Collider Phenomenology of Heavy Charged Gauge Bosons

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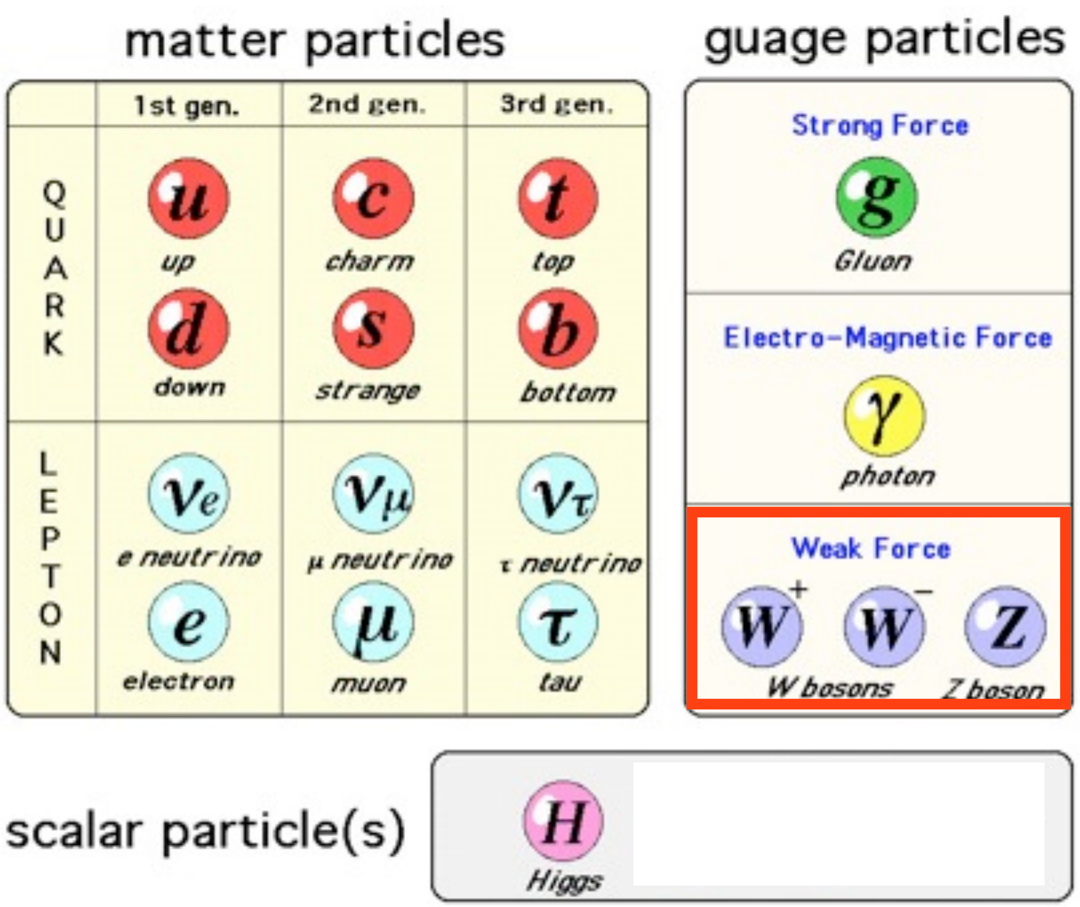
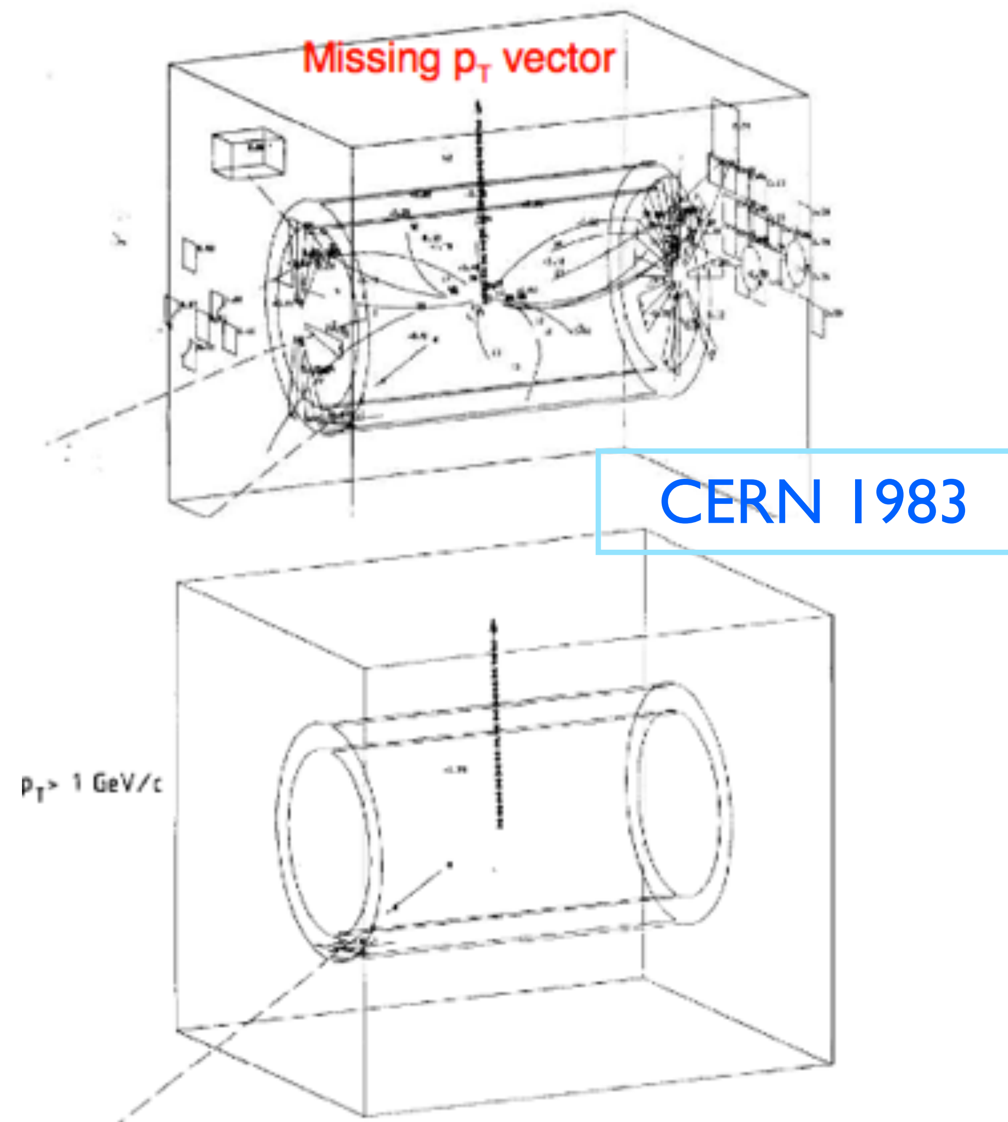
Charged Gauge Bosons (W^+, W^-)

- **Why important? W-bosons are weak force mediators !**
- **Standard model predicts W-bosons. Later W-bosons (with predicted mass) were discovered!**

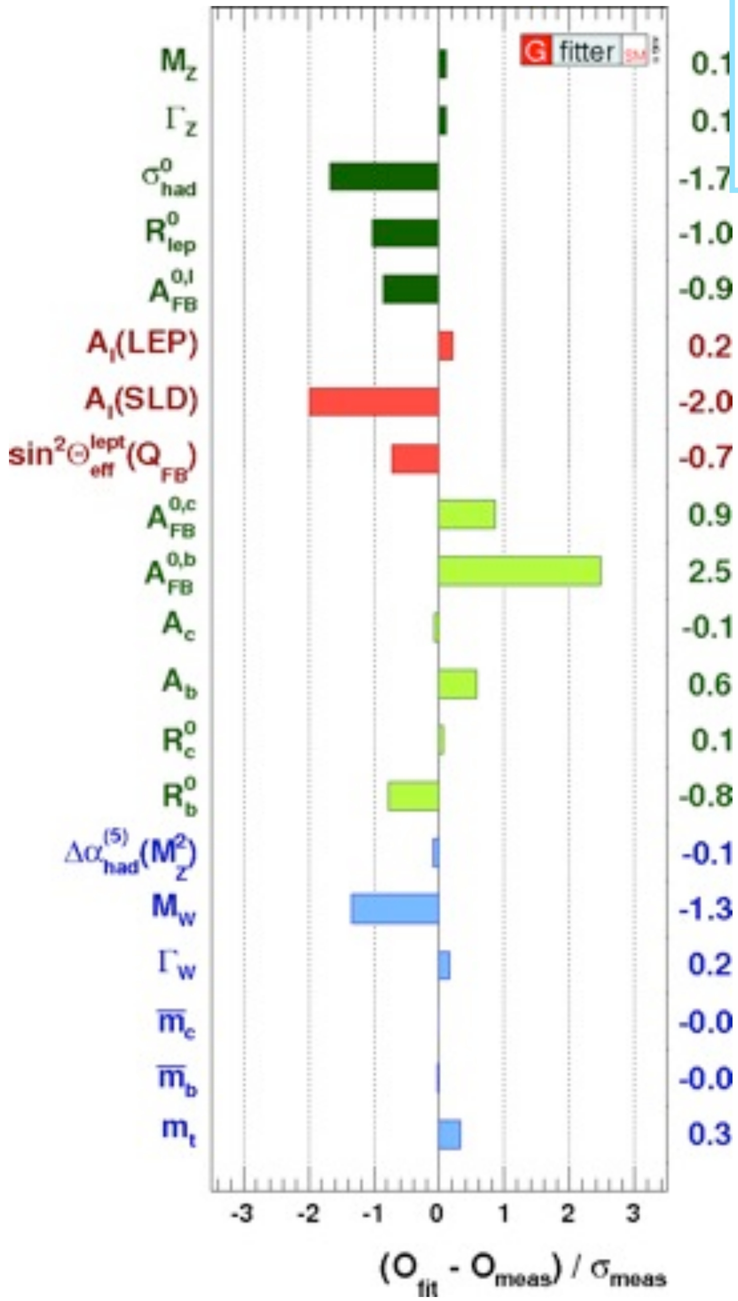


Elements of the Standard Model

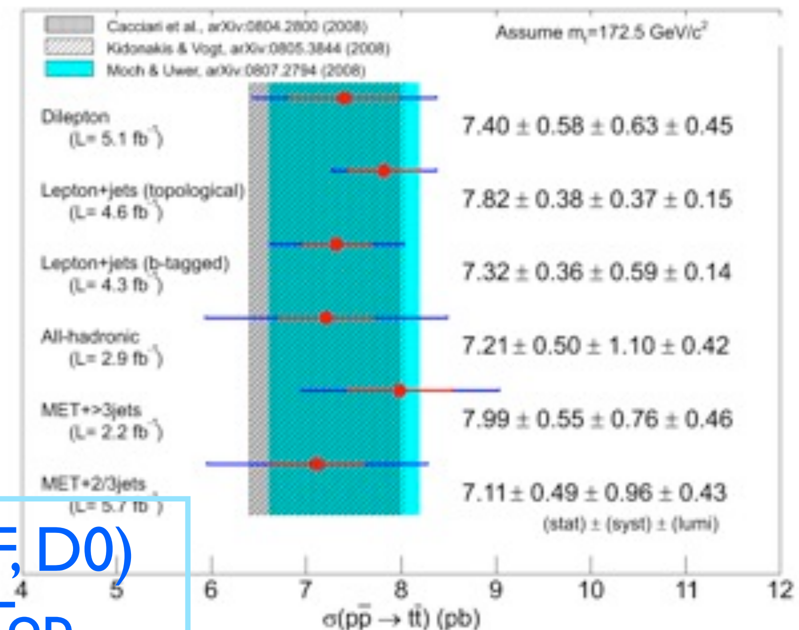


Success of Standard Model (SM)

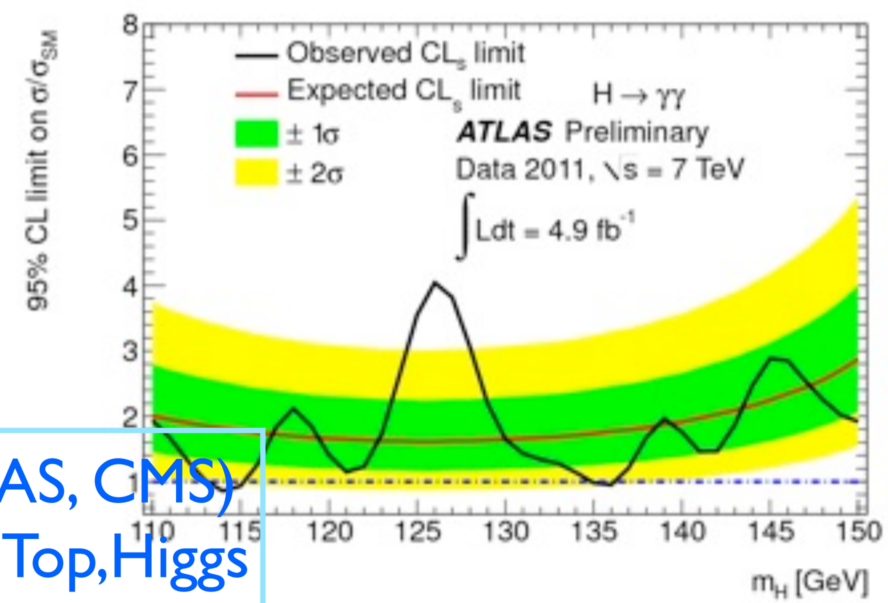
- Current data agree with SM very well



Precision Data(LEP, SLD, low energy) W and Z physics



Tevatron (CDF, D0) QCD, W, Z, Top

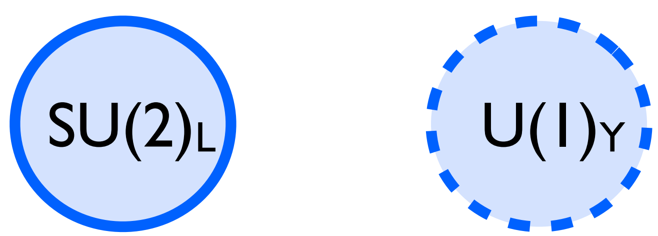


LHC (ATLAS, CMS) QCD, W, Z, Top, Higgs

Standard Model in One Figure

- **Moose notation to remember SM Lagrangian**

$$\mathcal{L}_{\rm circle} = -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}$$



Glashow
Weinberg
Salam
H. Georgi

Standard Model in One Figure

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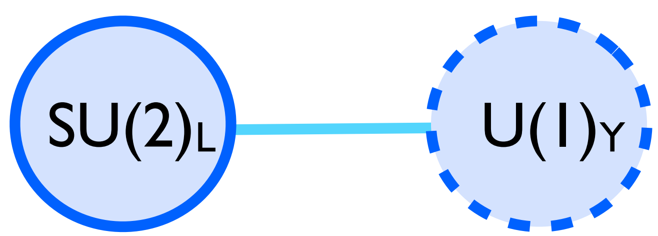
$$\mathcal{L}_{\text{link}} = (D^\mu\phi)^\dagger(D_\mu\phi) - V(\phi^\dagger\phi)$$

$$D_\mu = \partial_\mu Y + i\frac{g}{2}\vec{\tau}\cdot\mathcal{W}_\mu + i\frac{g'}{2}B_\mu$$



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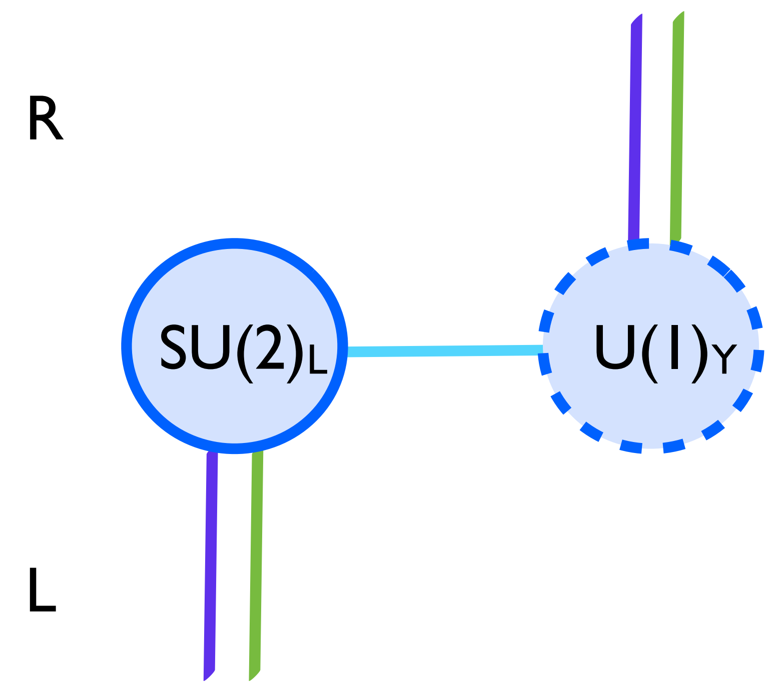

$$\mathcal{L}_{\rm SolidLine} = \overline{\rm R}\, i\gamma^\mu\left(\partial_\mu + i\frac{g'}{2}\mathcal{A}_\mu Y\right){\rm R}$$
$$+\overline{\rm L}\, i\gamma^\mu\left(\partial_\mu + i\frac{g'}{2}\mathcal{A}_\mu Y + i\frac{g}{2}\vec{\tau}\cdot\vec{b}_\mu\right){\rm L}$$

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Standard Model in One Figure

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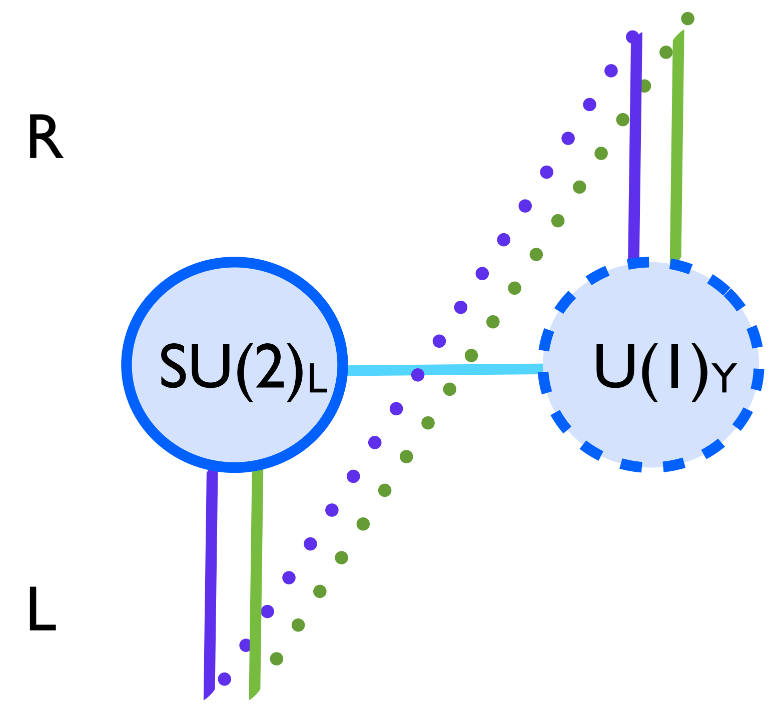

$$\mathcal{L}_{\rm SolidLine} = \overline{\mathsf{R}}\, i\gamma^\mu\left(\partial_\mu + i\frac{g'}{2}\mathcal{A}_\mu Y\right)\mathsf{R} + \overline{\mathsf{L}}\, i\gamma^\mu\left(\partial_\mu + i\frac{g'}{2}\mathcal{A}_\mu Y + i\frac{g}{2}\vec{\tau}\cdot\vec{b}_\mu\right)\mathsf{L}$$

$$\mathcal{L}_{\rm DotLine} = -\left[\overline{\mathsf{R}}(Y^\star\phi^\dagger\mathsf{L}) + (\overline{\mathsf{L}}Y\phi)\mathsf{R}\right]$$

Glashow
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Standard Model in One Figure

- **Moose notation to remember SM Lagrangian**

$$\mathcal{L}_{\rm circle} = -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}$$

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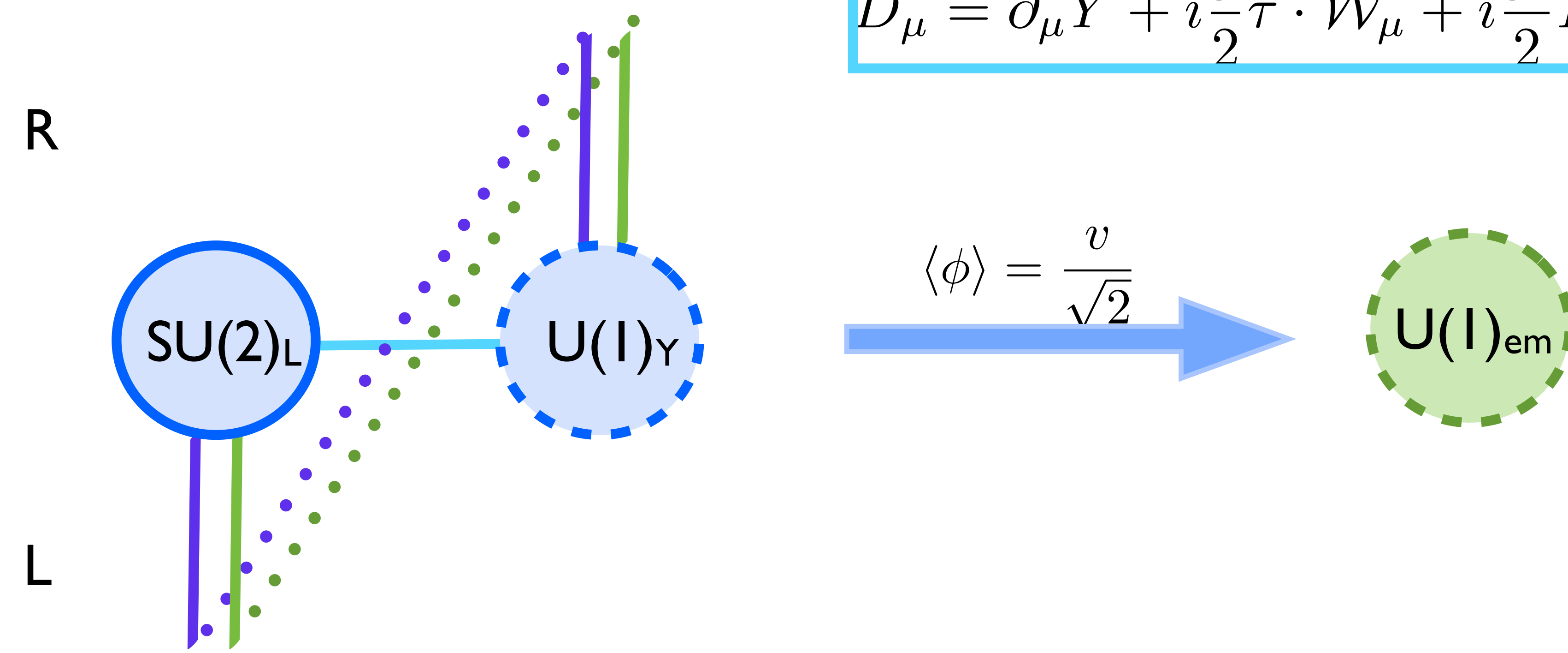

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Glashow
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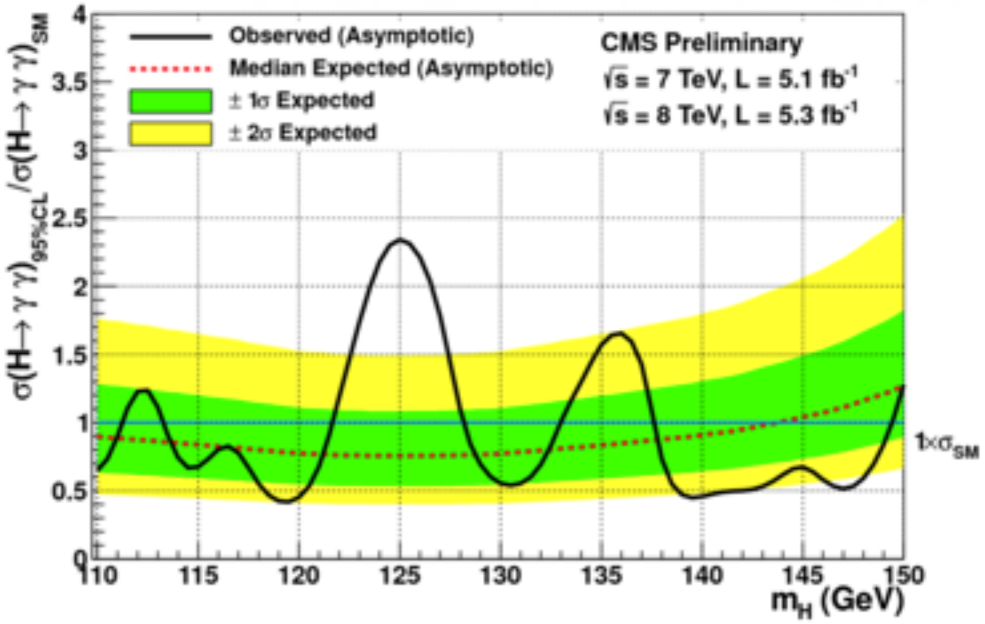
Motivation for New Physics

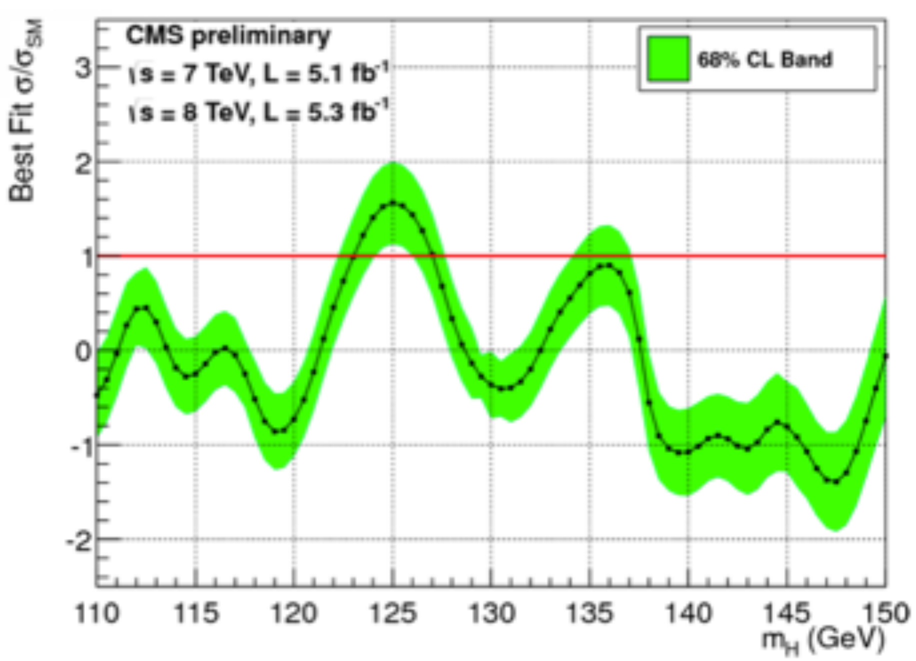
- A light Higgs (observation of a 125 GeV scalar)



Why Higgs so light?

