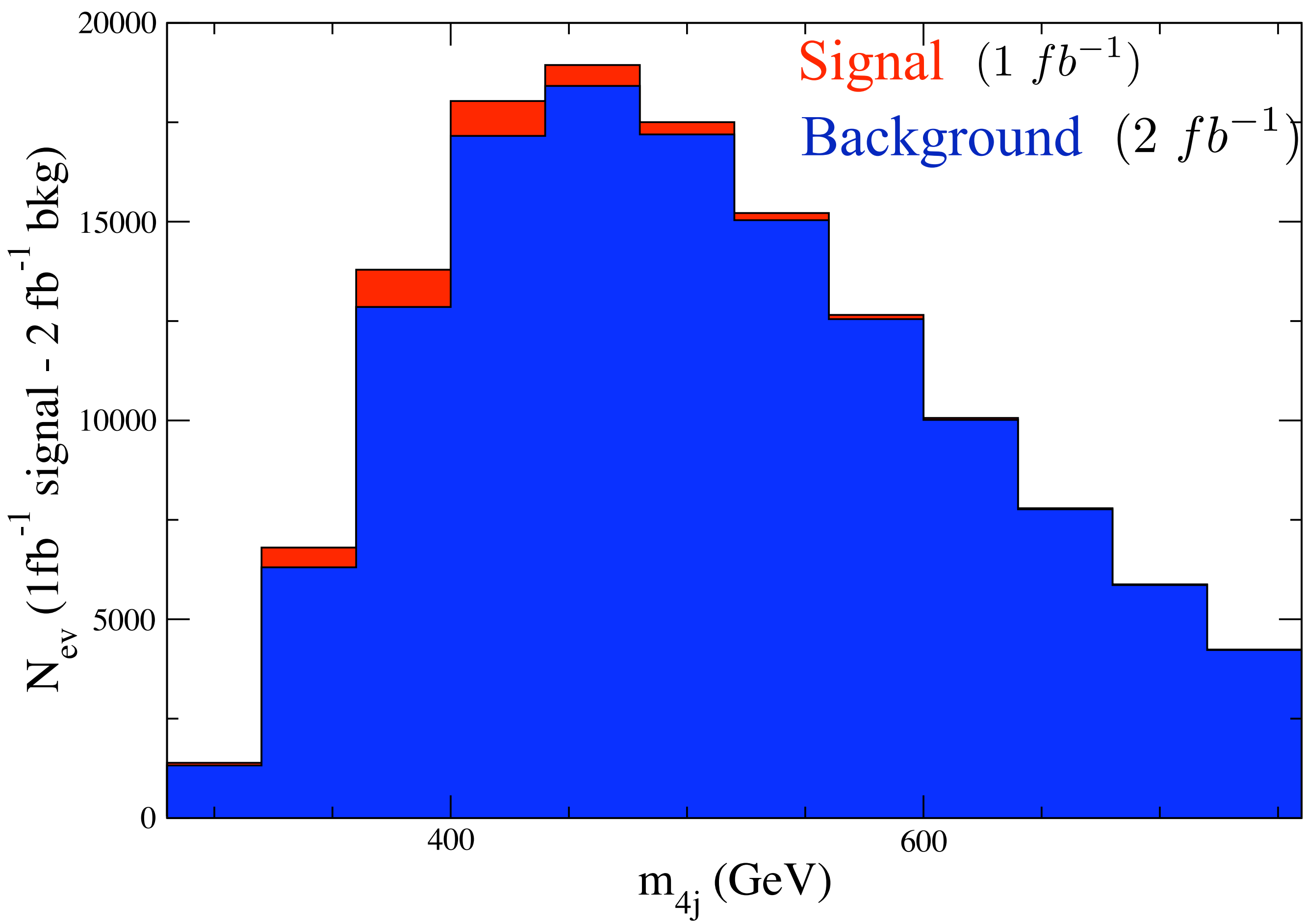
$\Gamma_{\pi^0 \to \gamma\gamma}$ $\longrightarrow$ $\widetilde{\pi}$-g-g coupling

$(m_{\pi^\pm}^2 - m_{\pi^0}^2)/m_\rho^2$ $\longrightarrow$ $m_{\widetilde{\pi}}^2 / m_{\widetilde{\rho}}^2$

Only one parameter $m_{\widetilde{\rho}}$!

T. OKUI (JHU&UMD)

What if we don't pair up jets?



$$m_{\tilde{\rho}} = 350 \text{ GeV}$$

$$(m_{\tilde{\pi}} = 100 \text{ GeV})$$

$$p_{T1} > 120 \text{ GeV}$$

$$p_{Ti} > 40 \text{ GeV}$$

Signal : 3.6 pb passing cuts

Background: 66 pb passing cuts

$$\sqrt{\sum_{\text{bins}} \left(\frac{S}{\sqrt{B}}\right)^2} = 13,$$

BUT too subtle to tell...

T. OKUI (FSU)