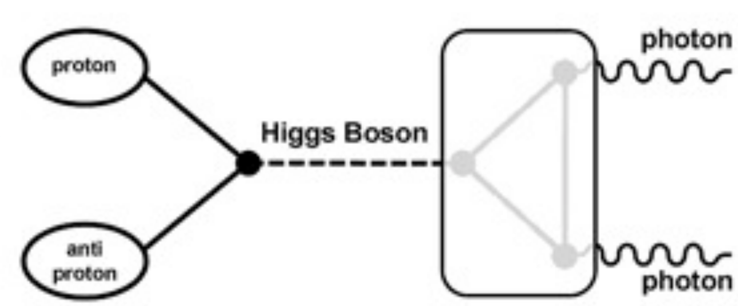
New physics to solve hierarch problem

- Diphoton Rate enhancement



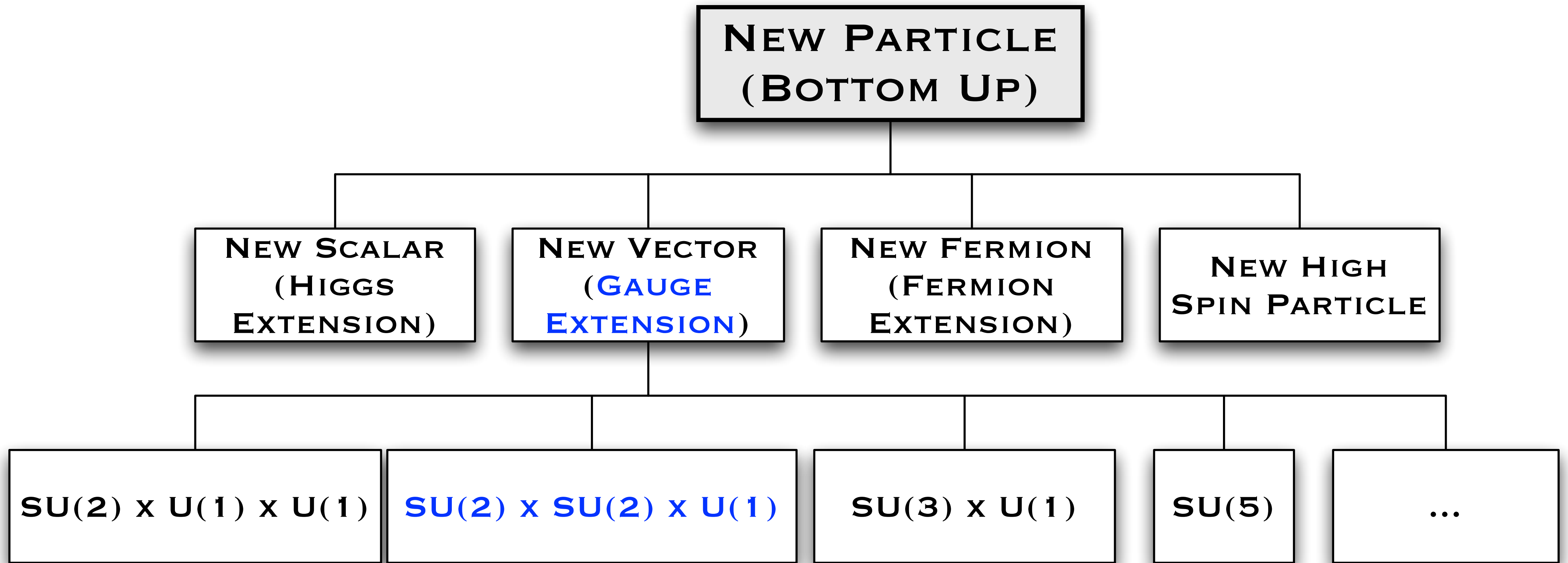
Why diphoton rate larger than SM?

Hint for New Physics

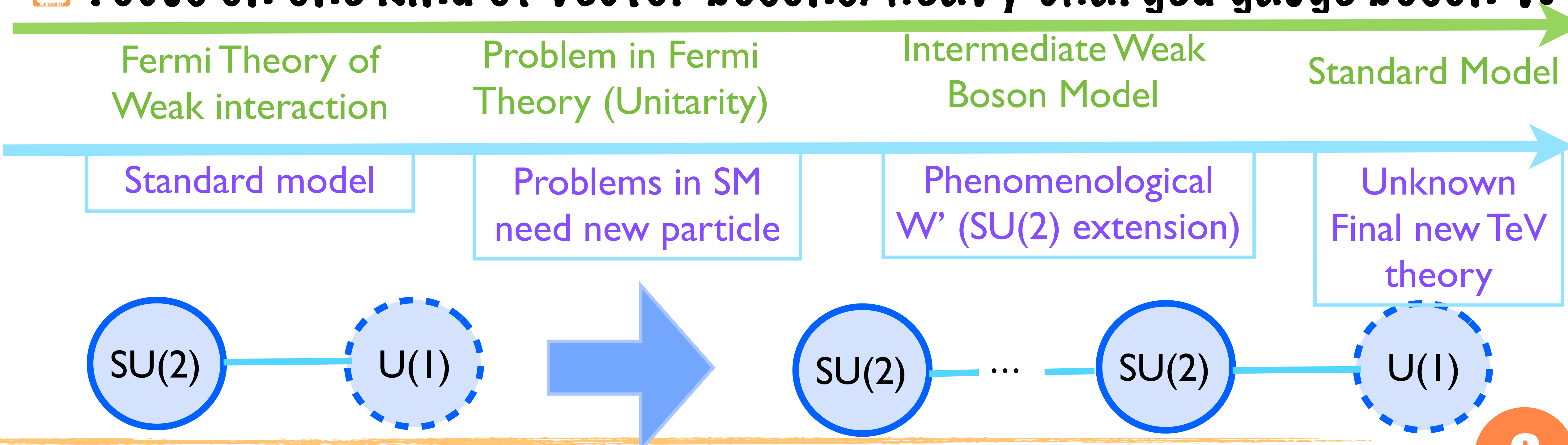


New particle in the loop

Heavy Charged Gauge Bosons

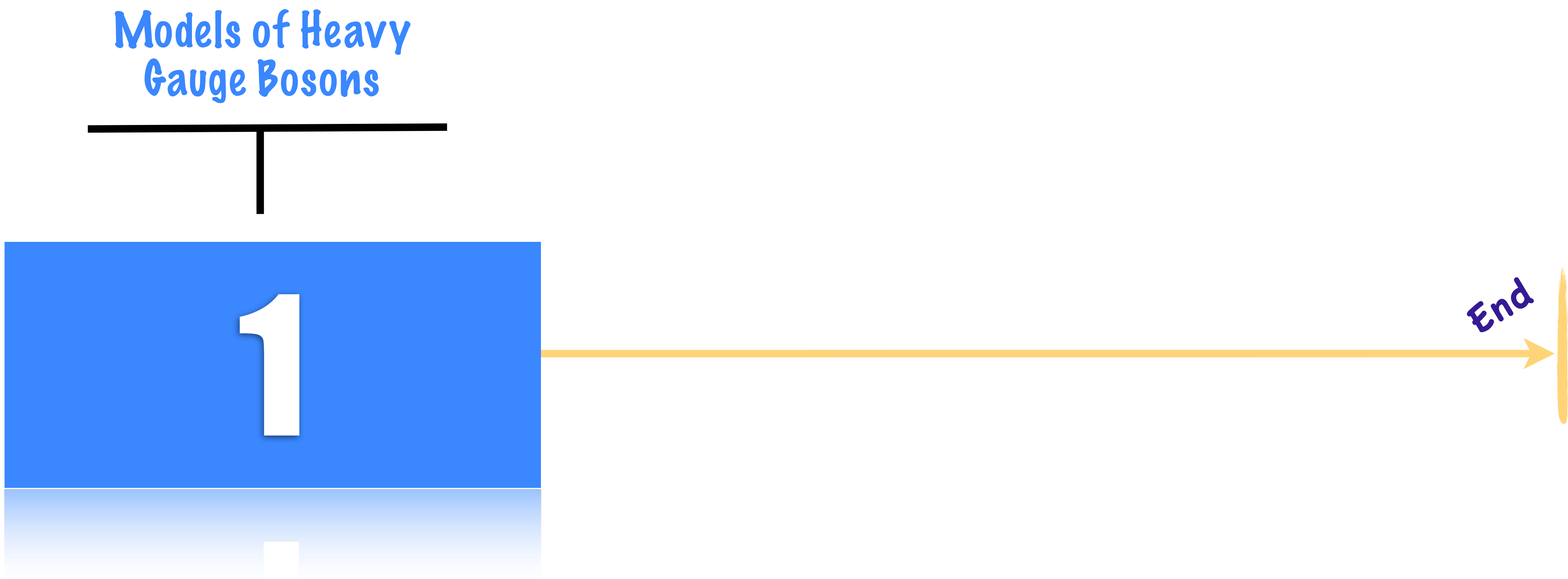


- Focus on one kind of vector bosons: heavy charged gauge boson W'



Outline

Outline



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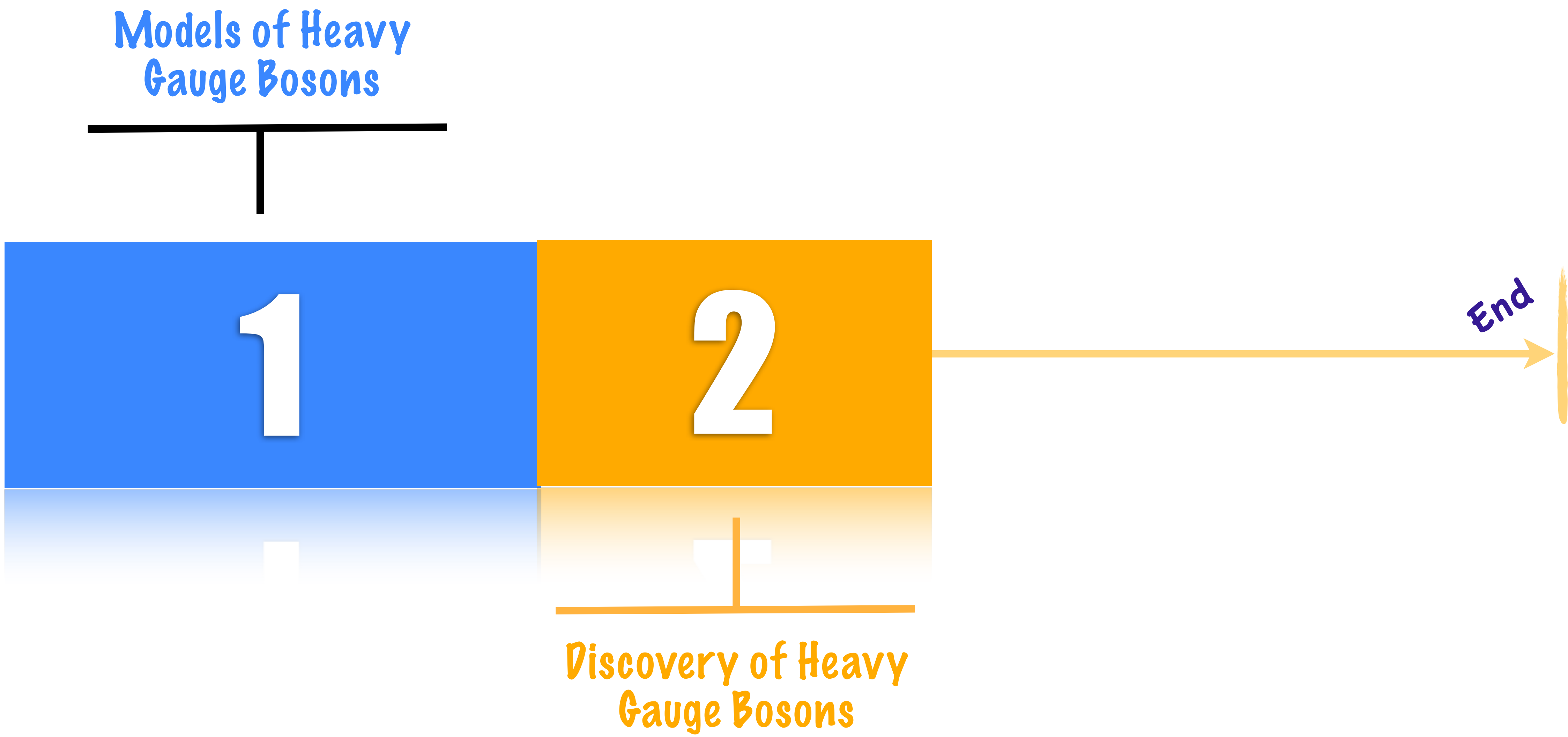
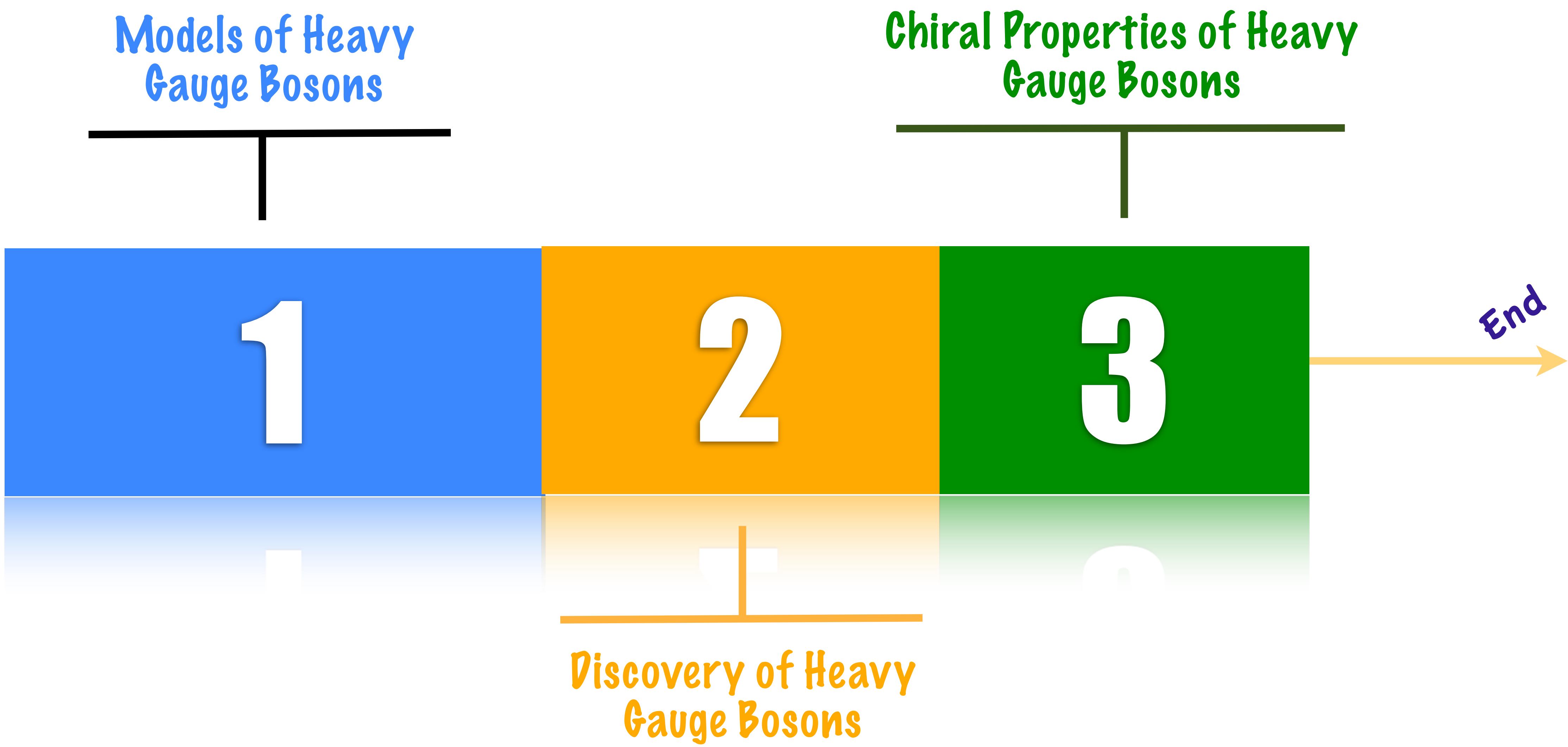

Models of Heavy Gauge Bosons
1
2
End
Discovery of Heavy Gauge Bosons

Outline



Models of Heavy Gauge Bosons
Chiral Properties of Heavy Gauge Bosons
1
2
3
End
Discovery of Heavy Gauge Bosons

Outline

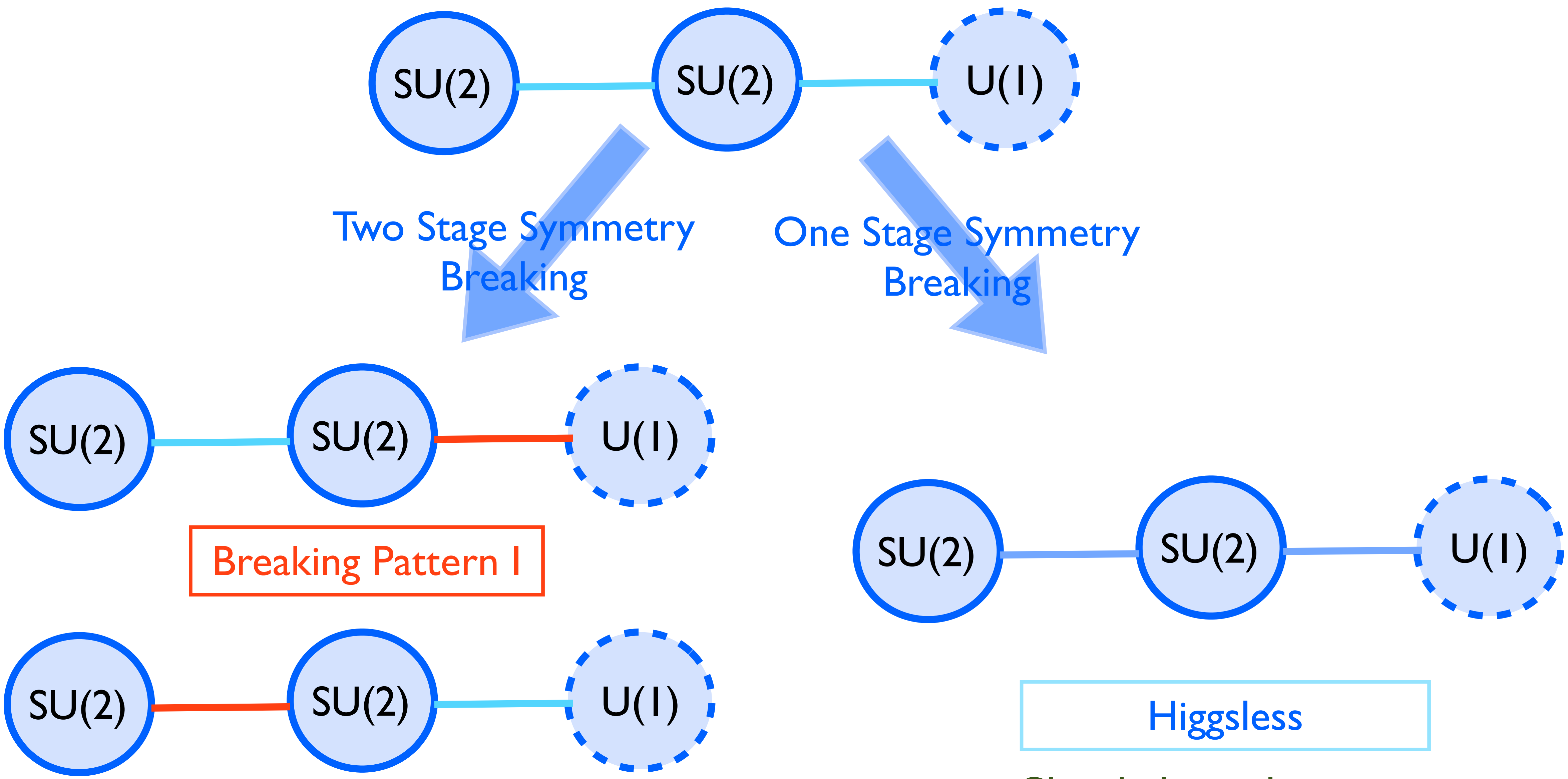
1. Models of Heavy Gauge Bosons
2. Discovery of Heavy Gauge Bosons
3. Chiral Properties of Heavy Gauge Bosons
4. Summary and Outlook

Models of Heavy Charged Gauge Bosons

SU(2) x SU(2) x U(1) Models (G221)

- **Minimal SU(2) Extension**

Classified by different Link fields

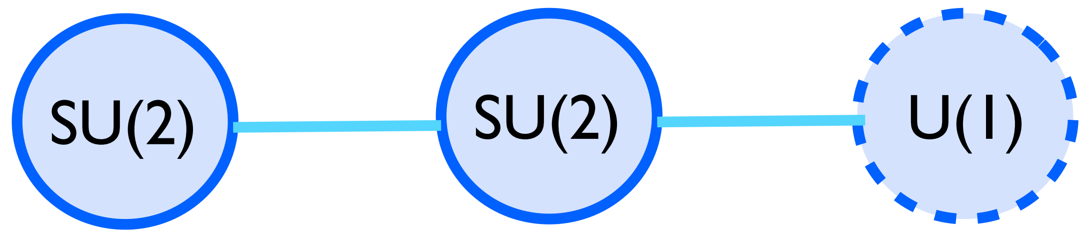


Breaking Pattern II

Chivukula. et.al.
Foadi, Gopalakrishna, Schmidt

SU(2) x SU(2) x U(1) Models (G221)

- Minimal SU(2) Extension



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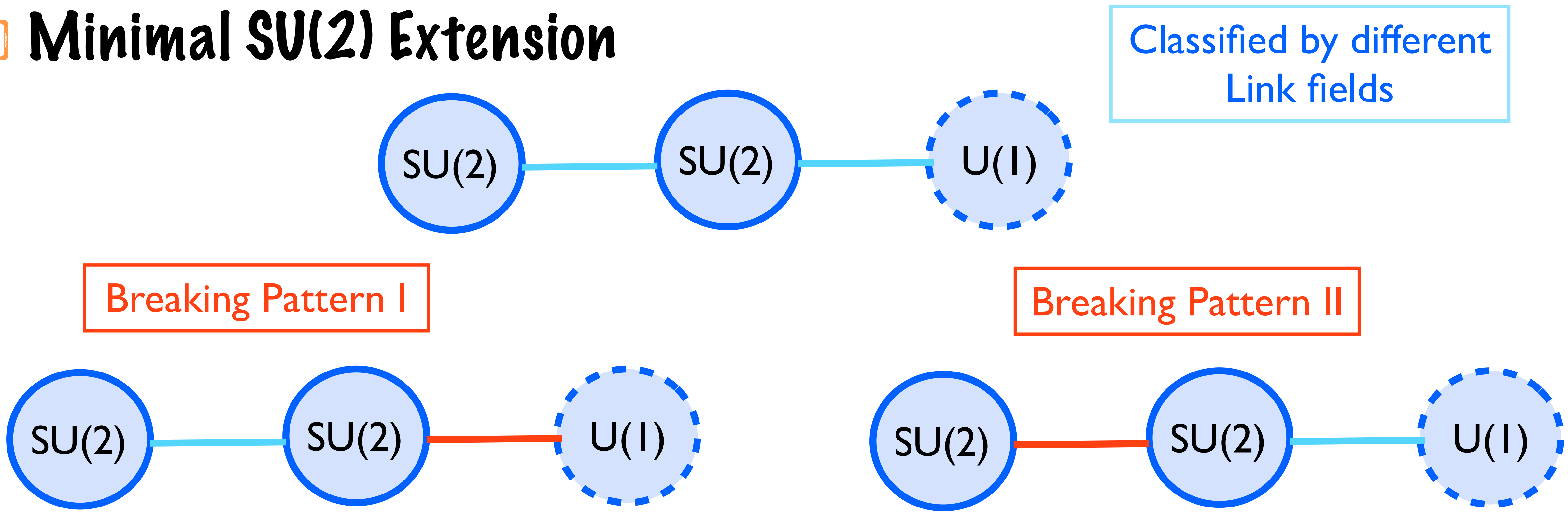

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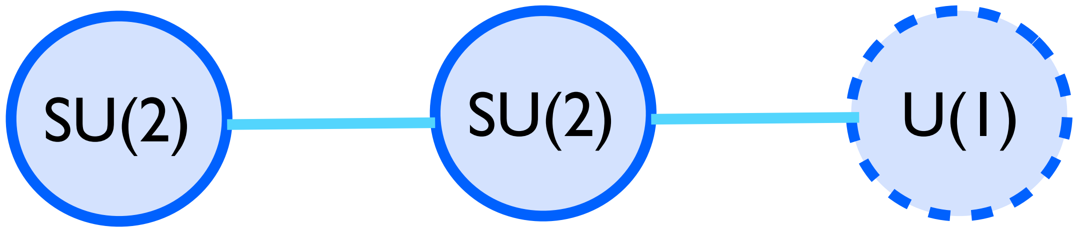
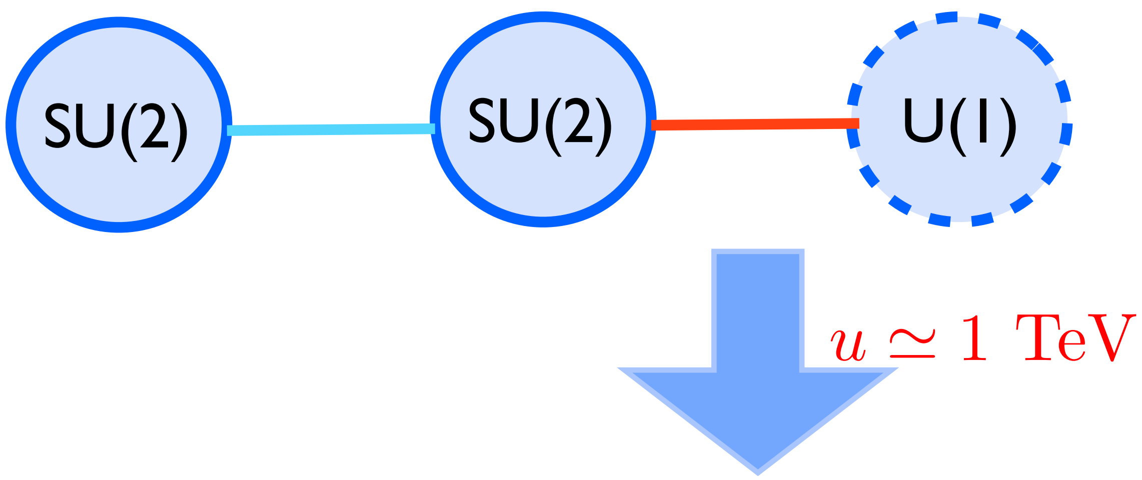
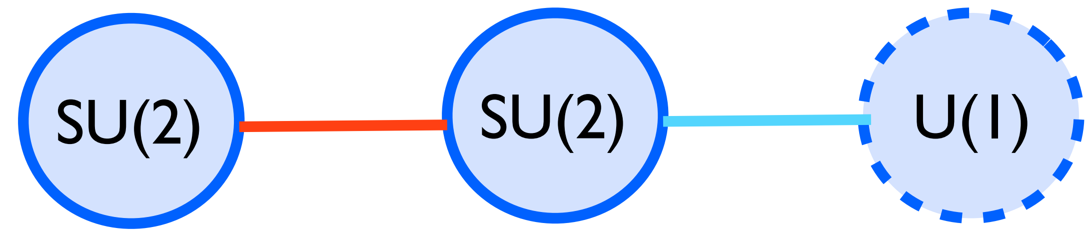


Breaking Pattern I



Breaking Pattern II



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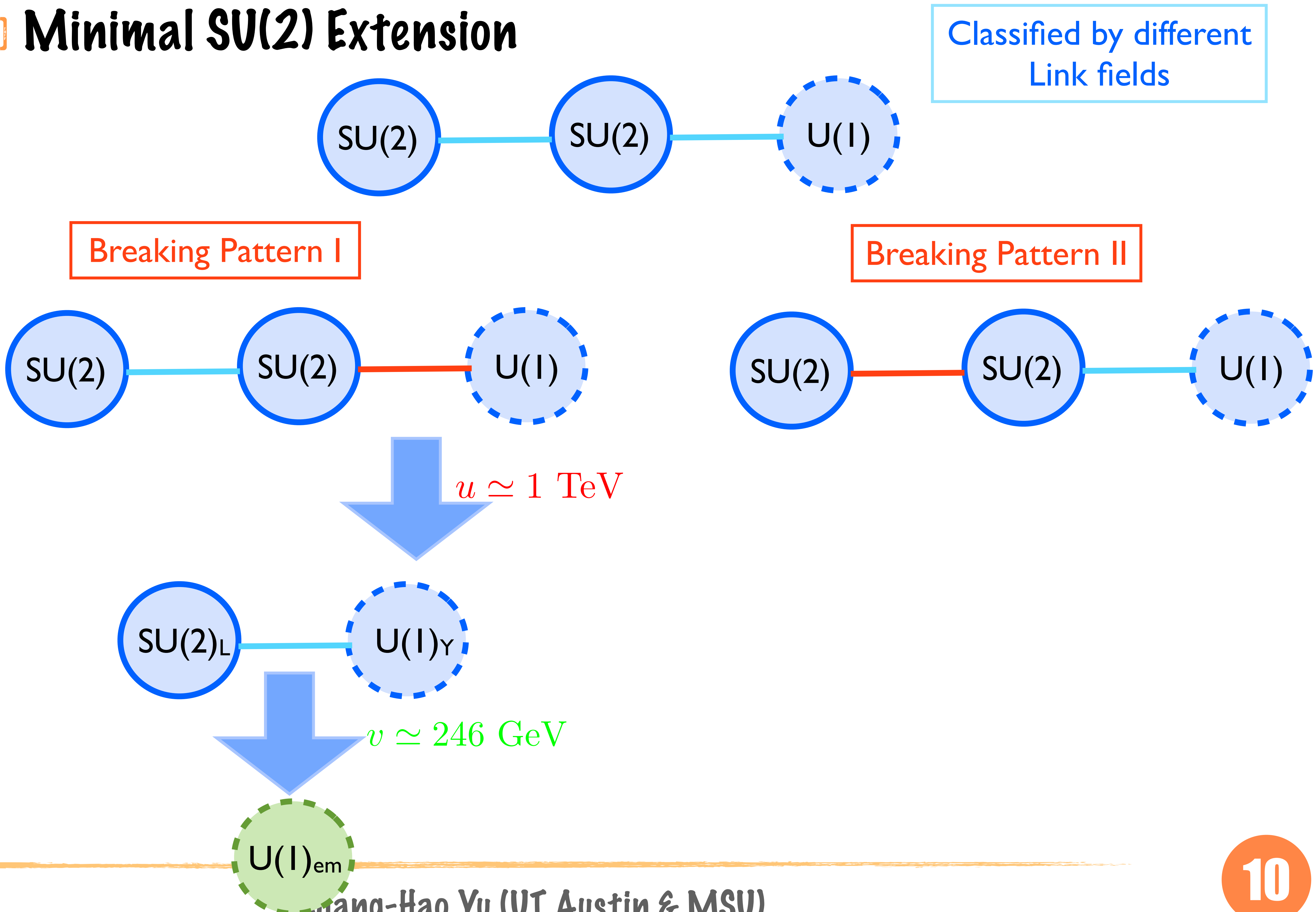

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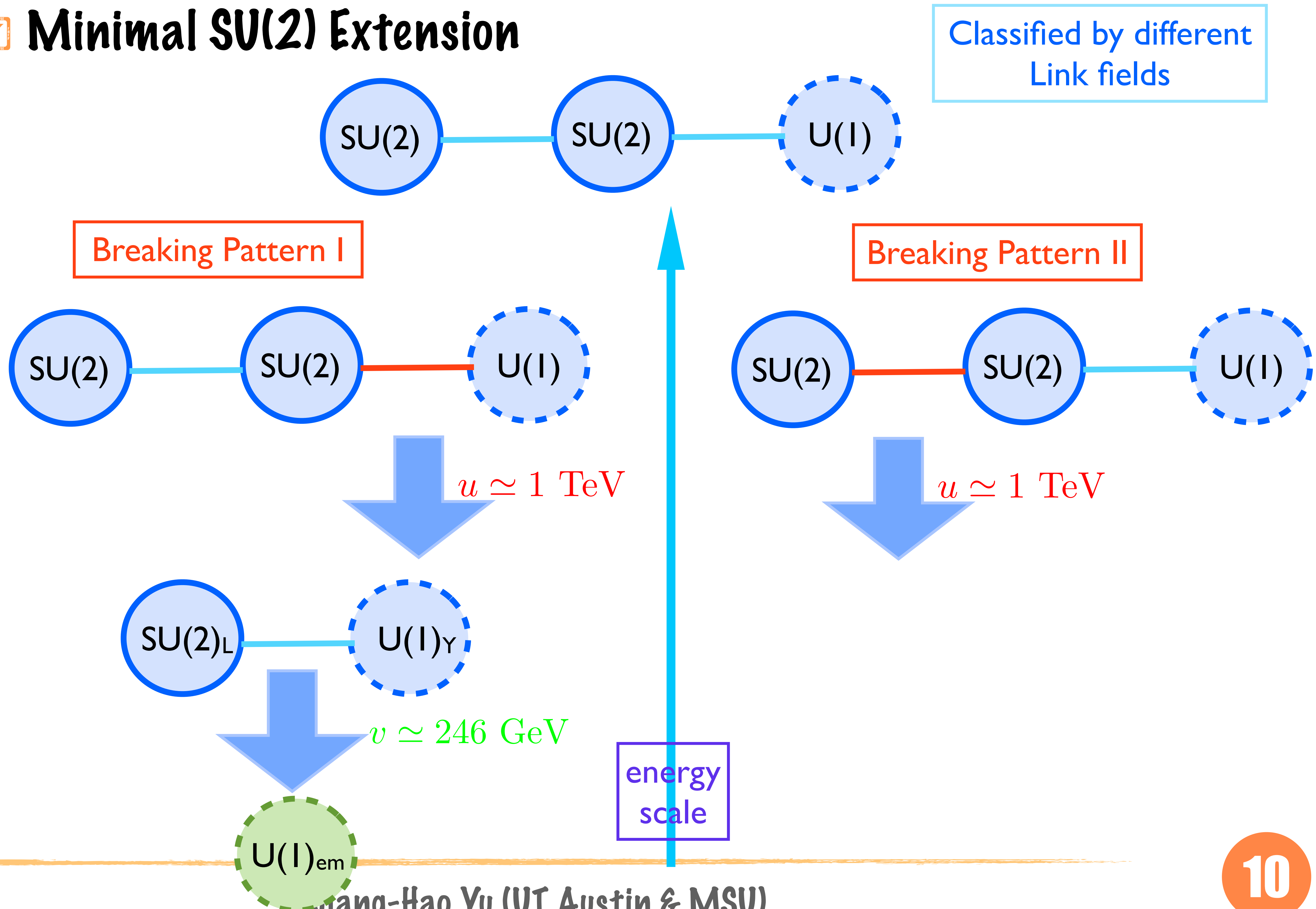

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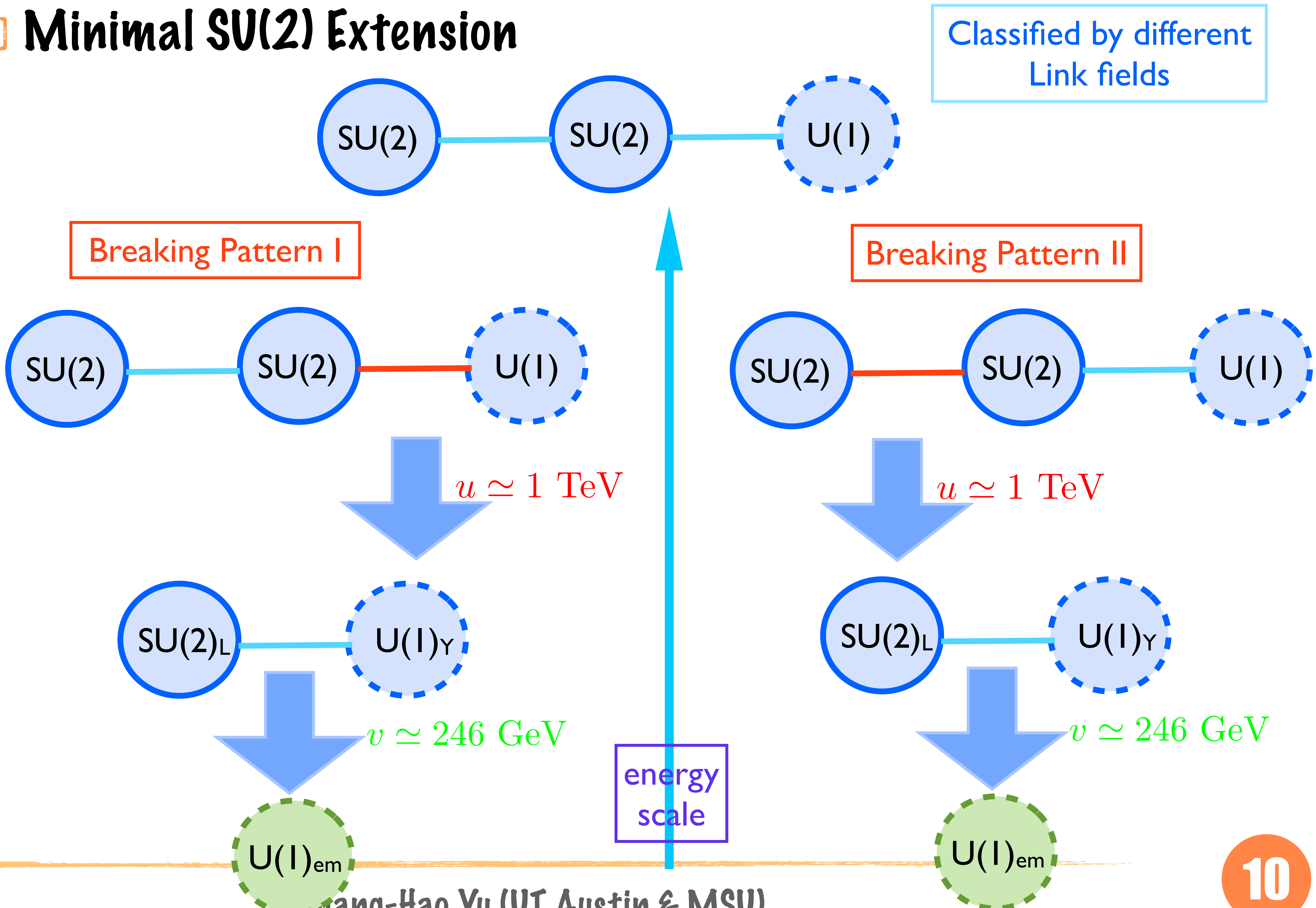
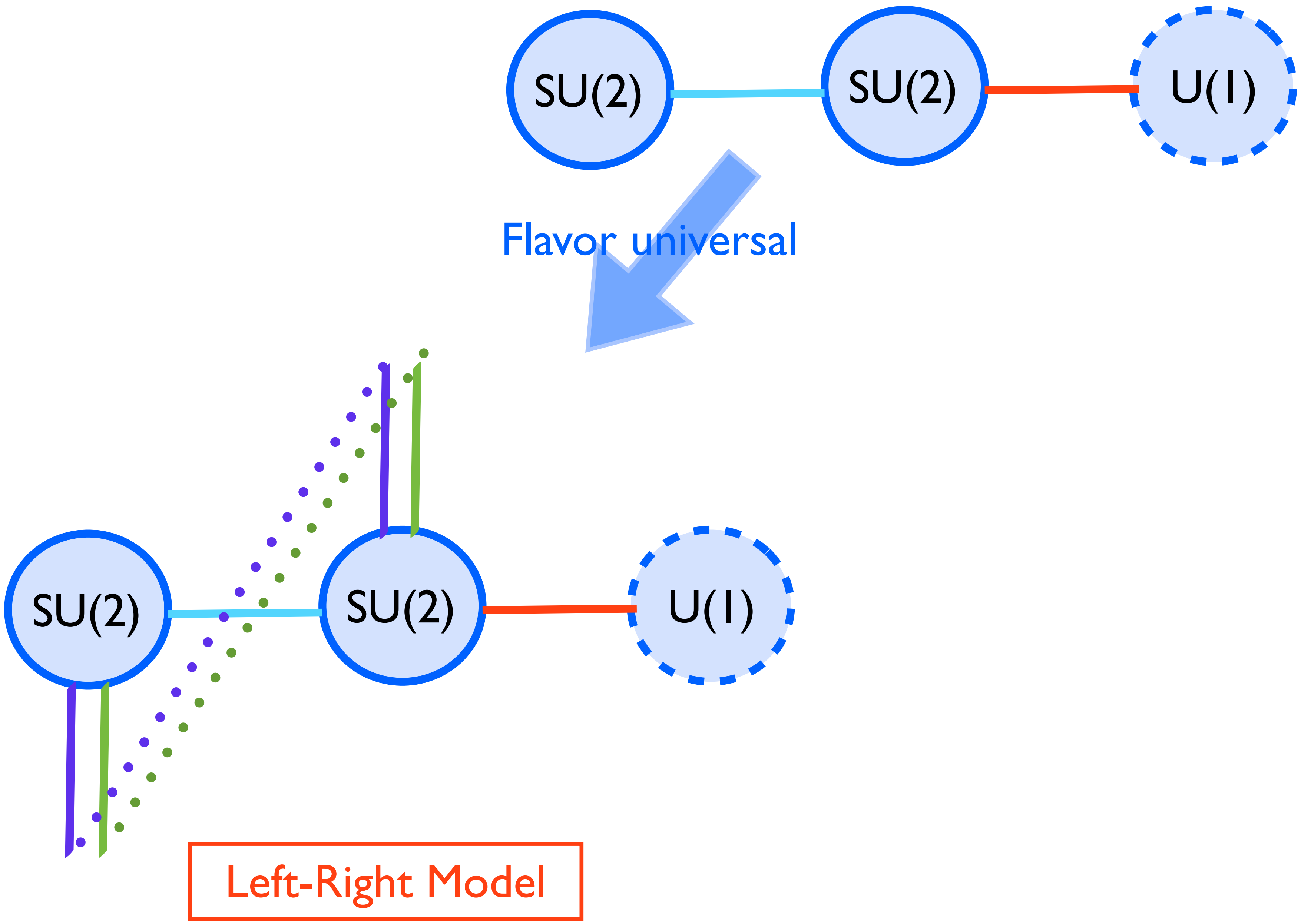


Breaking Pattern I

- Further classified by fermion assignments



Mahapatra, Pati, Senjanovic

Breaking Pattern I

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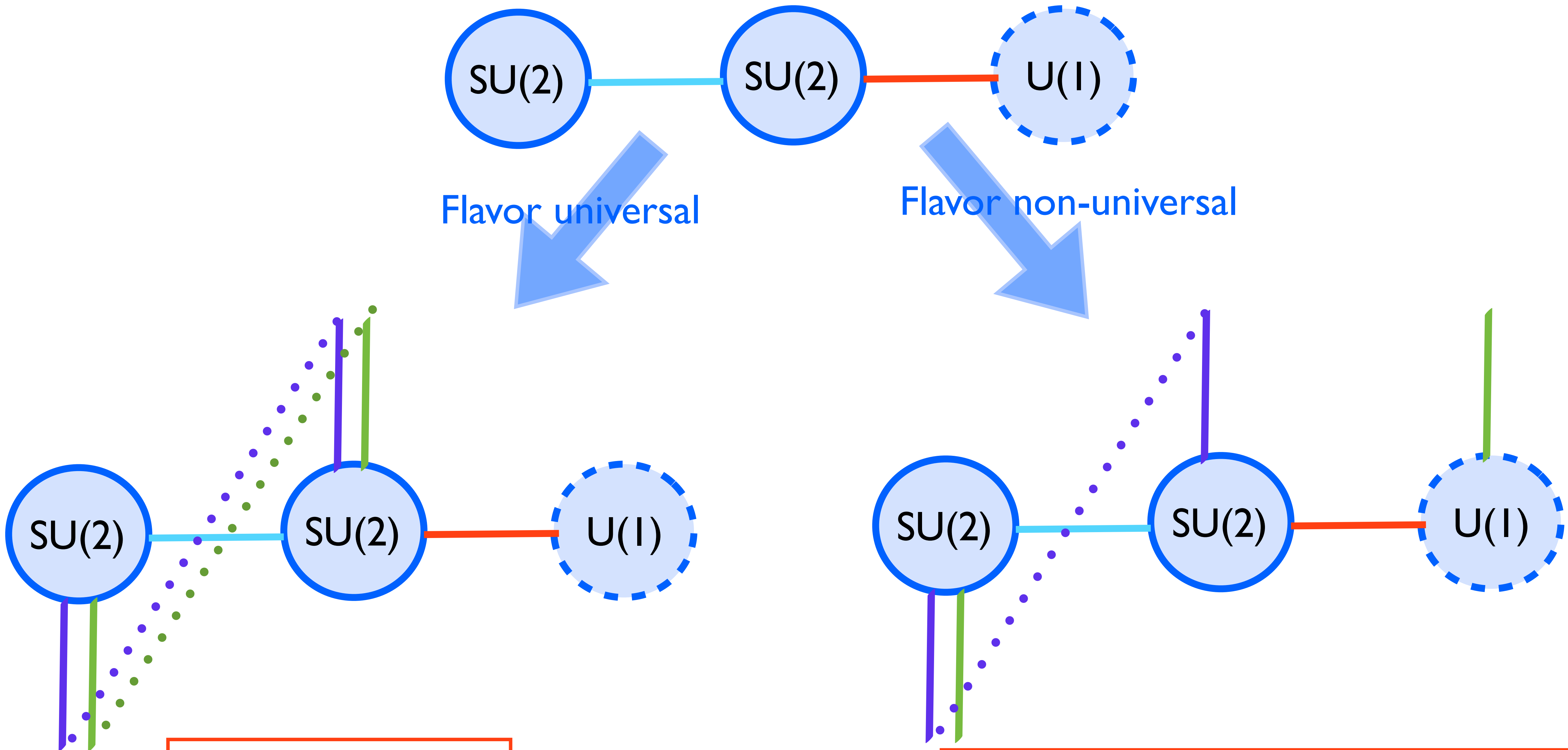


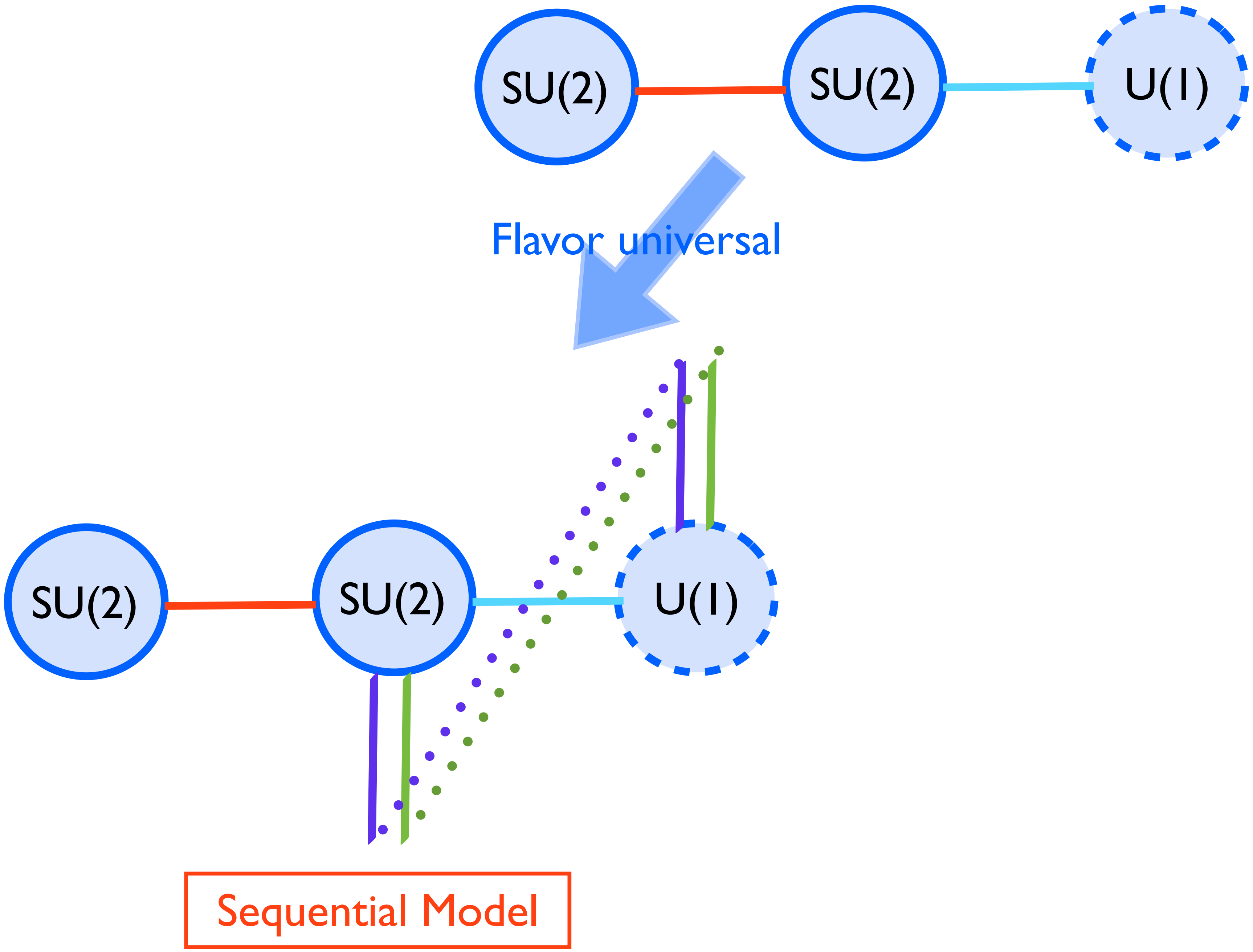
Left-Right Model

Mahapatra, Pati, Senjanovic

Lepto-phobic Model (Quark, Lepton)
Hadro-phobic Model (Quark, Lepton)
Fermio-phobic Model (Quark, Lepton)

BREAKING PATTERN II

- Further classified by fermion assignments



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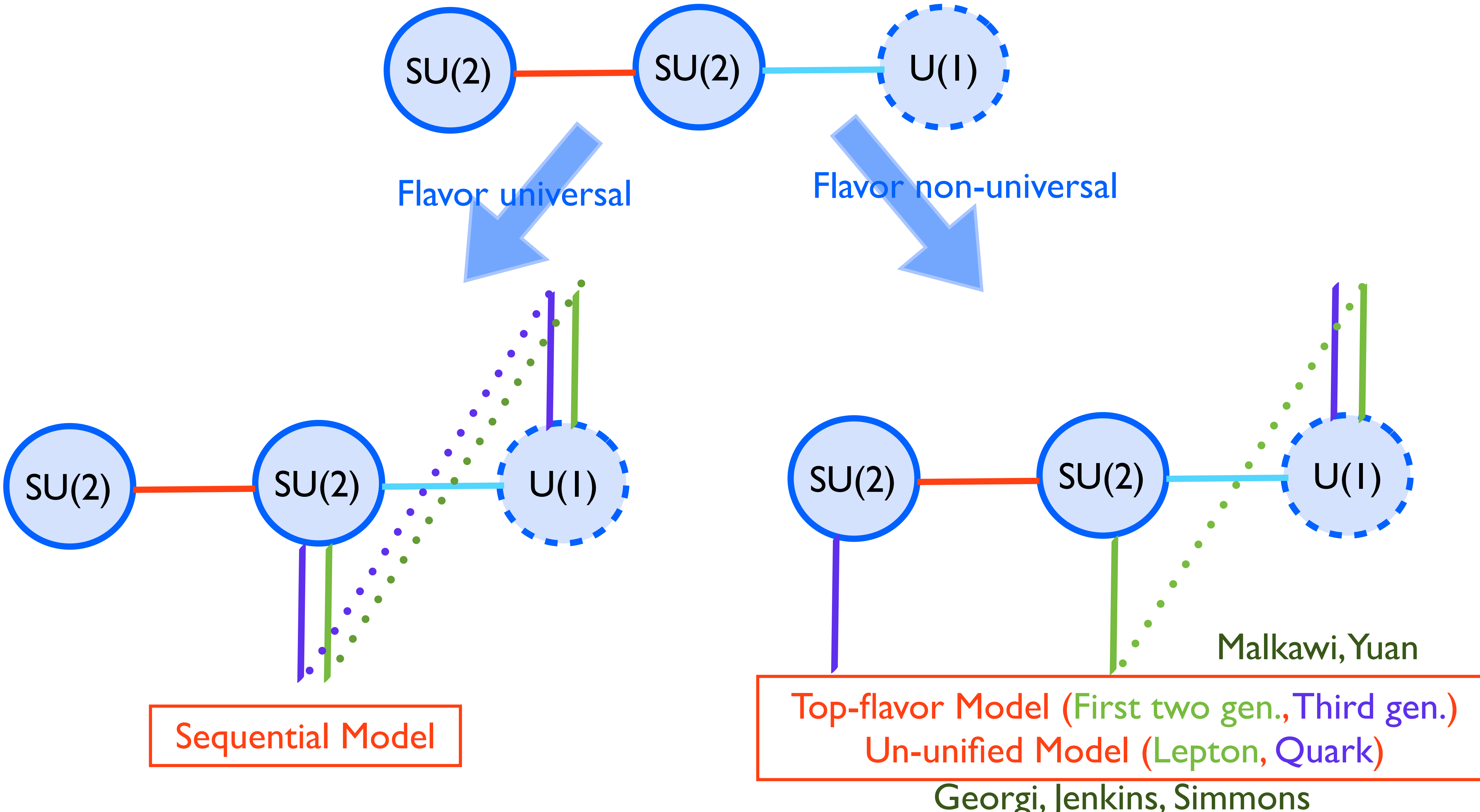
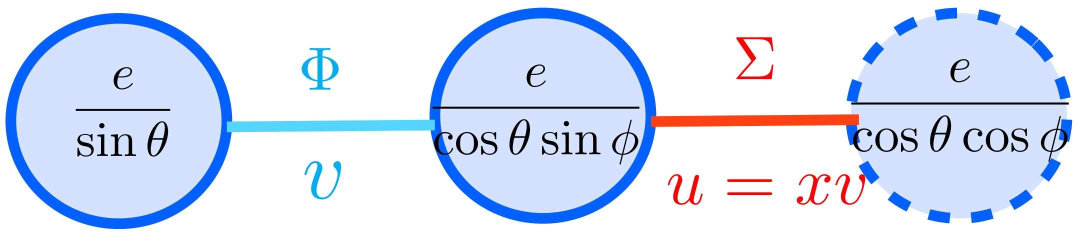
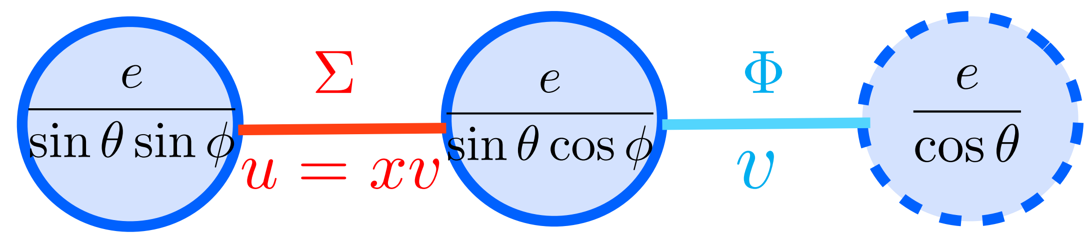


G221 Lagrangians

G221 Lagrangians in Moose notation

The ratio of two scales x = u/v





$$\mathcal{L}_{\text{Links}} = \text{Tr}\left|(D_\mu\Sigma)^\dagger (D^\mu\Sigma)\right| + \text{Tr}\left|(D_\mu\Phi)^\dagger (D^\mu\Phi)\right| - V(\Sigma,\Phi)$$

$$\Sigma = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \to \begin{pmatrix} 0 \\ u/\sqrt{2} \end{pmatrix}$$

$$\Phi = \begin{pmatrix} \phi_1^0 & \phi_1^+ \\ \phi_2^- & \phi_2^0 \end{pmatrix} \to \begin{pmatrix} \frac{v\cos\beta}{\sqrt{2}} & 0 \\ 0 & \frac{v\sin\beta}{\sqrt{2}} \end{pmatrix}$$

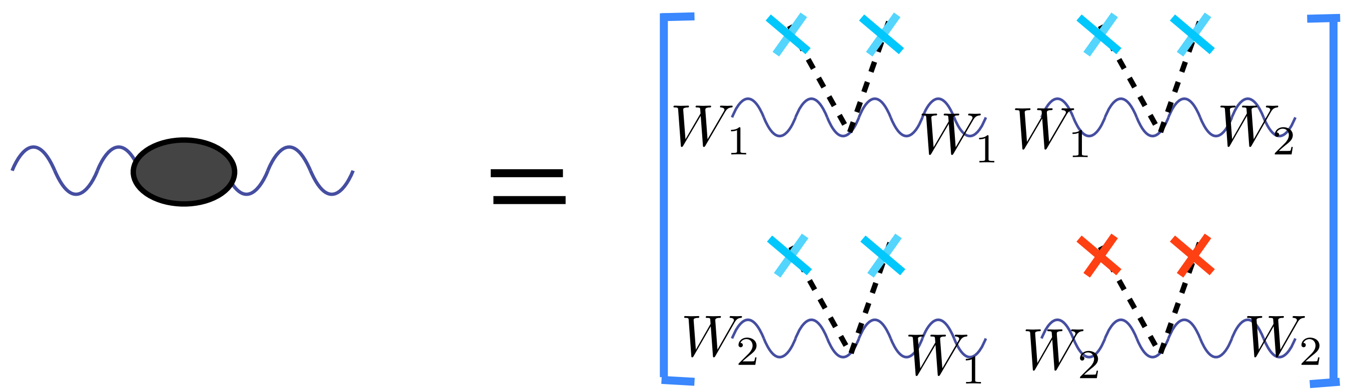
$$M_W^2 = \frac{v^2}{4}\frac{e^2}{\sin^2\theta}\begin{pmatrix} 1 & -\frac{\tan\theta}{\sin\phi}\sin 2\beta \\ -\frac{\tan\theta}{\sin\phi}\sin 2\beta & \frac{\tan^2\theta}{\sin^2\phi}(1+x) \end{pmatrix}$$

$$\Sigma = \begin{pmatrix} \frac{\sigma+i\pi^3}{\sqrt{2}} & \frac{\pi^1+i\pi^2}{\sqrt{2}} \\ -\frac{\pi^1-i\pi^2}{\sqrt{2}} & \frac{\sigma-i\pi^3}{\sqrt{2}} \end{pmatrix} \to \frac{1}{\sqrt{2}}\begin{pmatrix} u & 0 \\ 0 & u \end{pmatrix}$$

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \to \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$$

$$M_W^2 = \frac{v^2}{4}\frac{e^2}{\sin^2\theta}\begin{pmatrix} 1 & -\tan\phi \\ -\tan\phi & \frac{x}{\sin^2\phi\cos^2\phi} + \tan^2\phi \end{pmatrix}$$

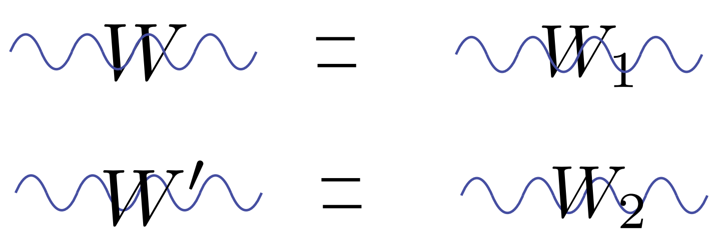
Mass Matrices and Mixing

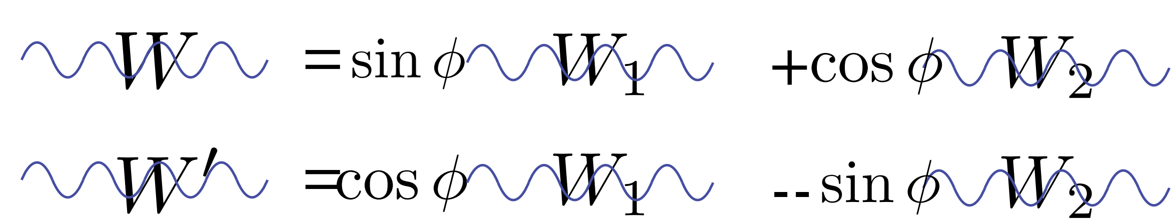


x is large (EWPTs)
Expansion on the ratio of
two scales v/u = 1/x

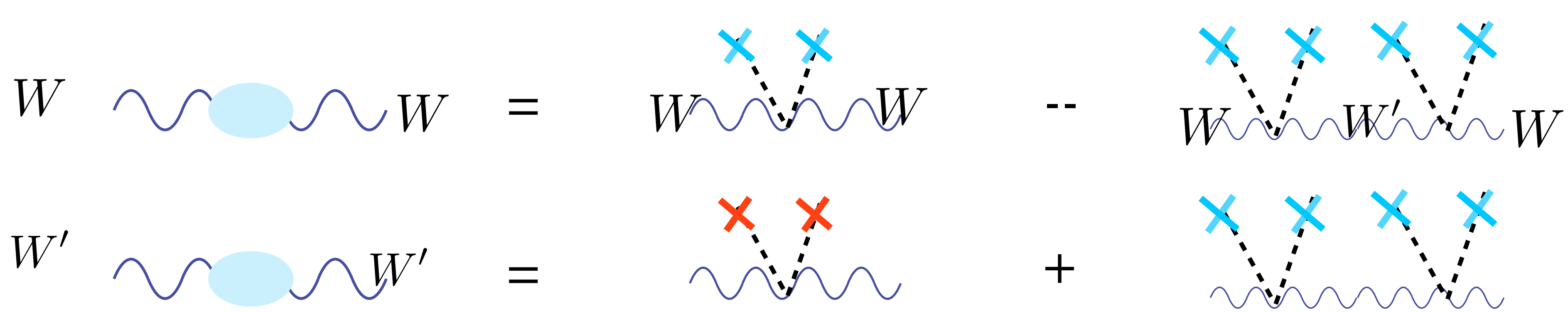
Zero-th order Wave-function

perturbation theory in quantum mechanics

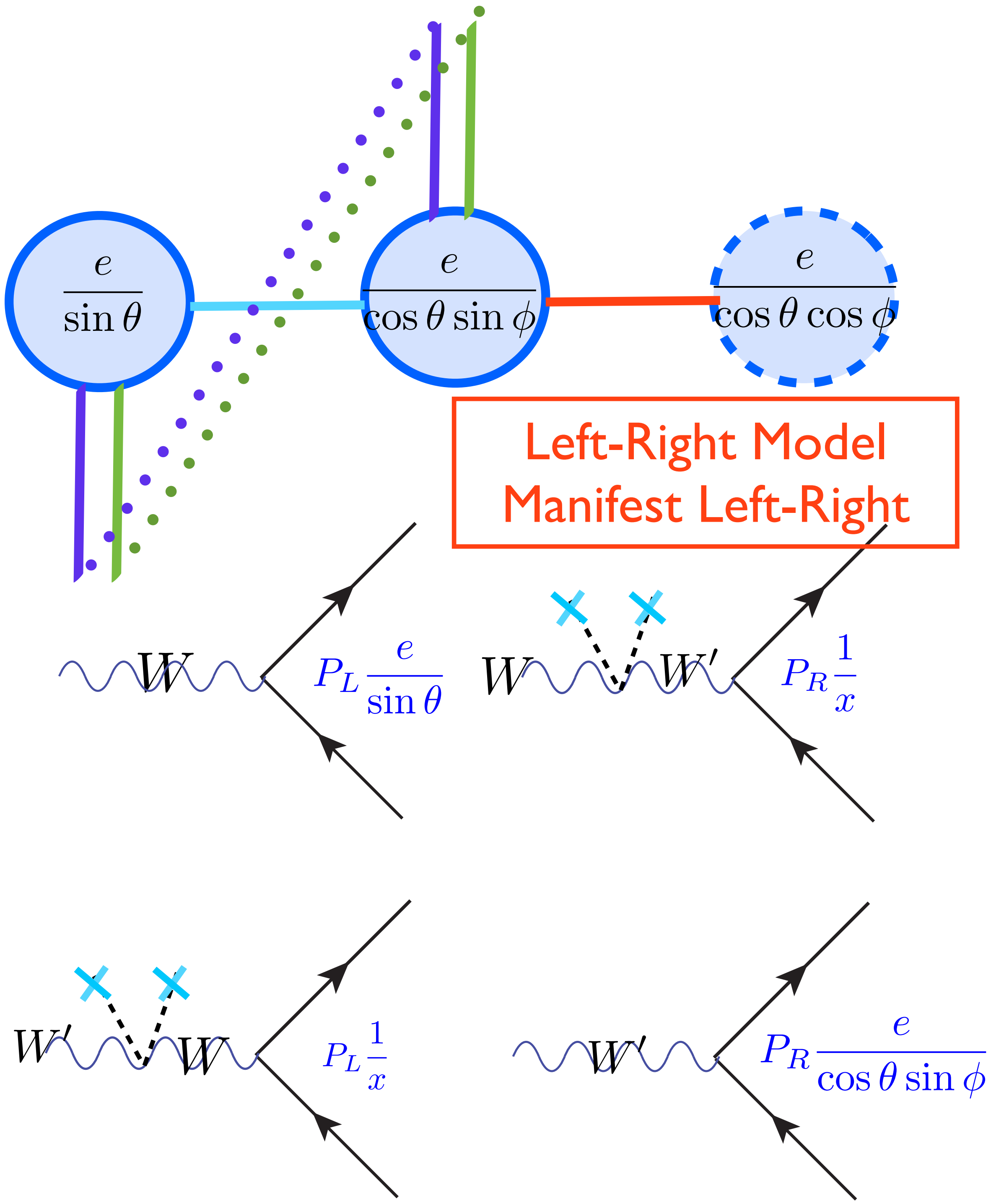




First order Eigenvalue (W' mass)



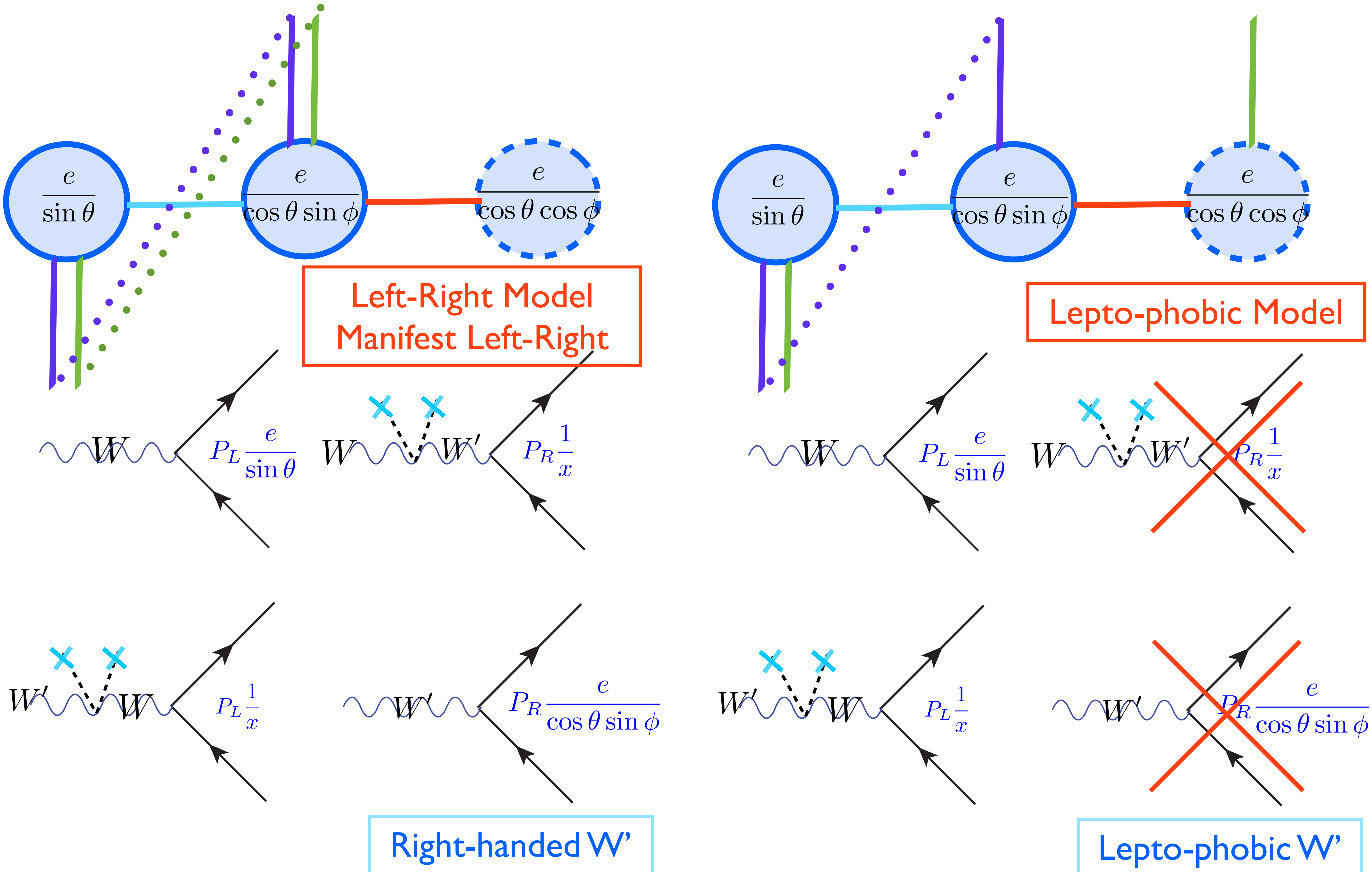
Couplings and Feynman Rules



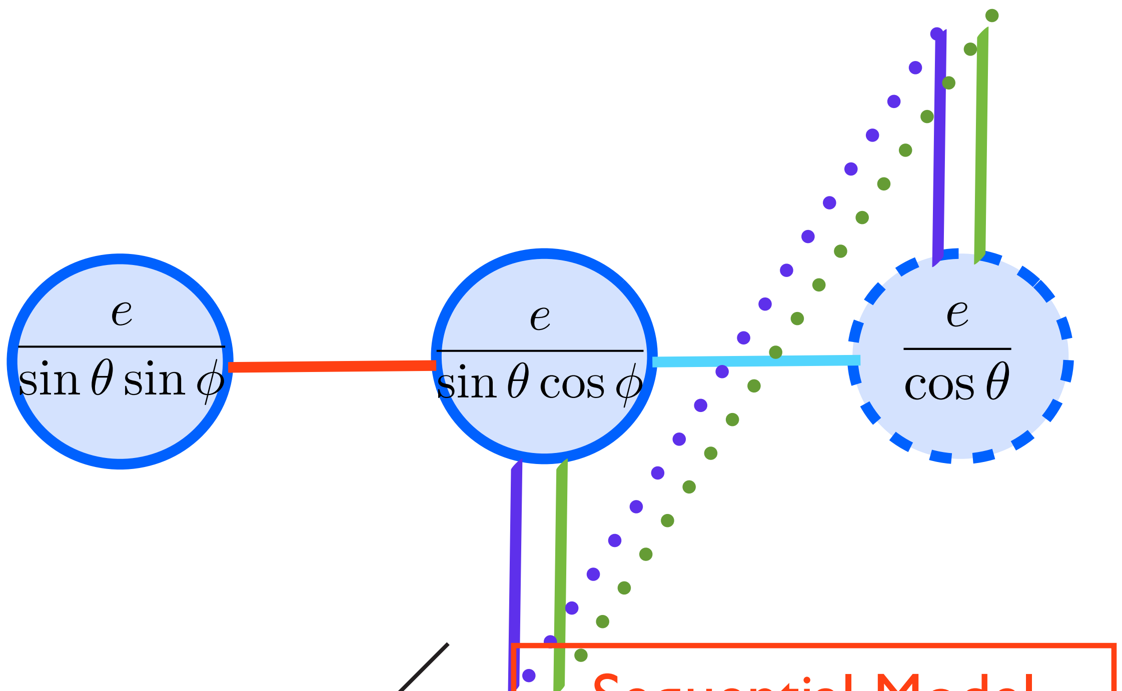
Left-Right Model
Manifest Left-Right

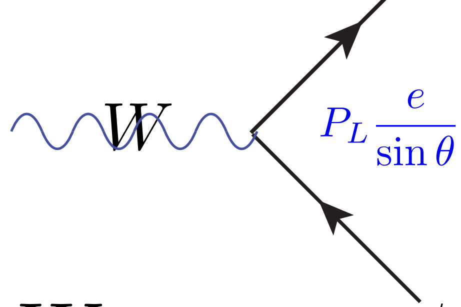
Right-handed W'

Couplings and Feynman Rules

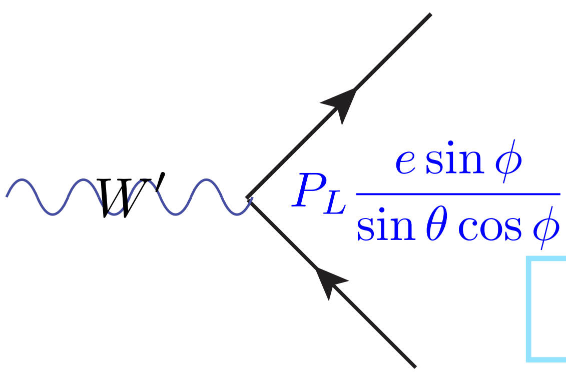


Couplings and Feynman Rules(cont.)





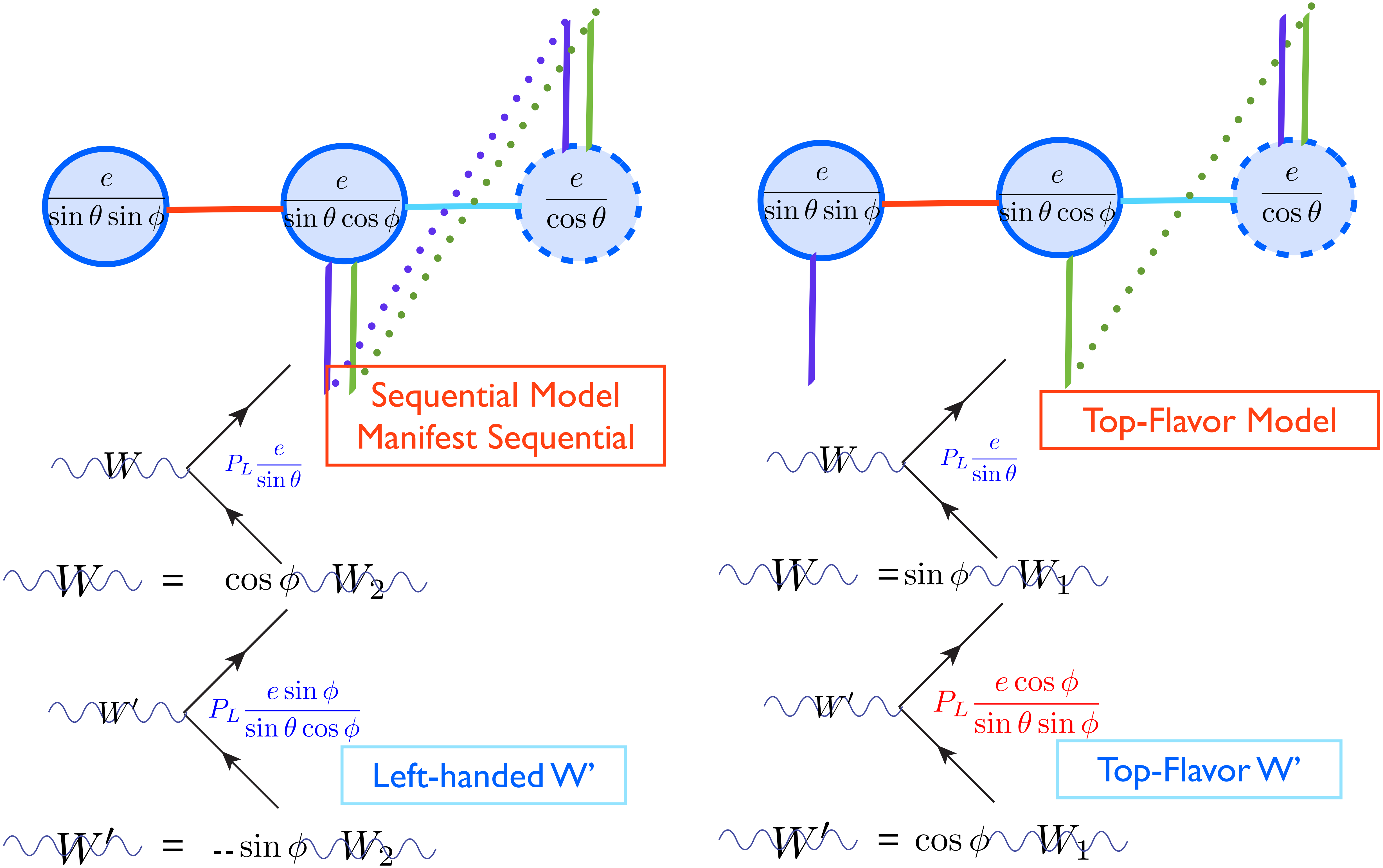
$$W = \cos\phi \; W_2$$



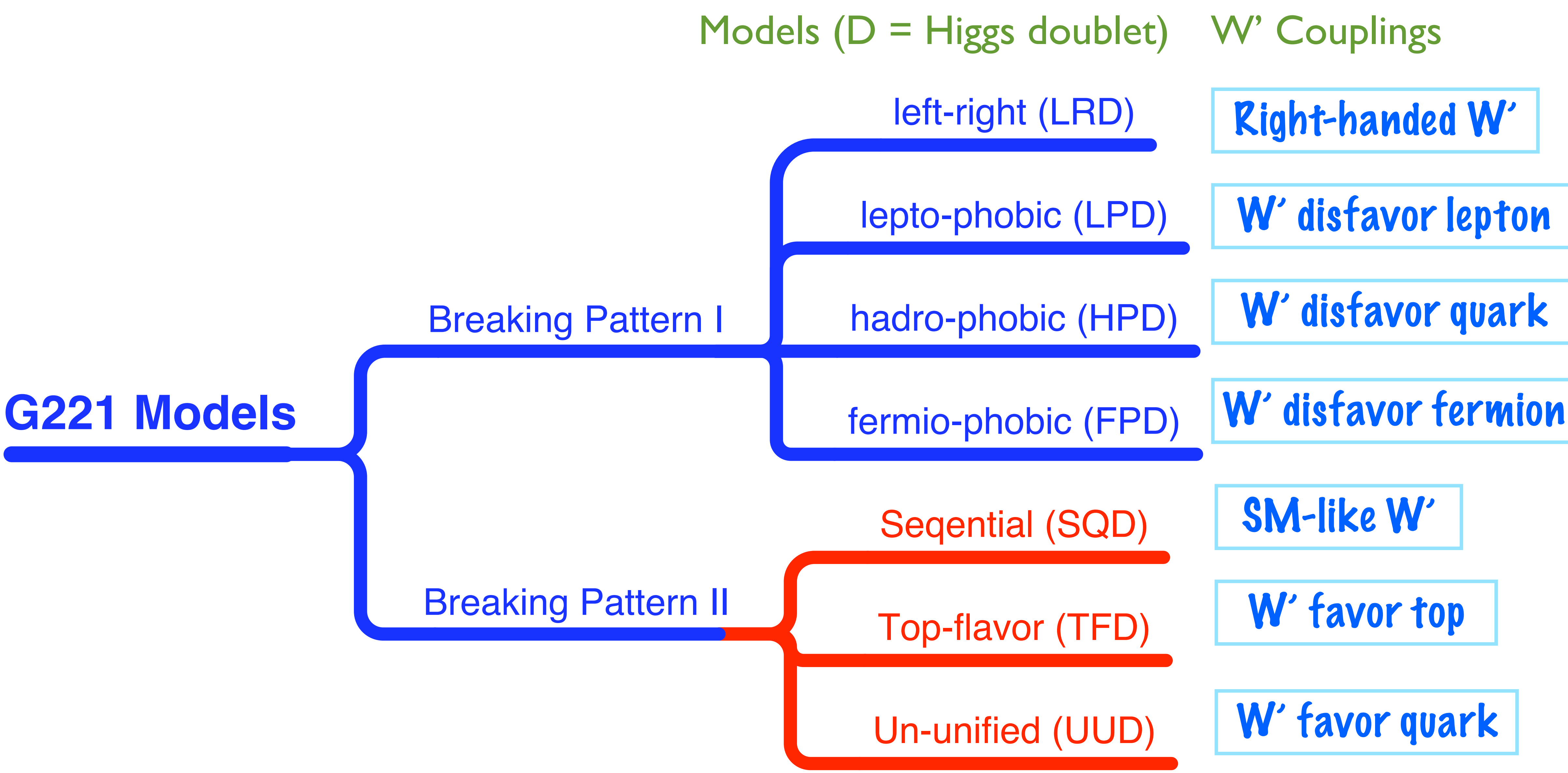
Left-handed W'

$$W' = -\sin\phi \; W_2$$

Couplings and Feynman Rules(cont.)



Summary of G221 Models

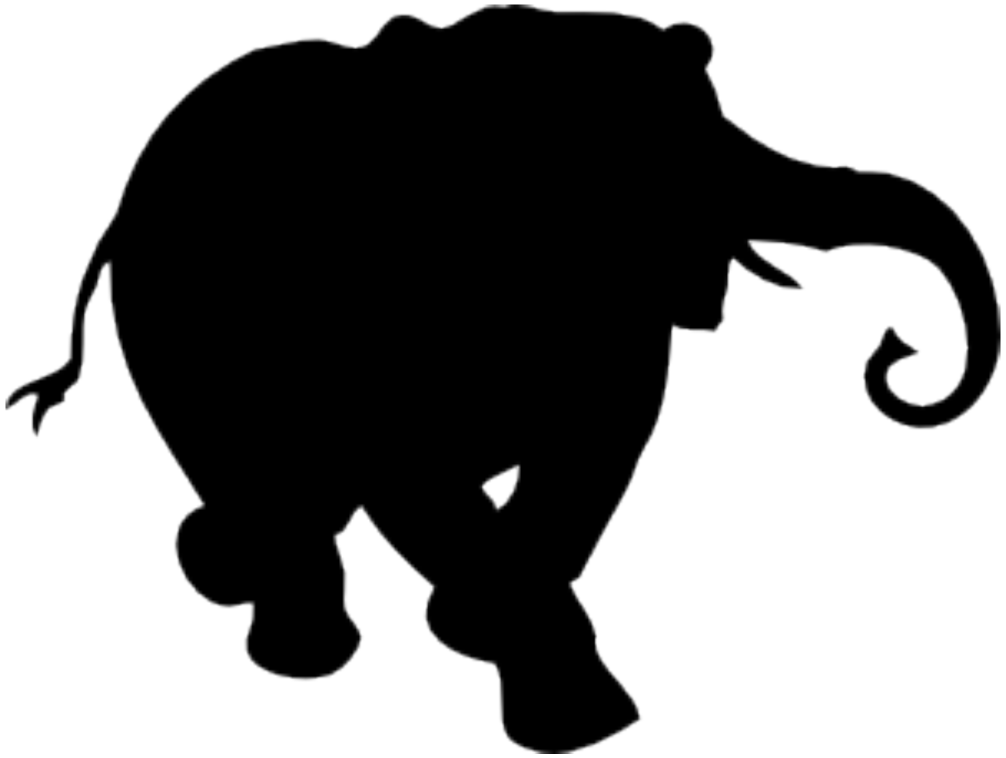


Hsieh, Schmitz, JHY, Yuan

Also other kinds of fermion assignments and Higgs representation ....
Total 10 models

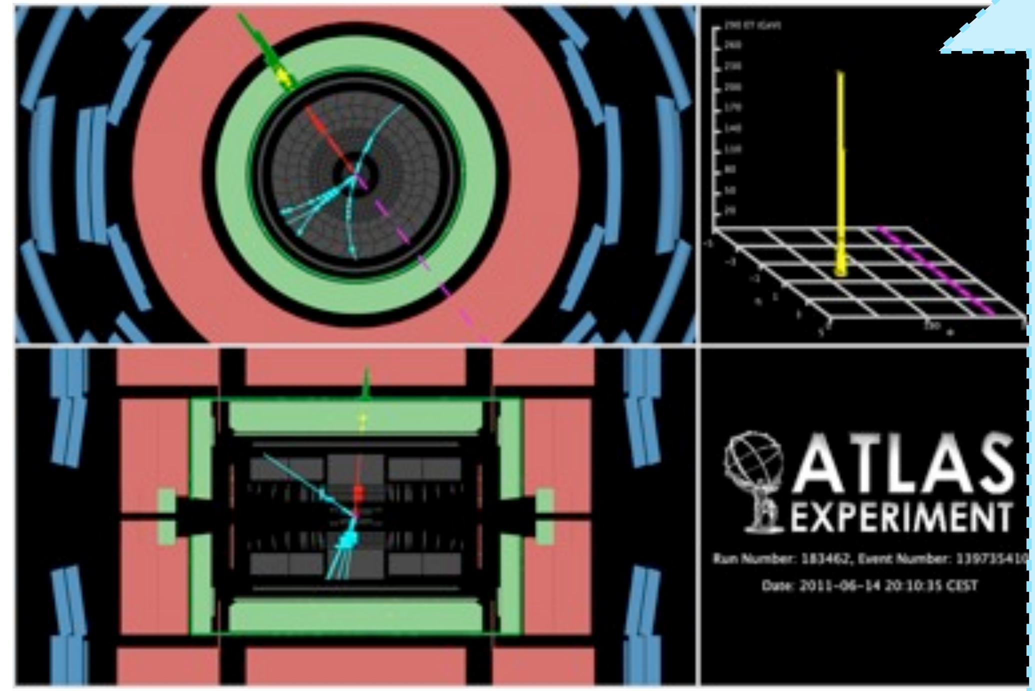
Discovery of Heavy Charged Gauge Bosons (W-primes)

Find an Elephant/a W-prime

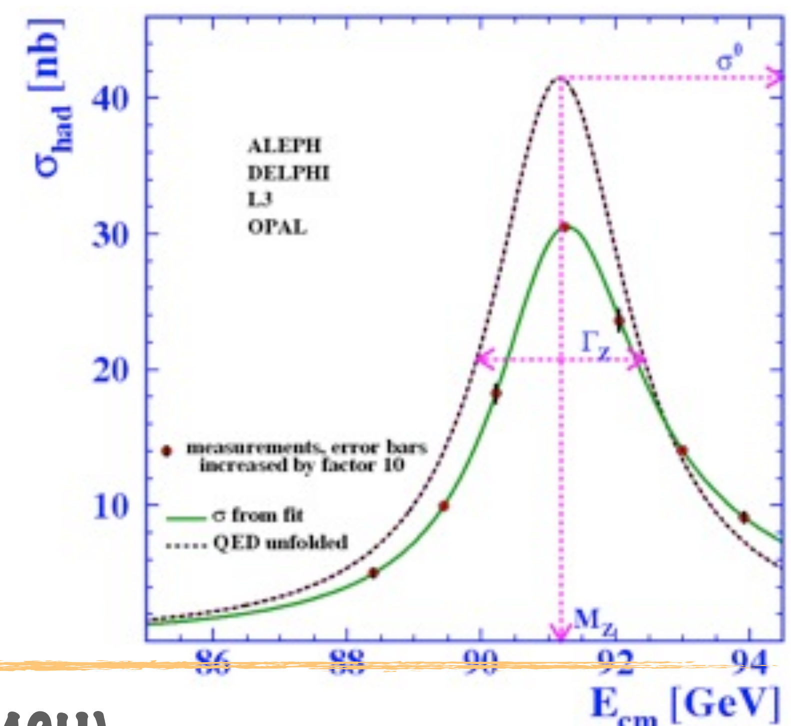


Find elephant!
Direct Searches

Find footprint!
Indirect Searches



Find W-prime! Direct Searches



Low energy, Z-pole data! Indirect Searches

INDIRECT SEARCHES

Quantity	Value	Standard Model	Pull	Dev.
m_t [GeV]	173.1 ± 1.3	173.2 ± 1.3	−0.1	−0.5
M_W [GeV]	80.420 ± 0.031	80.384 ± 0.014	1.2	1.5
	80.376 ± 0.033		−0.2	0.1
g_L^2	0.3027 ± 0.0018	0.30399 ± 0.00017	−0.7	−0.6
g_R^2	0.0308 ± 0.0011	0.03001 ± 0.00002	0.7	0.7
$g_V^{\nu e}$	-0.040 ± 0.015	-0.0398 ± 0.0003	0.0	0.0
$g_A^{\nu e}$	-0.507 ± 0.014	-0.5064 ± 0.0001	0.0	0.0
$Q_W(e)$	-0.0403 ± 0.0053	-0.0473 ± 0.0005	1.3	1.2
$Q_W(\mathrm{Cs})$	-73.20 ± 0.35	-73.15 ± 0.02	−0.1	−0.1
$Q_W(\mathrm{Tl})$	-116.4 ± 3.6	-116.76 ± 0.04	0.1	0.1
τ_τ [fs]	291.09 ± 0.48	290.02 ± 2.09	0.5	0.5
M_Z [GeV]	91.1876 ± 0.0021	91.1874 ± 0.0021	0.1	0.0
Γ_Z [GeV]	2.4952 ± 0.0023	2.4954 ± 0.0009	−0.1	0.1
$\Gamma(\mathrm{had})$ [GeV]	1.7444 ± 0.0020	1.7418 ± 0.0009	—	—
$\Gamma(\mathrm{inv})$ [MeV]	499.0 ± 1.5	501.69 ± 0.07	—	—
$\Gamma(\ell^+\ell^-)$ [MeV]	83.984 ± 0.086	84.005 ± 0.015	—	—
σ_{had}[nb]	41.541 ± 0.037	41.484 ± 0.008	1.5	1.5
R_e	20.804 ± 0.050	20.735 ± 0.010	1.4	1.4
R_μ	20.785 ± 0.033	20.735 ± 0.010	1.5	1.6
R_τ	20.764 ± 0.045	20.780 ± 0.010	−0.4	−0.3
R_b	0.21629 ± 0.00066	0.21578 ± 0.00005	0.8	0.8
R_c	0.1721 ± 0.0030	0.17224 ± 0.00003	0.0	0.0
$A_{FB}^{(0,e)}$	0.0145 ± 0.0025	0.01633 ± 0.00021	−0.7	−0.7
$A_{FB}^{(0,\mu)}$	0.0169 ± 0.0013		0.4	0.6
$A_{FB}^{(0,\tau)}$	0.0188 ± 0.0017		1.5	1.6
$A_{FB}^{(0,b)}$	0.0992 ± 0.0016	0.1034 ± 0.0007	−2.7	−2.3
$A_{FB}^{(0,c)}$	0.0707 ± 0.0035	0.0739 ± 0.0005	−0.9	−0.8
$A_{FB}^{(0,s)}$	0.0976 ± 0.0114	0.1035 ± 0.0007	−0.6	−0.4
$\bar{s}_\ell^2(A_{FB}^{(0,q)})$	0.2324 ± 0.0012	0.23146 ± 0.00012	0.8	0.7
	0.2316 ± 0.0018		0.1	0.0
A_e	0.15138 ± 0.00216	0.1475 ± 0.0010	1.8	2.2
	0.1544 ± 0.0060		1.1	1.3
	0.1498 ± 0.0049		0.5	0.6
A_μ	0.142 ± 0.015		−0.4	−0.3
A_τ	0.136 ± 0.015		−0.8	−0.7
	0.1439 ± 0.0043		−0.8	−0.7
A_b	0.923 ± 0.020	0.9348 ± 0.0001	−0.6	−0.6
A_c	0.670 ± 0.027	0.6680 ± 0.0004	0.1	0.1
A_s	0.895 ± 0.091	0.9357 ± 0.0001	−0.4	−0.4

- 37 Observables: Low energy + LEP
- Global fits (GAPP code) shows no more than 3 sigma excess in SM prediction

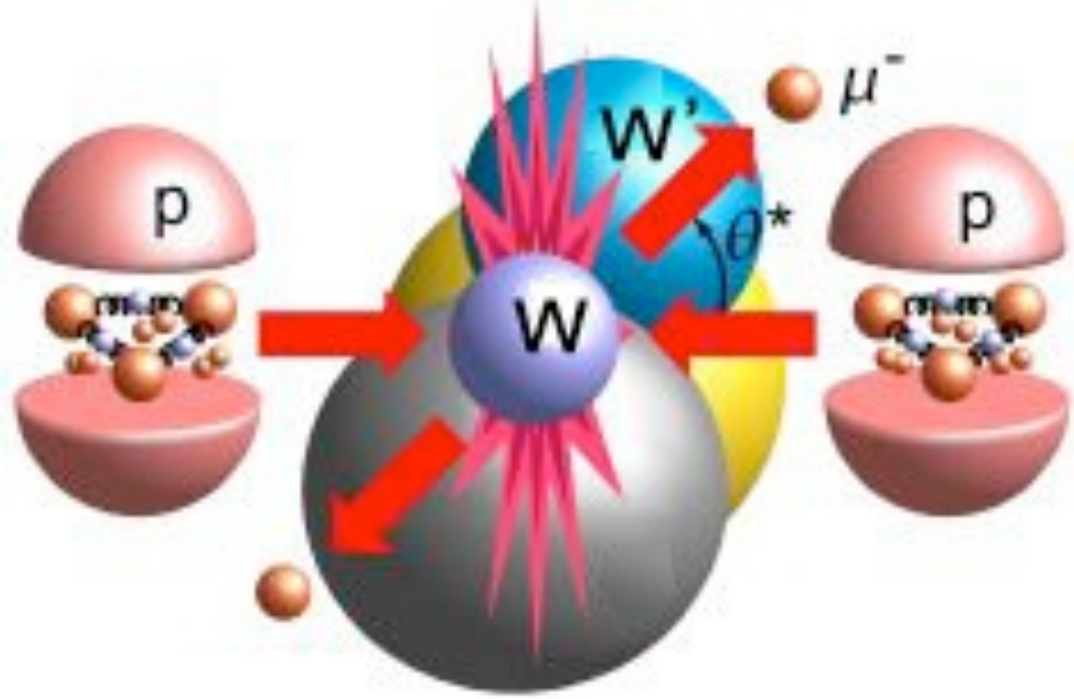
Bad news: No hint on the existence of W-prime!
Good news: Limits on W-prime mass and coupling.

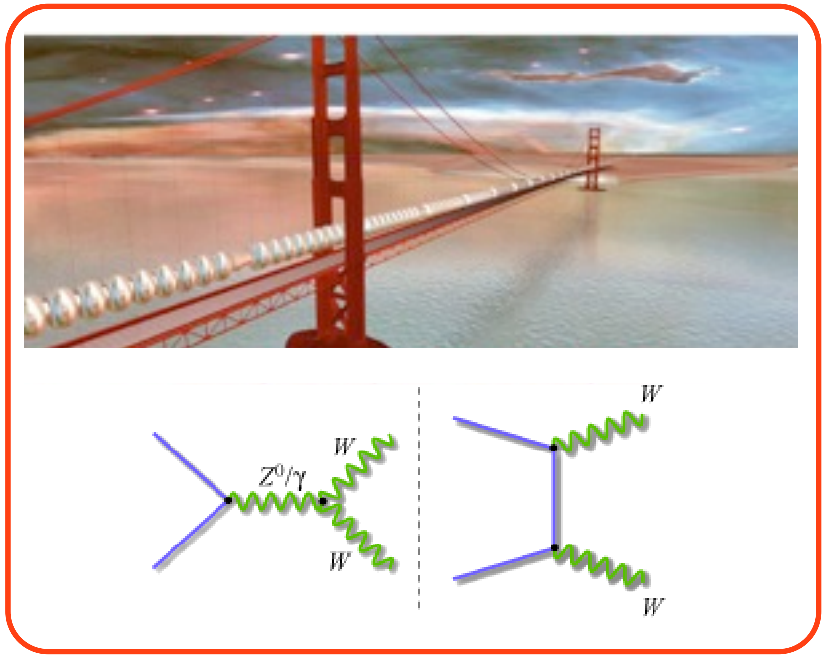
- Re-calculate 37 observables in G221 models and implement to GAPP code
- Redo the global fitting in G221 models

$$\chi^2 = \sum_{i=1}^{37} \left(\frac{\mathcal{O}_i^{\mathrm{exp}} - \mathcal{O}_i^{\mathrm{th}}}{\sigma_i^{\mathrm{exp}}} \right)^2$$

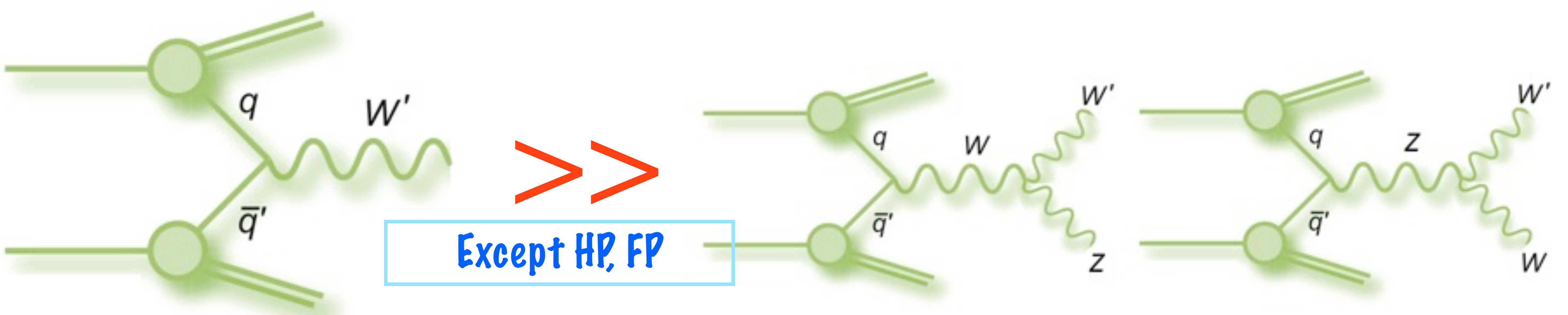
Direct Searches

- Hadron collider: Best machine to discover W-prime



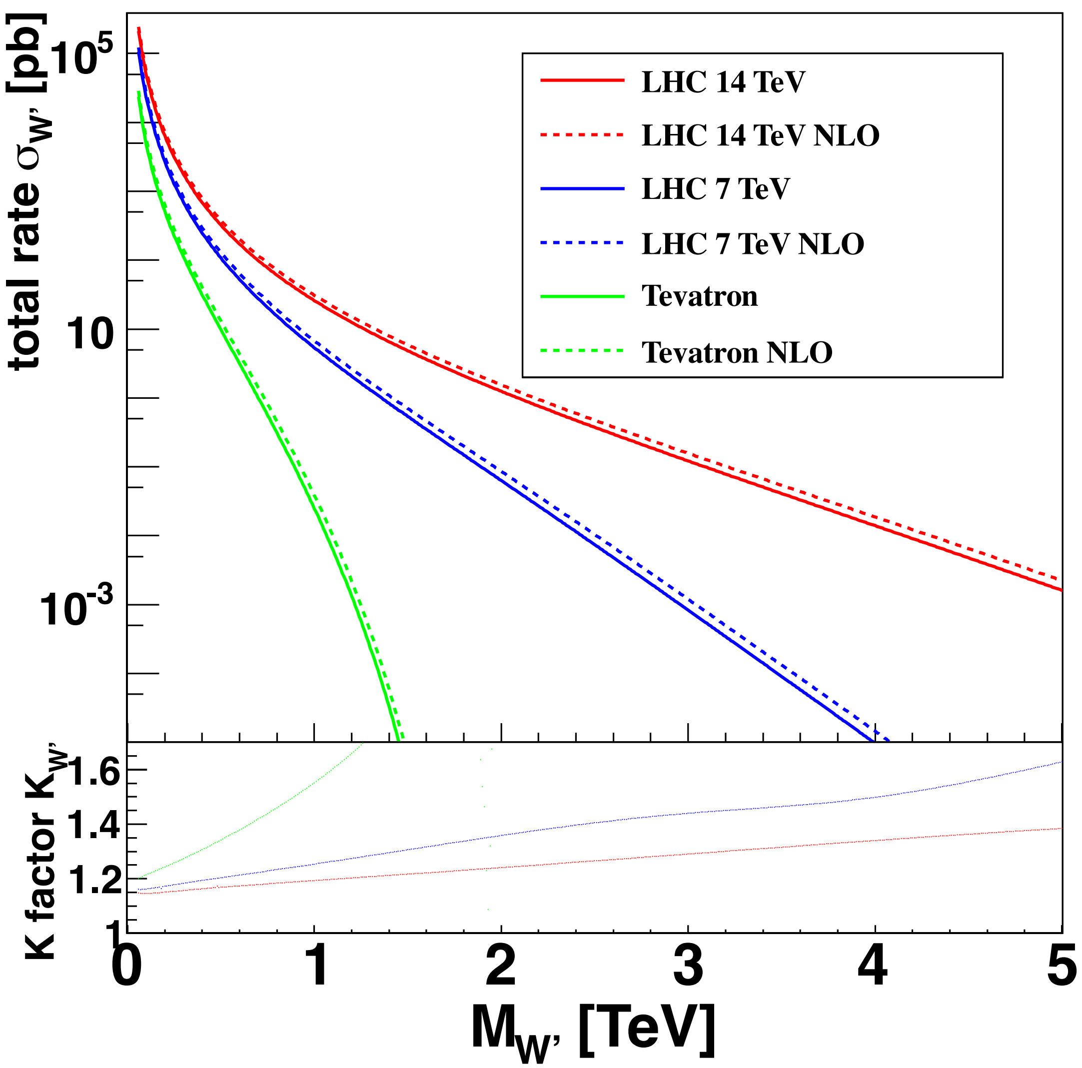


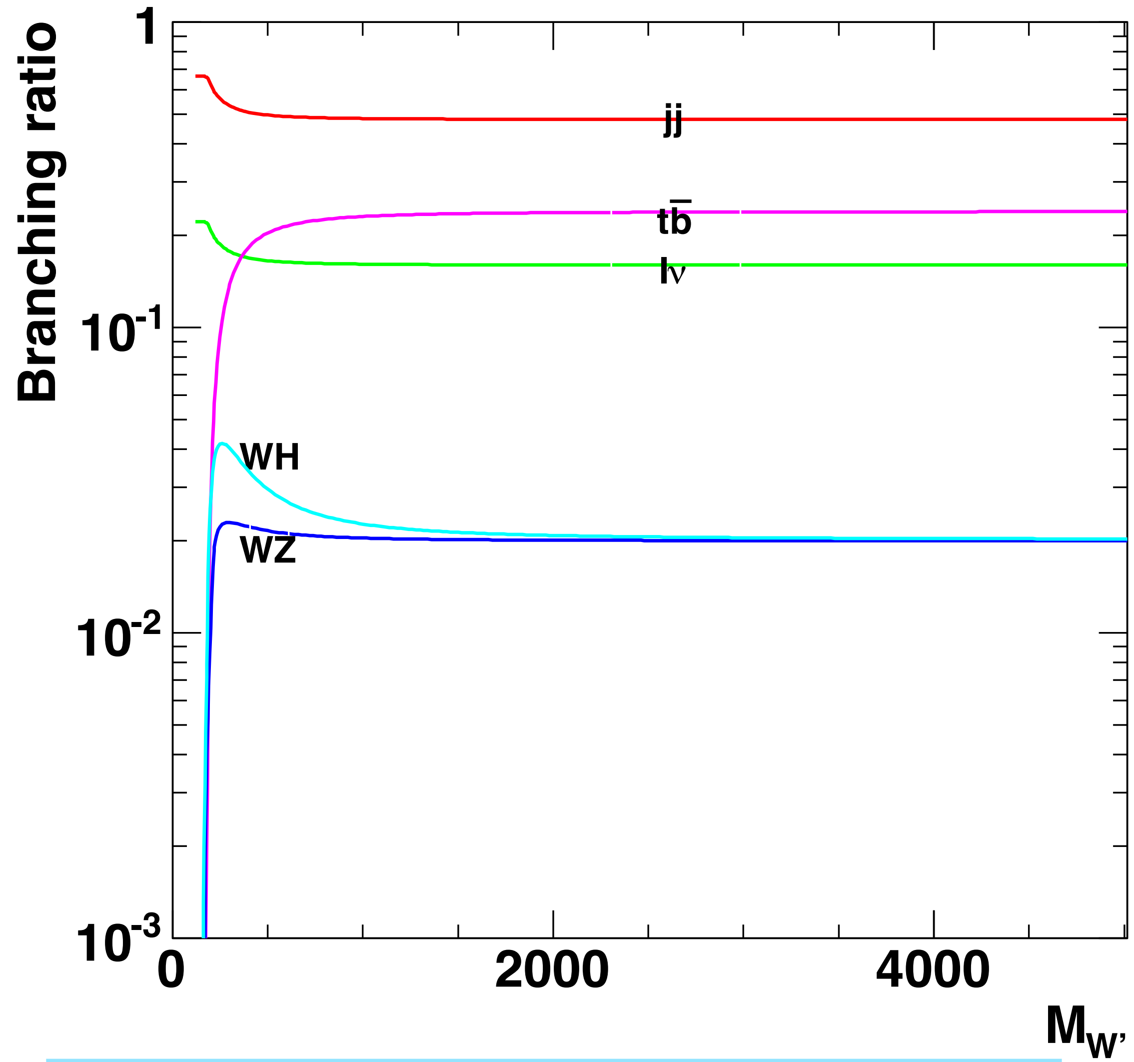
- Production Channels



Production and Decay

- Manifest Sequential Model (Narrow Width Approx.)

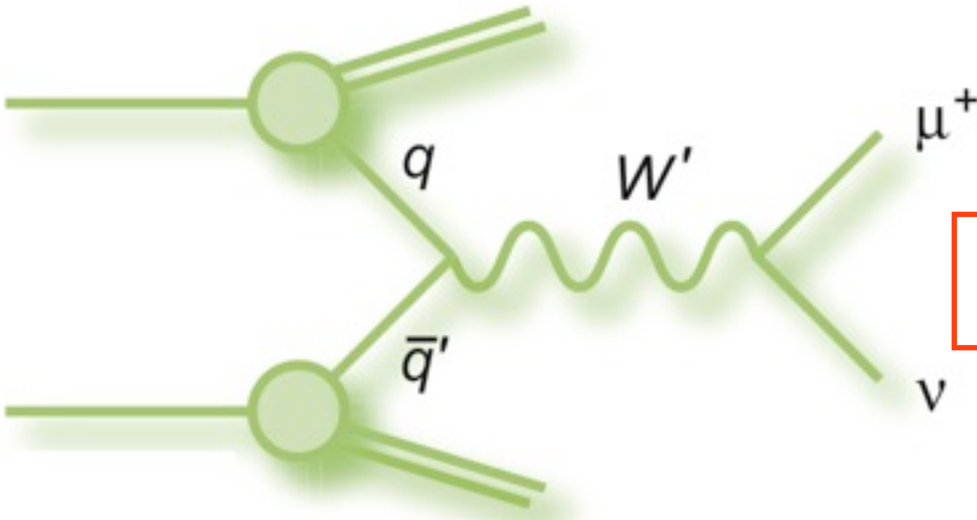




production cross section =
parton luminosity x Coupling squared
Scaling behavior!

jj: huge QCD backgrounds
tb: good, but many decay products
lv: cleanest channel at hadron collider
WH and WZ: small branching ratio

Drell-Yan Process

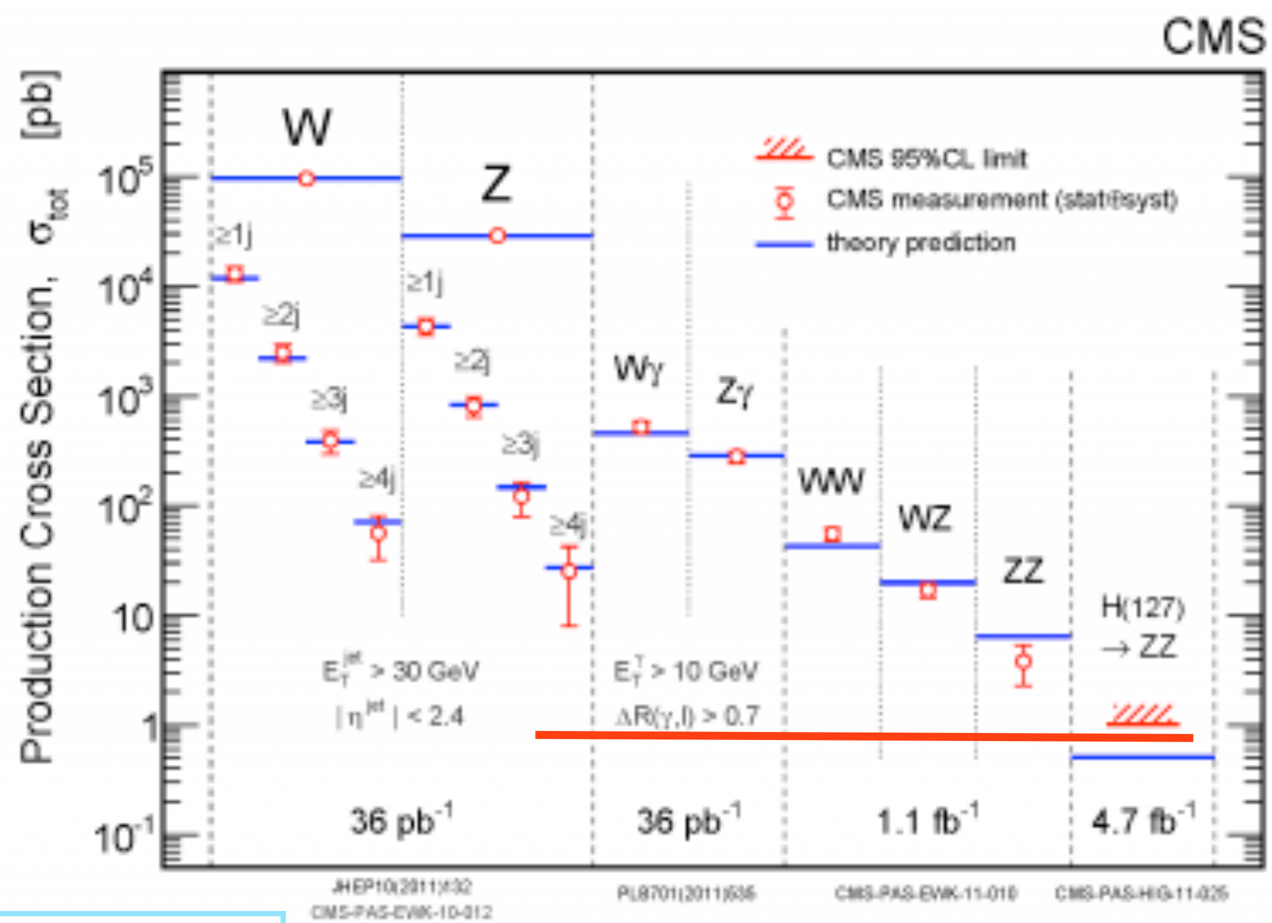


final states: charged lepton plus missing energy
signature: transverse mass (Jacobian Peak)

$$M_T(e,\nu) = \sqrt{(|\vec{p}_T^{\,e}| + |\vec{p}_T^{\,\nu}|)^2 - (\vec{p}_T^{\,e} + \vec{p}_T^{\,\nu})^2} = \sqrt{2E_T^e E_T^\nu(1-\cos(\phi_e - \phi_\nu))}$$

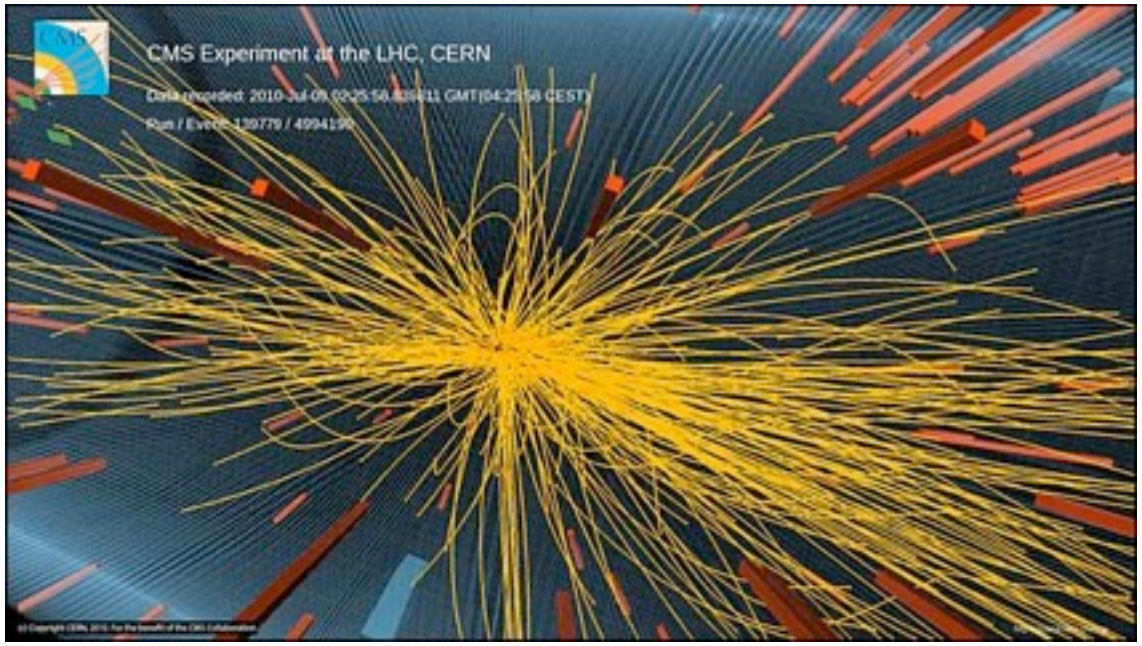
$$\frac{d\sigma}{dM_T} = \frac{d\sigma}{d\cos\theta}\frac{d\cos\theta}{dM_T} = \frac{d\sigma}{d\cos\theta}\frac{M_T}{2M_{W'}\sqrt{M_{W'}^2 - M_T^2}},$$

Process	Mass [GeV]	σB [pb]
$W' \to \ell\nu$	500	17.25
	600	8.27
	750	3.20
	1000	0.837
	1250	0.261
	1500	0.0887
	1750	0.0325
	2000	0.0126
	2250	0.00526
	2500	0.00234
$W \to \ell\nu$		10460
$Z/\gamma* \to \ell\ell$ ($m_{Z/\gamma*} > 60$ GeV)		989
$t\bar{t} \to \ell X$		89.4



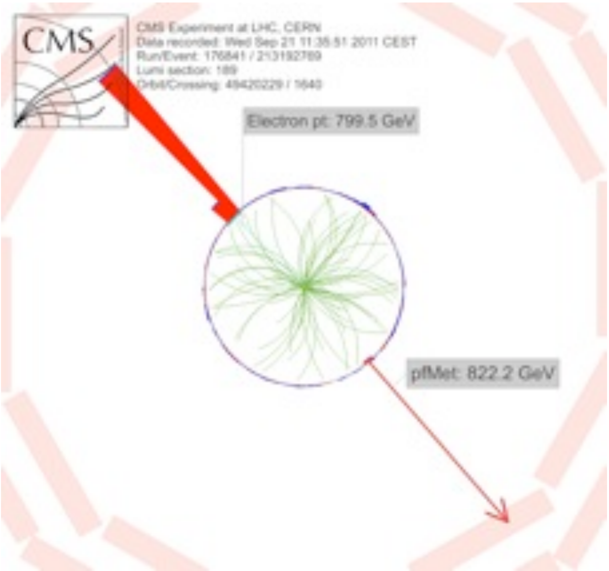
Huge backgrounds!

Find a Needle in a Haystack

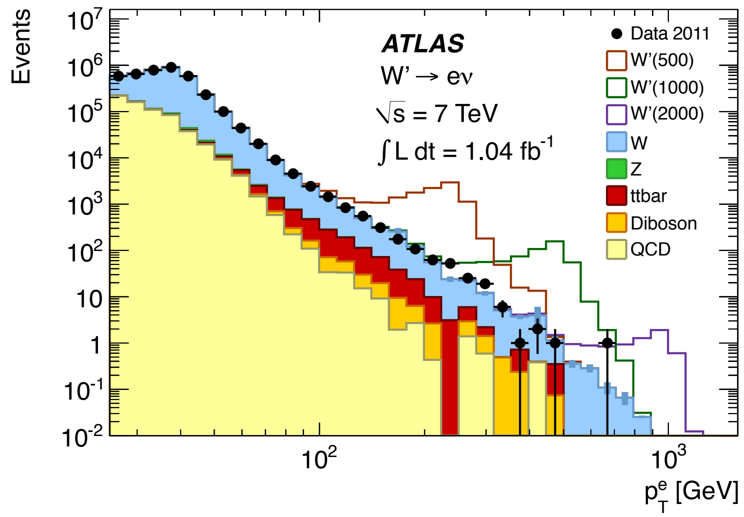


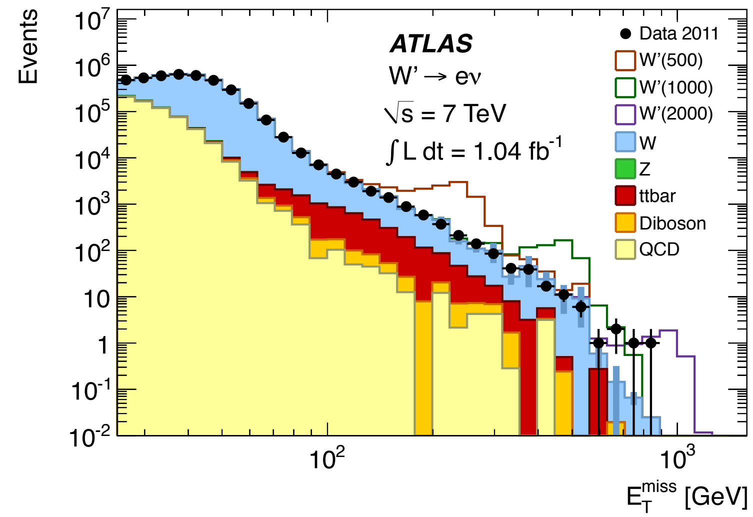
Suppress backgrounds

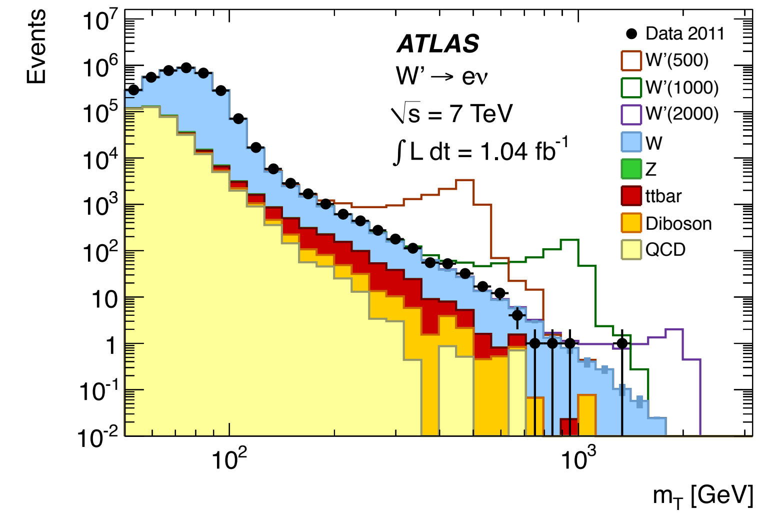
Remove almost all haystack



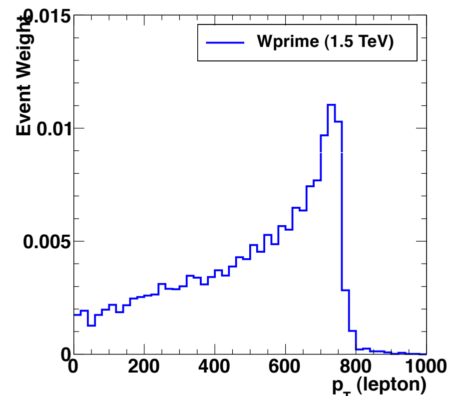
Background Suppression

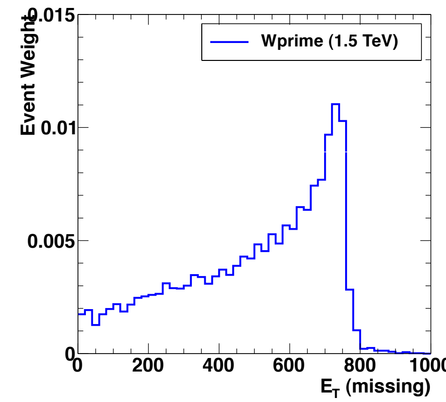


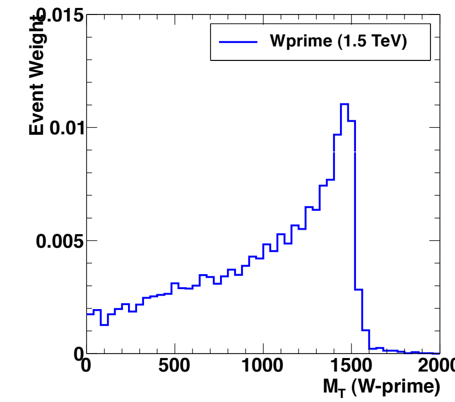




Benchmark Model:
W' 1500 GeV,
manifest sequential model
Width 50 GeV







$$p_T^\ell > 20 \text{ GeV}$$
$$|\eta^\ell| < 2.5$$
$$\Delta R < 0.4 \text{ isolation}$$
$$E_T^{\text{mis}} > 25 \text{ GeV}$$
$$M_T > 891 \text{ GeV}$$

	$e\nu$	$\mu\nu$
$\sigma B \mathcal{L}$	92.248	92.248
ϵ_{sig}	0.541 $\pm$ 0.026	0.347 $\pm$ 0.024
N_{sig}	49.6 $\pm$ 6.0	34.4 $\pm$ 4.4
$W \to l\nu$	1.59 $\pm$ 0.13	1.36 $\pm$ 0.13
$Z \to ll$	0.00010 $\pm$ 0.00004	0.095 $\pm$ 0.005
diboson	0.08 $\pm$ 0.08	0.11 $\pm$ 0.08
$t\bar{t}$	0.08 $\pm$ 0.08	0
QCD	$0^{+0.17}_{-0}$	$0.01^{+0.02}_{-0.01}$
Total N_{bg}	$1.75^{+0.24}_{-0.18}$	1.57 $\pm$ 0.15
N_{obs}	2	2

Upper Limits in Counting Experiments

N observed events, modeled as Poisson distribution with mean $N_{\rm exp} = \epsilon_{\rm sig}\mathcal{L}_{\rm int}\sigma B + N_{\rm bg}$

Likelihood function

$$\mathcal{L}(N_{\rm obs}|\sigma B) = \frac{(\epsilon_{\rm sig}\mathcal{L}_{\rm int}\sigma B + N_{\rm bg})^{N_{\rm obs}}}{N_{\rm obs}!} e^{-(\epsilon_{\rm sig}\mathcal{L}_{\rm int}\sigma B + N_{\rm bg})}$$

Posterior Probability

$$\mathcal{P}(\sigma B|N_{obs}) = \frac{1}{N}\mathcal{L}(N_{obs}|\sigma B)\pi(\sigma)$$

Bayesian statistics

Upper Limits

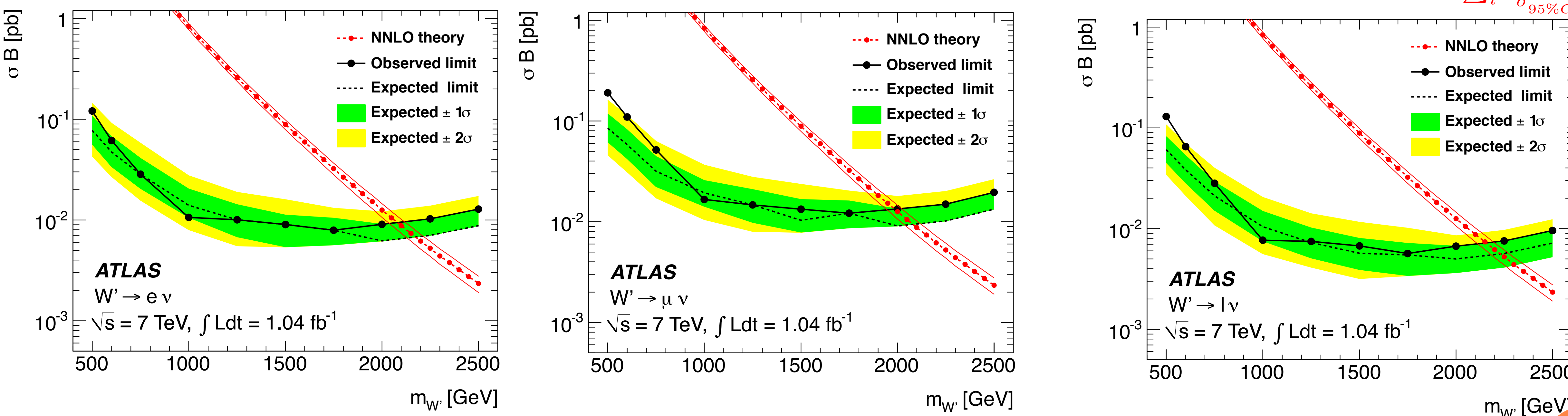
$$\int_0^{(\sigma B)_{95\%CL}} \mathcal{P}(\sigma B|N_{\rm obs})d(\sigma B) = 95\%$$

Flat prior in counting exp.

Neglect uncertainties

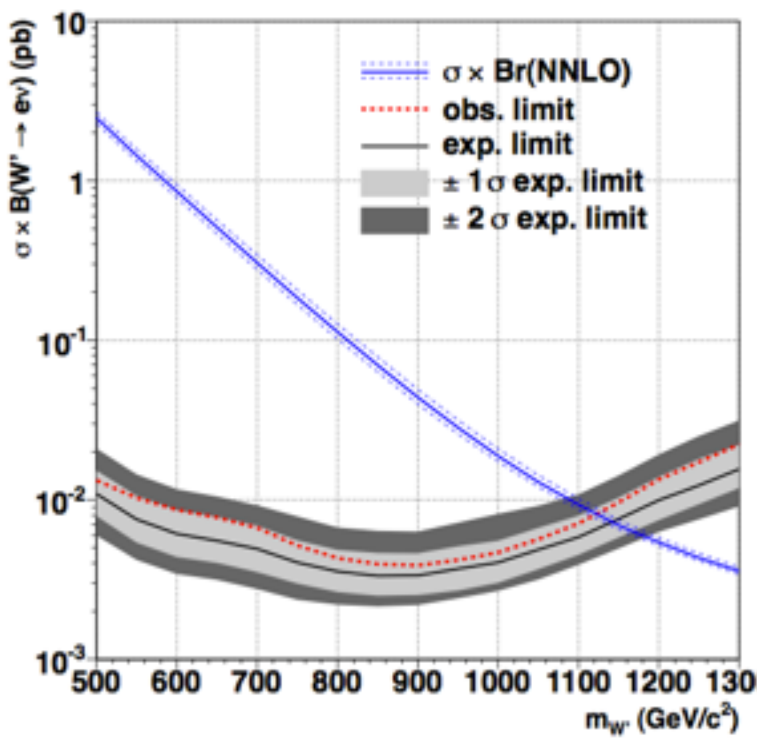
$$1 - \frac{\Gamma(N_{\rm obs}+1, (\sigma B)_{95\%CL}\epsilon_{\rm sig}\mathcal{L}_{\rm int})}{\Gamma(N_{\rm obs}+1, N_{\rm bg})} = 95\%$$

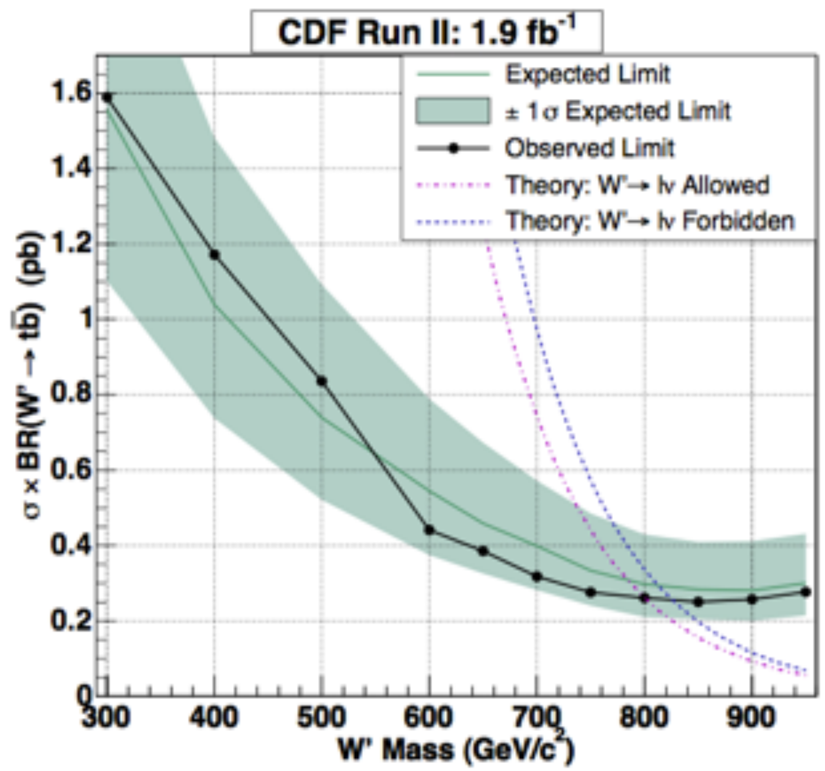
$$\sigma^2_{95\%CL} = \frac{1}{\sum_i^N \frac{1}{\sigma^2_{95\%CL\ i}}}$$

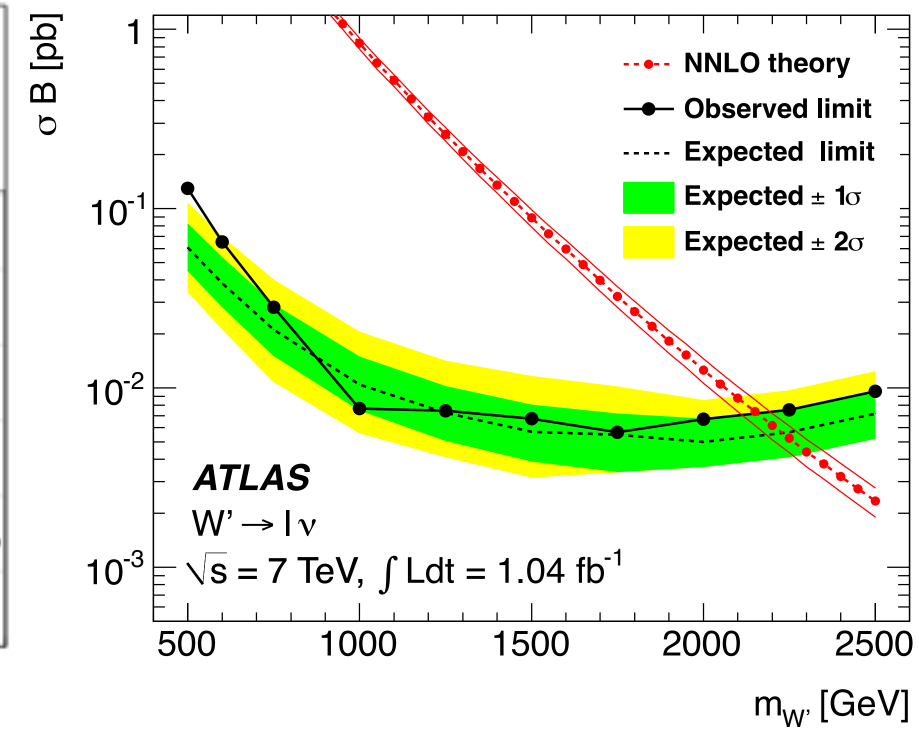


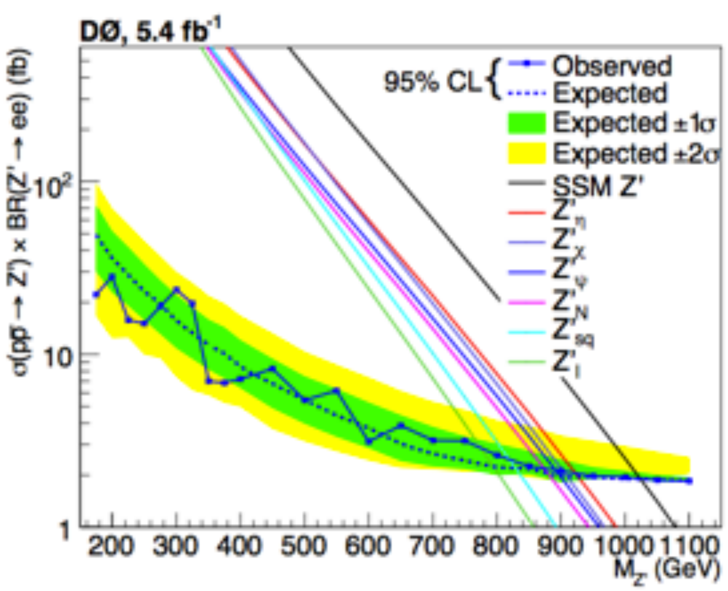
Direct Searches

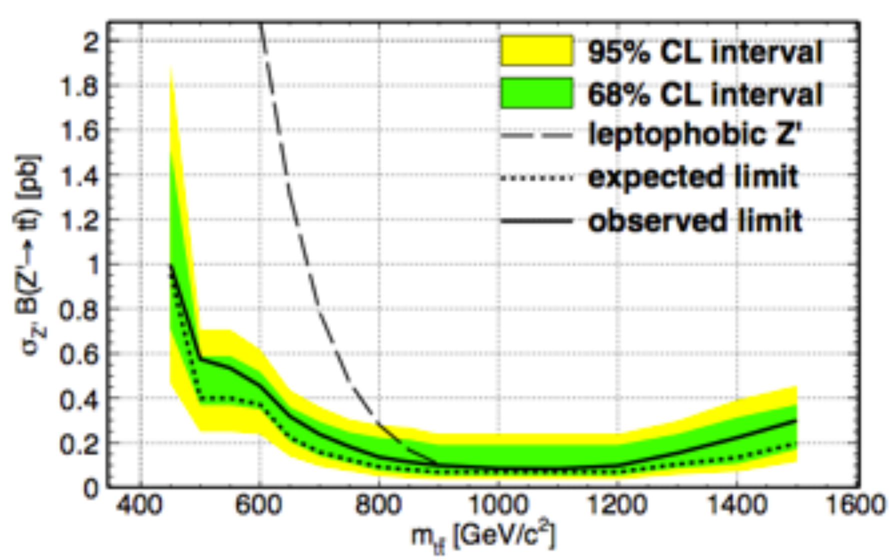
Tevatron and LHC Data for W' and Z' are used

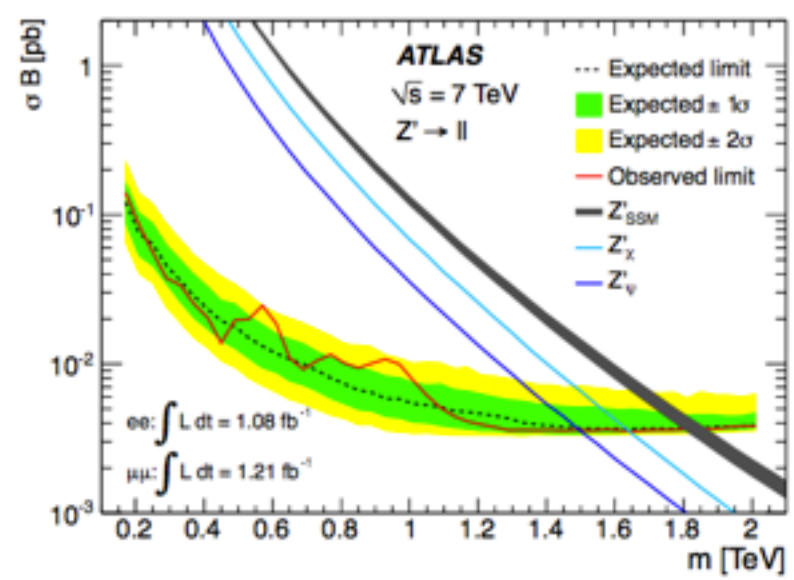




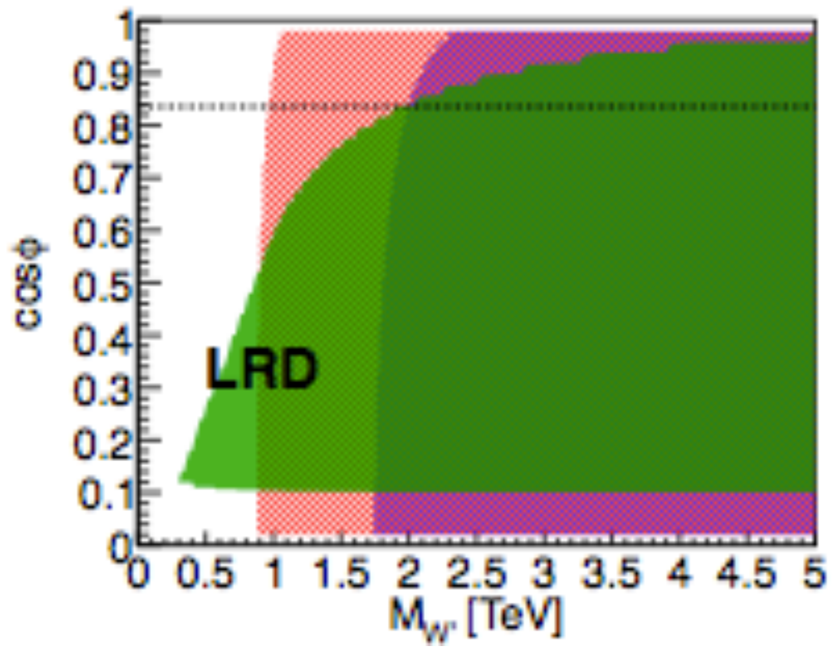


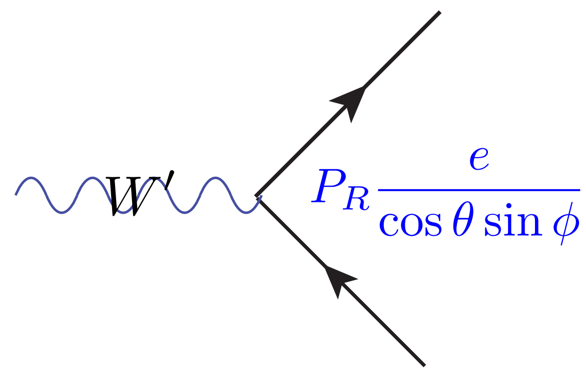


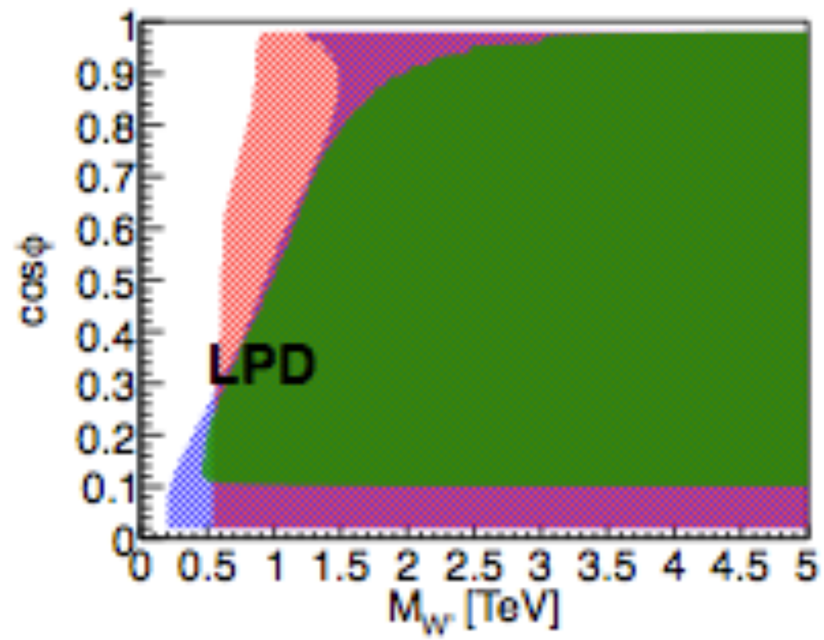




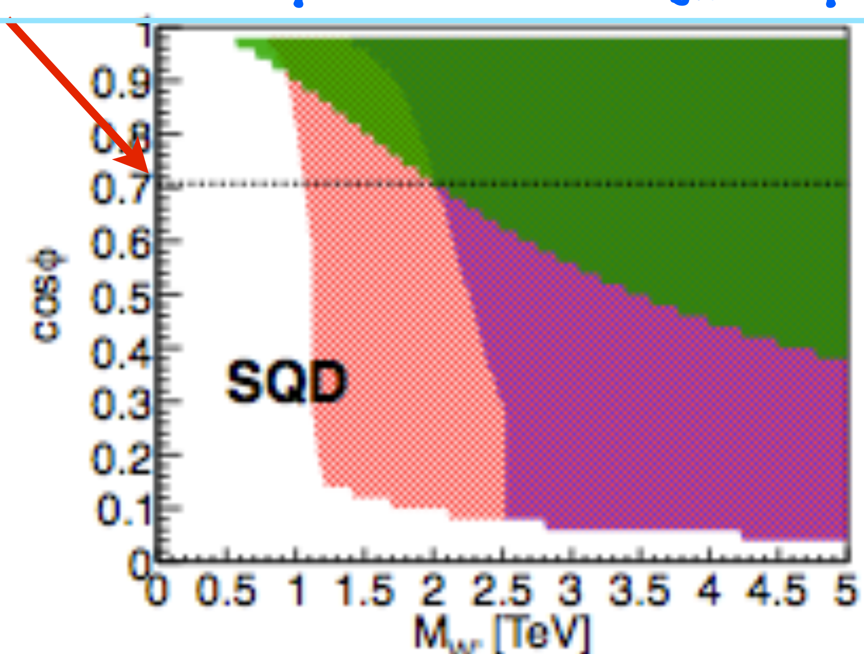
G221 Models Allowed Region (95%CL)

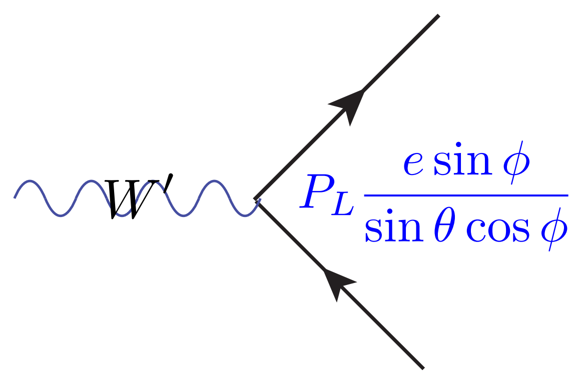


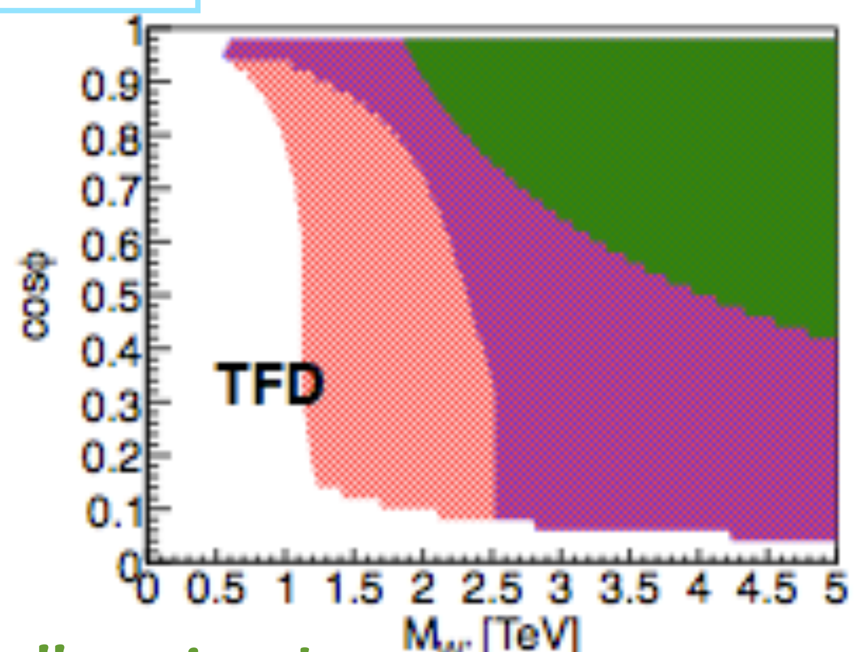




Manifest sequential model g_W coupling (Limits in experiments)







Indirect search allowed region

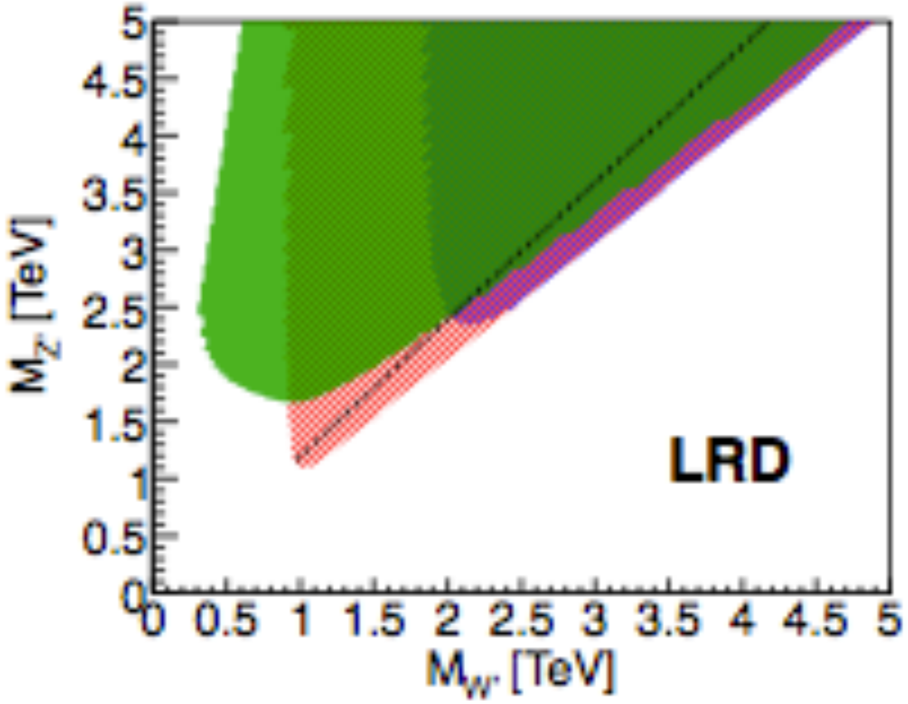
Tevatron direct search allowed region

LHC direct search allowed region

Hsieh, Schmitz, JHY, Yuan

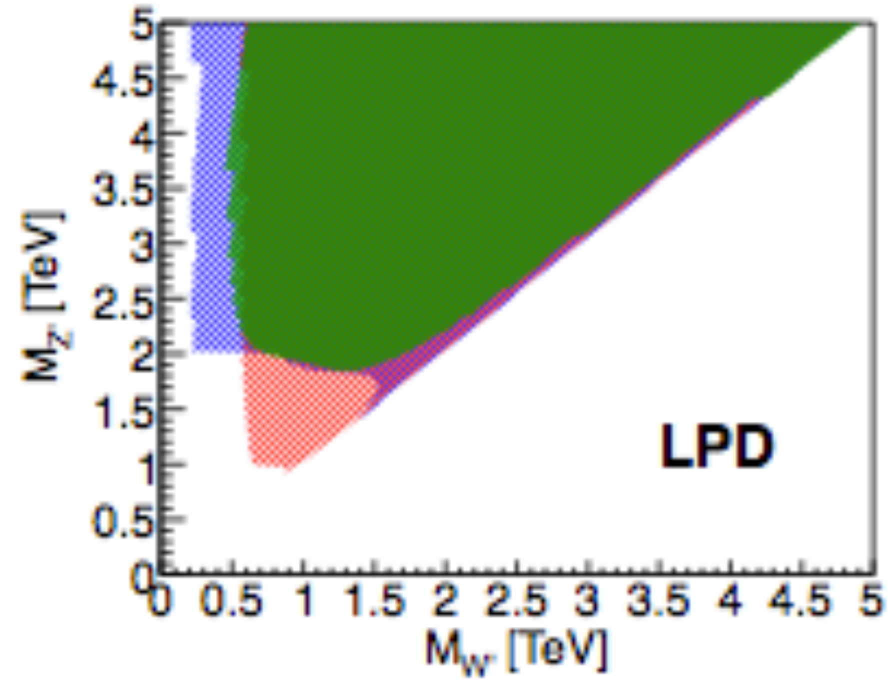
Cao, Li, JHY, Yuan

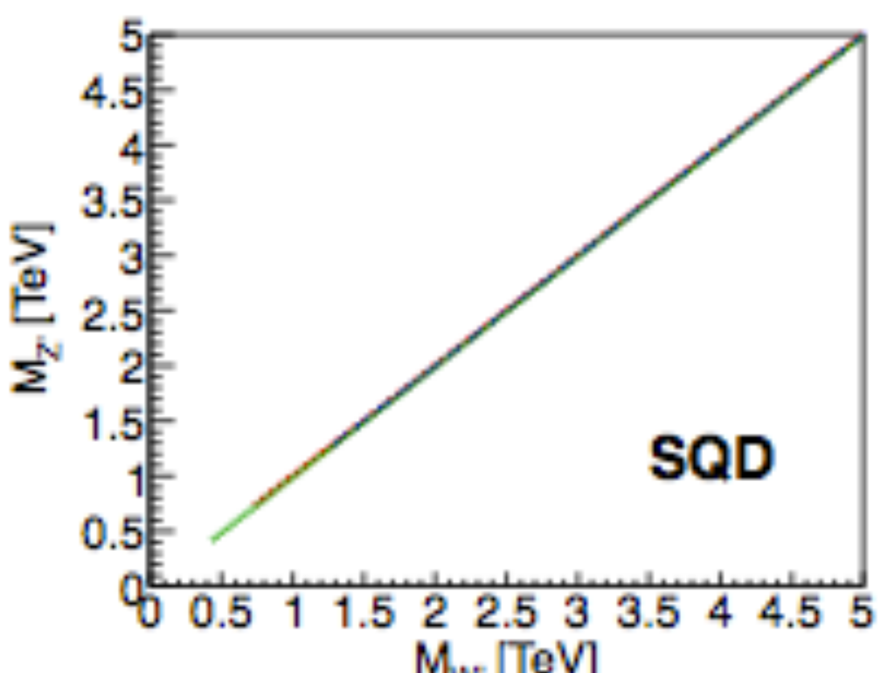
Correlation Between W' and Z'



Z' constraints are much tighter than W'

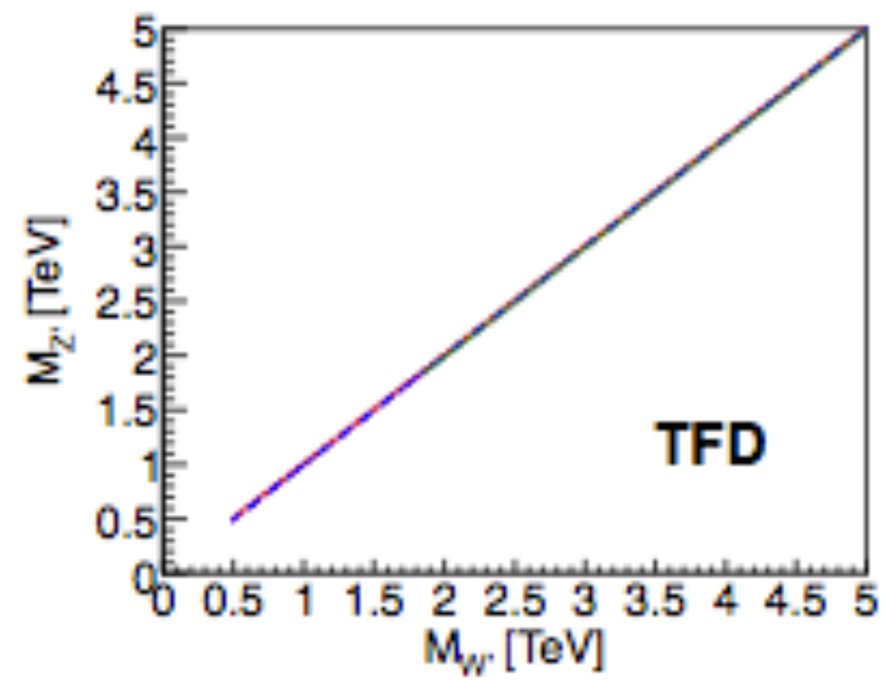
Z' heavier than W'





Degenerate masses for W' and Z'

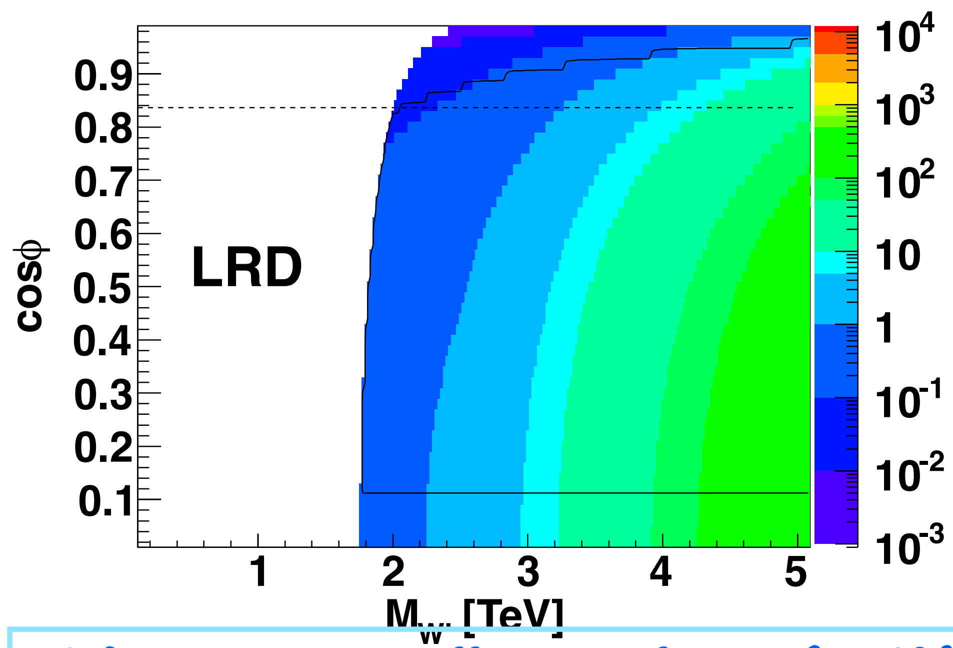
Distinguish BPII from BP1

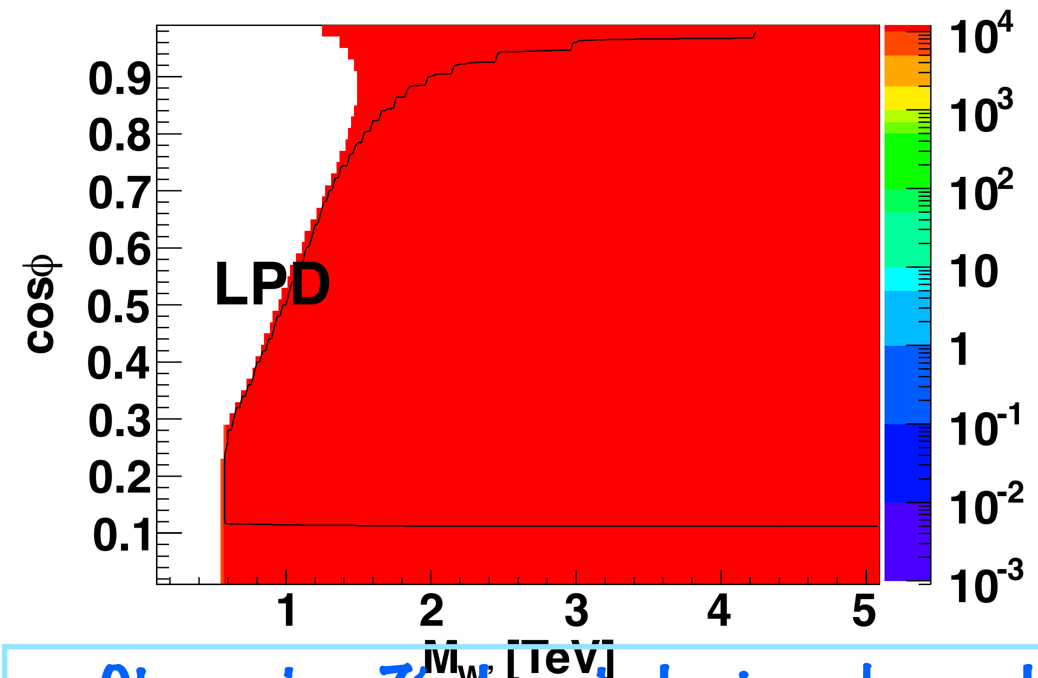


Hsieh, Schmitz, JHY, Yuan

Cao, Li, JHY, Yuan

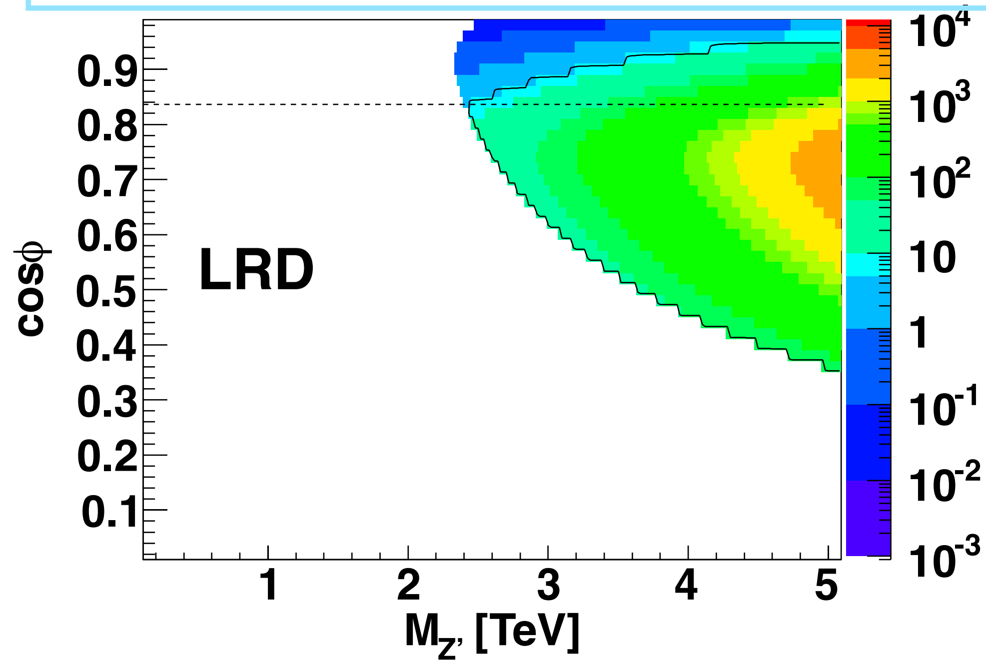
G221 Discovery Potential (14 LHC)

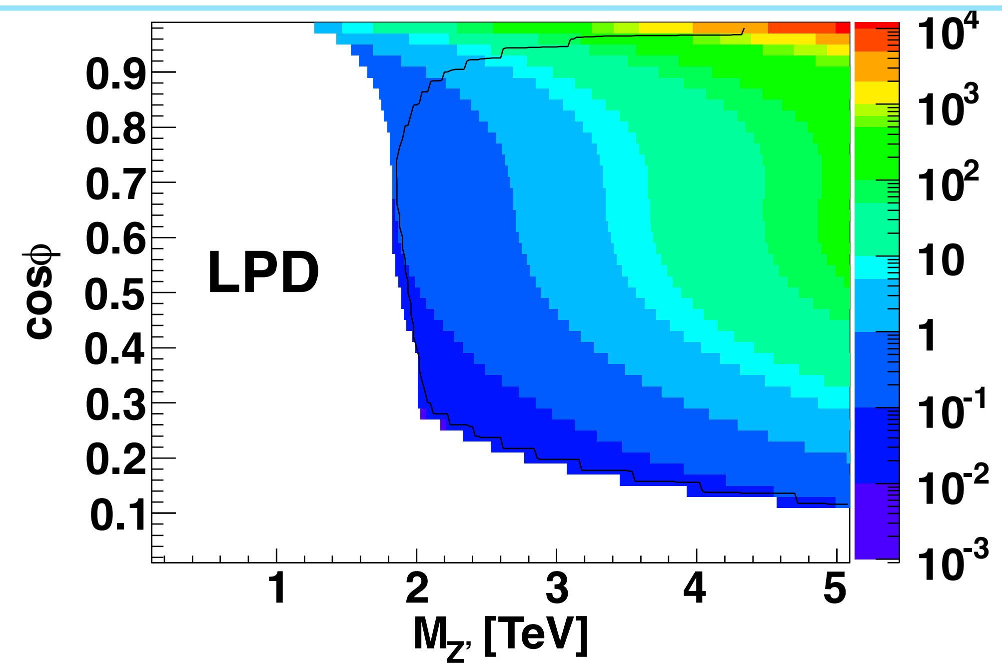




More region will be explored for W' but not Z'

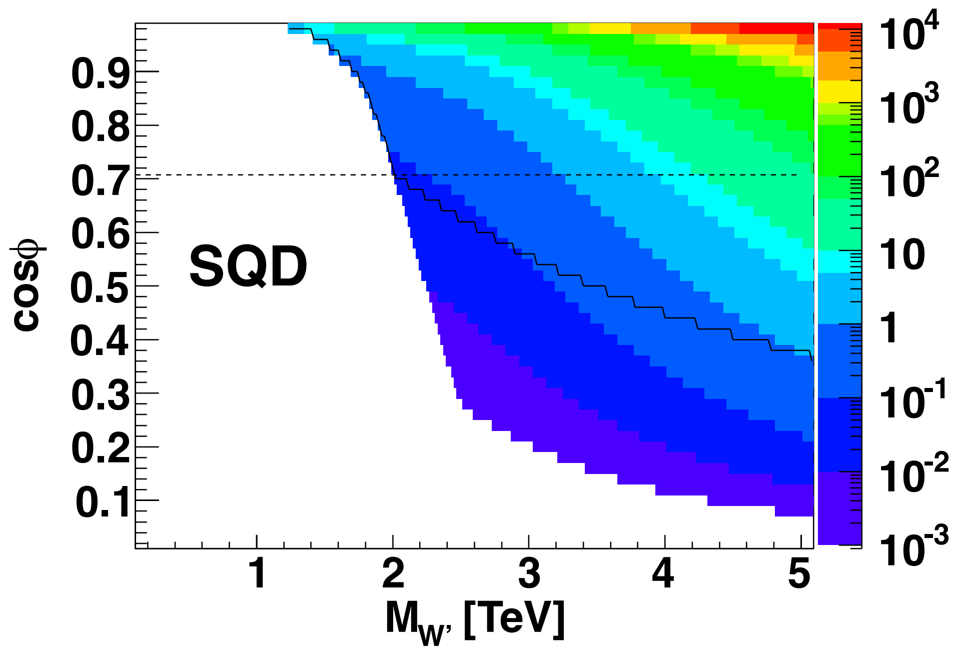
Observing Z' alone in lepton channel doesn't mean no W'!

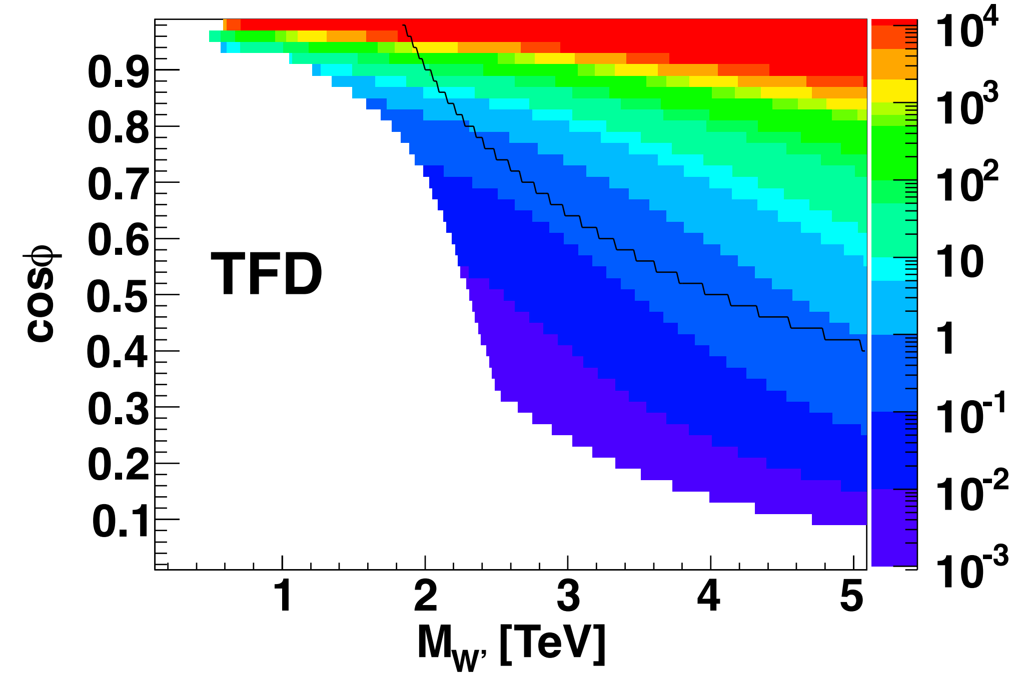




Cao, Li, JHY, Yuan

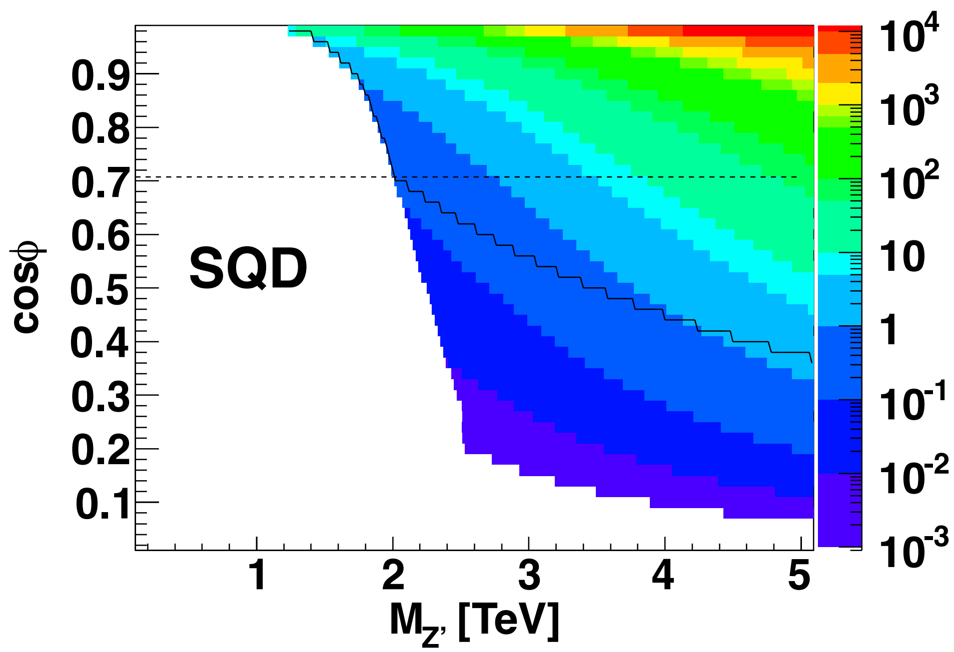
G221 Discovery Potential (14 LHC)

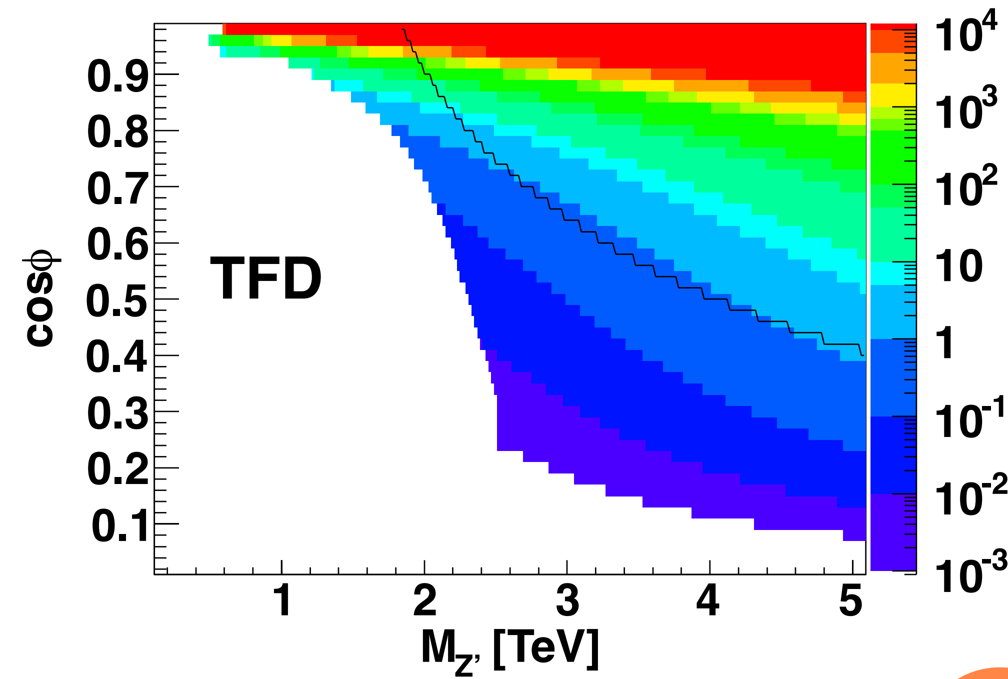




Manifest Sequential model probes up to 4 TeV W' and Z' (100 fb-1 data)

Observing W' and Z' at the same timescale





Cao, Li, JHY, Yuan

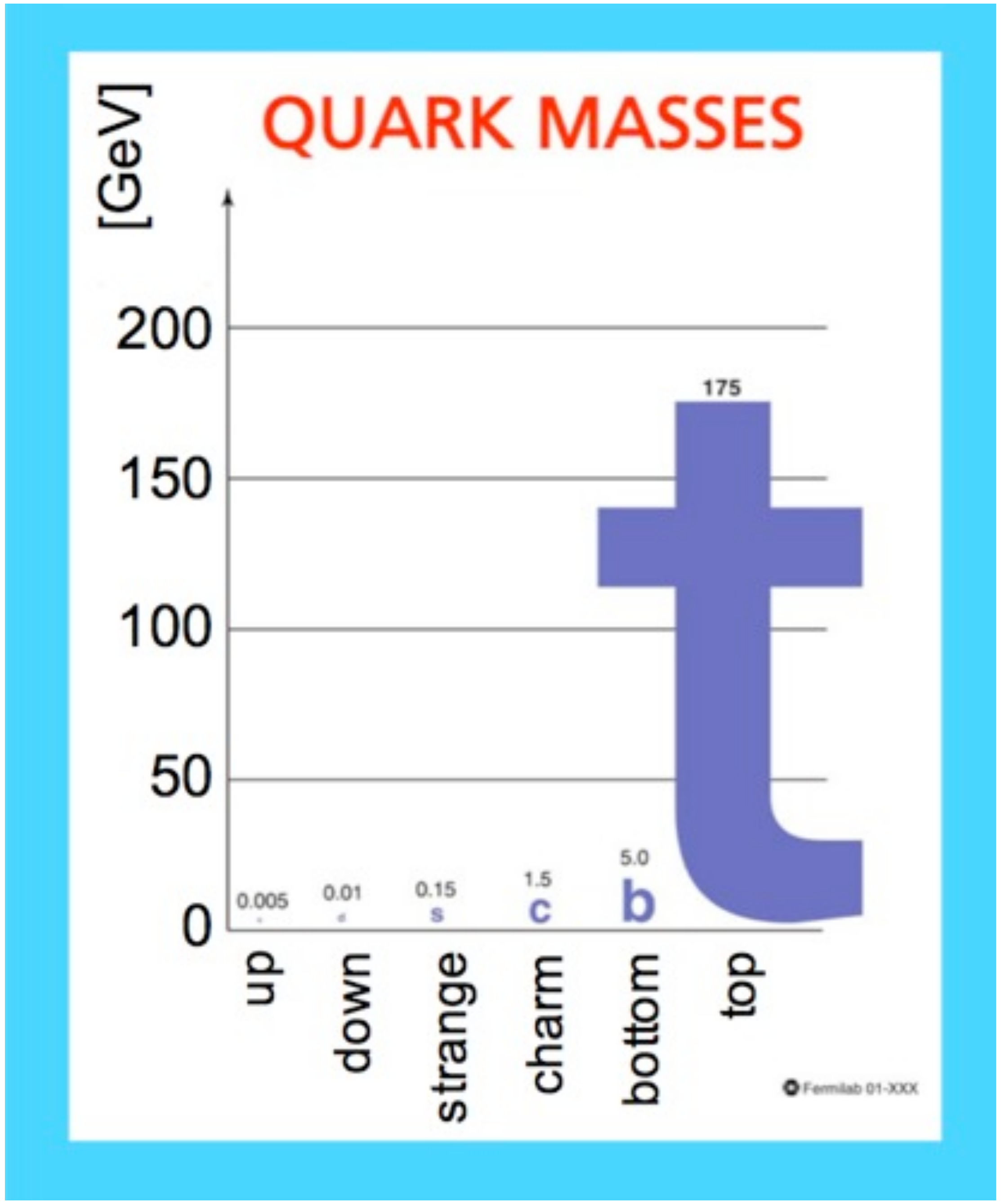
Summary of G221 W' Discovery

G221 Models	Model	Constraints	Discovery Potential (lepton channel)
Breaking Pattern I	left-right (LRD)	1.7 TeV	3.2 - 5 TeV
Breaking Pattern I	lepto-phobic (LPD)	0.55 TeV	No improve
Breaking Pattern I	hadro-phobic (HPD)	0.5 TeV	0.55 TeV
Breaking Pattern I	fermio-phobic (FPD)	0.5 TeV	No improve
Breaking Pattern II	Seqential (SQD)	1.4 TeV	3.5 - 5 TeV
Breaking Pattern II	Top-flavor (TFD)	1.7 TeV	2 - 5 TeV
Breaking Pattern II	Un-unified (UUD)	3.1 TeV	4.6 - 5 TeV

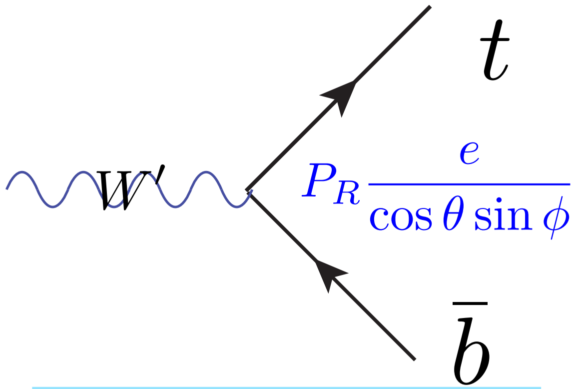
How to discover Lepto-phobic W'?
After discovery, how to determine W' properties?

Chiral Properties of Heavy Charged Gauge Bosons

Top Quark is Special

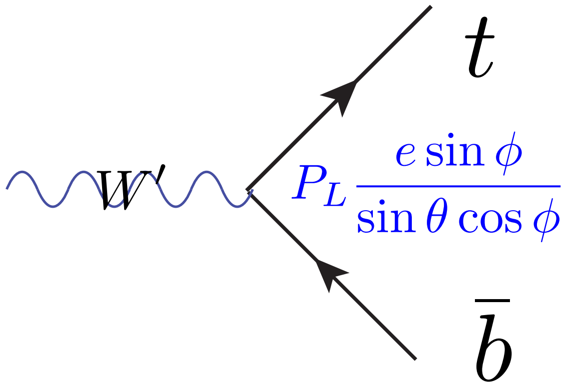


Breaking Pattern I



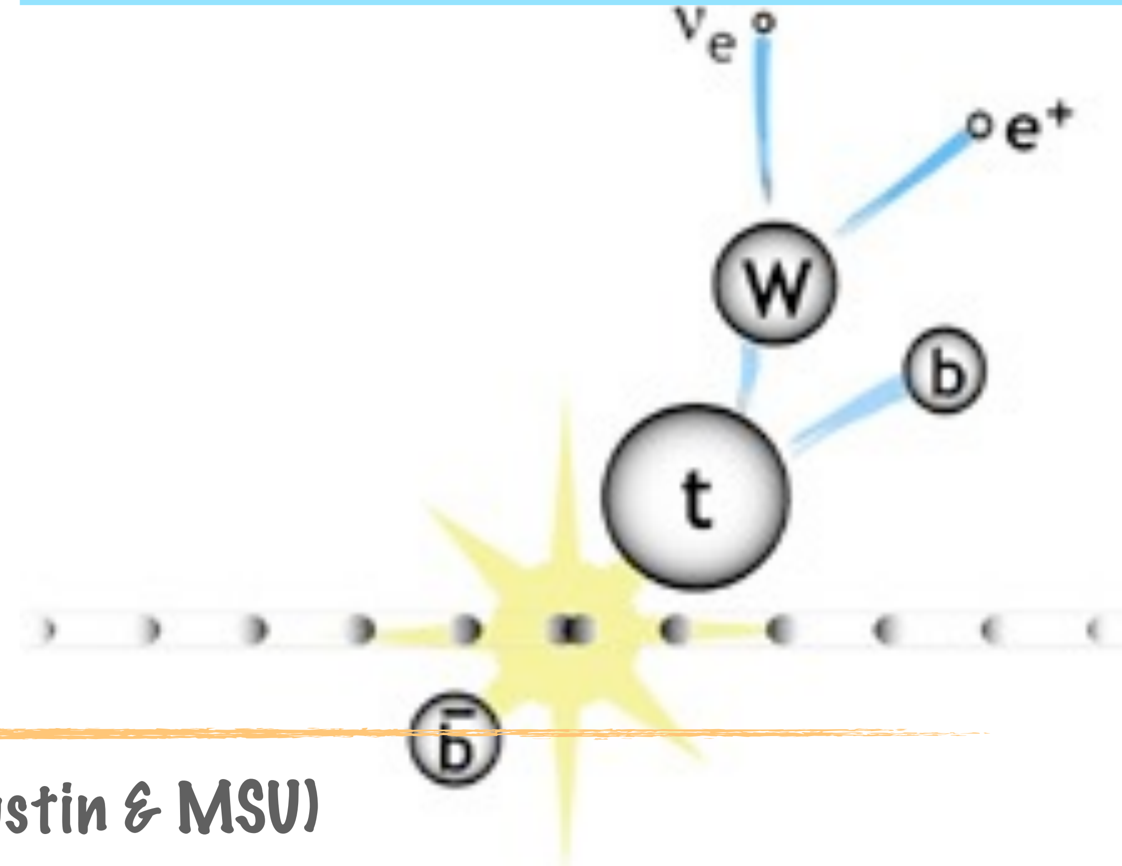
Right-handed W'
Right-handed Top

Breaking Pattern II



Left-handed W'
Left-handed Top

Can we measure the top quark handedness?

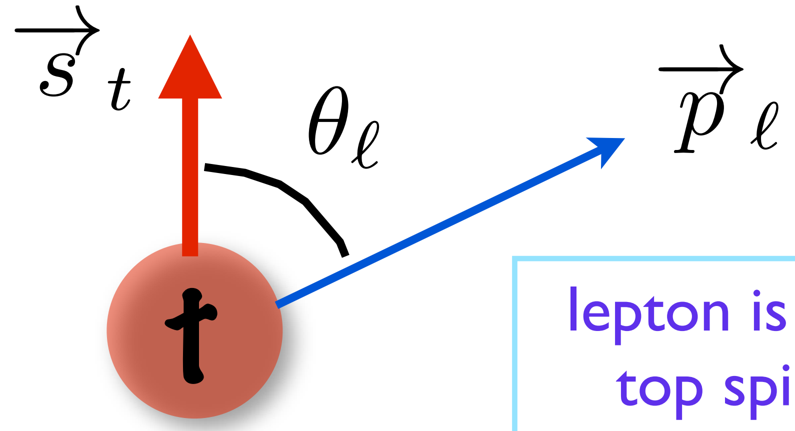


Jiang-Hao Yu (UT Austin & MSU)

Top Quark Decay

- In the top quark rest frame

$$\frac{d\Gamma}{\Gamma d\cos\theta_\ell} = \frac{1+\cos\theta_\ell}{2}$$



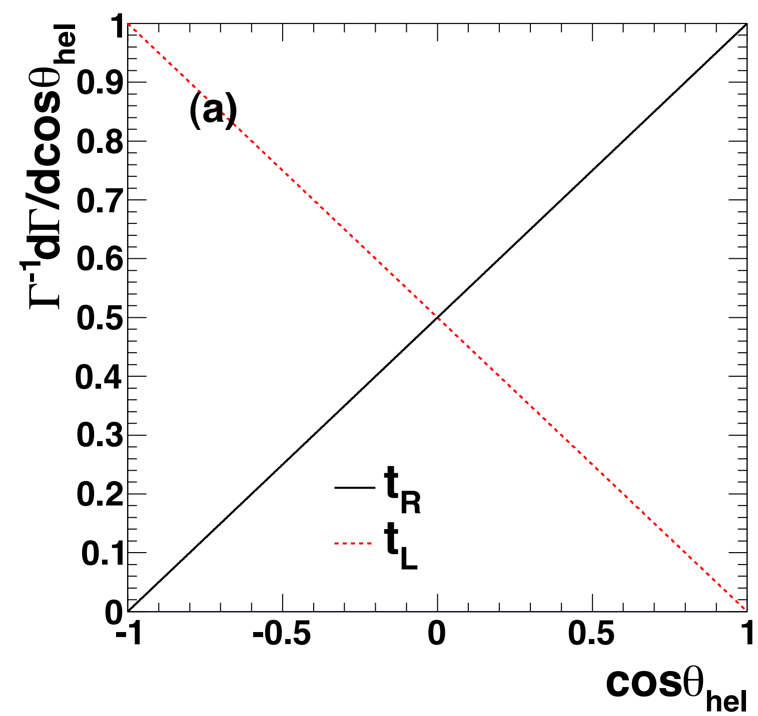
lepton is always along top spin direction

- In helicity basis

$$\frac{d\Gamma}{\Gamma d\cos\theta_{\rm hel}} = \frac{1+\lambda_t\cos\theta_{\rm hel}}{2}$$

$\lambda_t = +1$ — positive helicity, right-handed

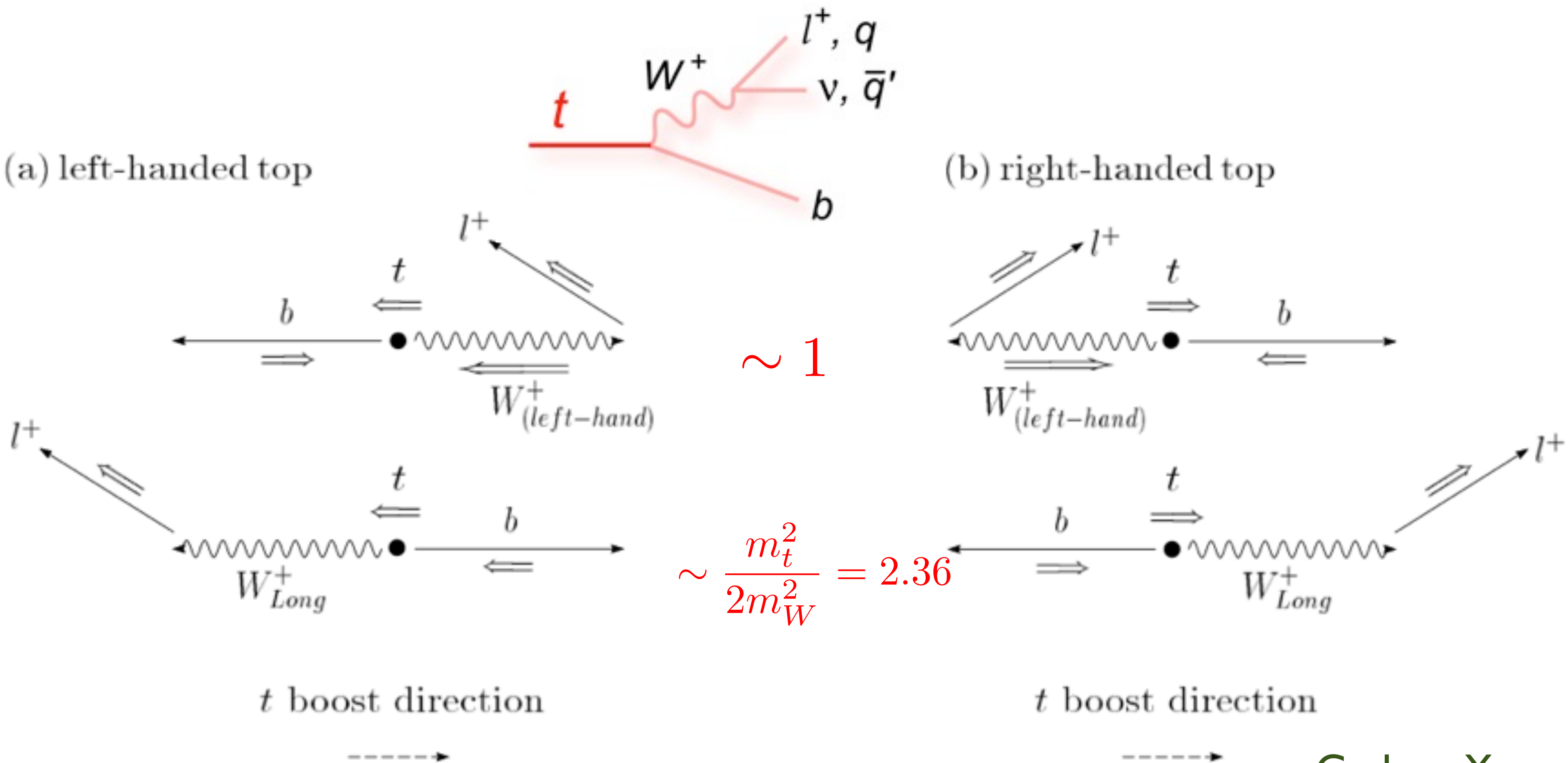
$\lambda_t = -1$ — negative helicity, left-handed



Kane, Ladinsky, Yuan
Berger, Cao, Chen, JHY, Zhang

Correlation Between Top and Lepton

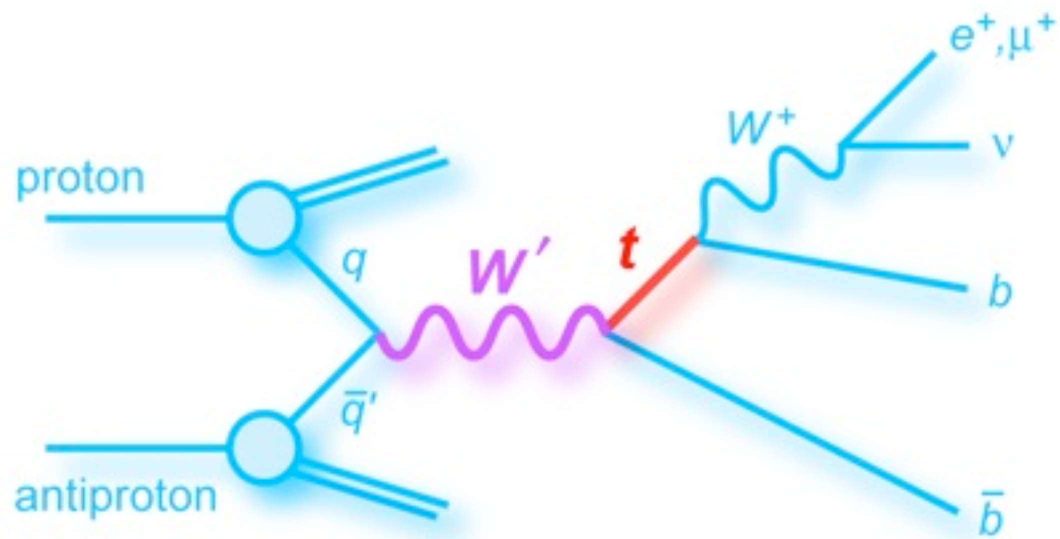
- W' decays to right-handed top in BPI, left-handed top in BPII



Carlson, Yuan

In top rest frame, lepton is maximally polarized
(always along top spin direction)

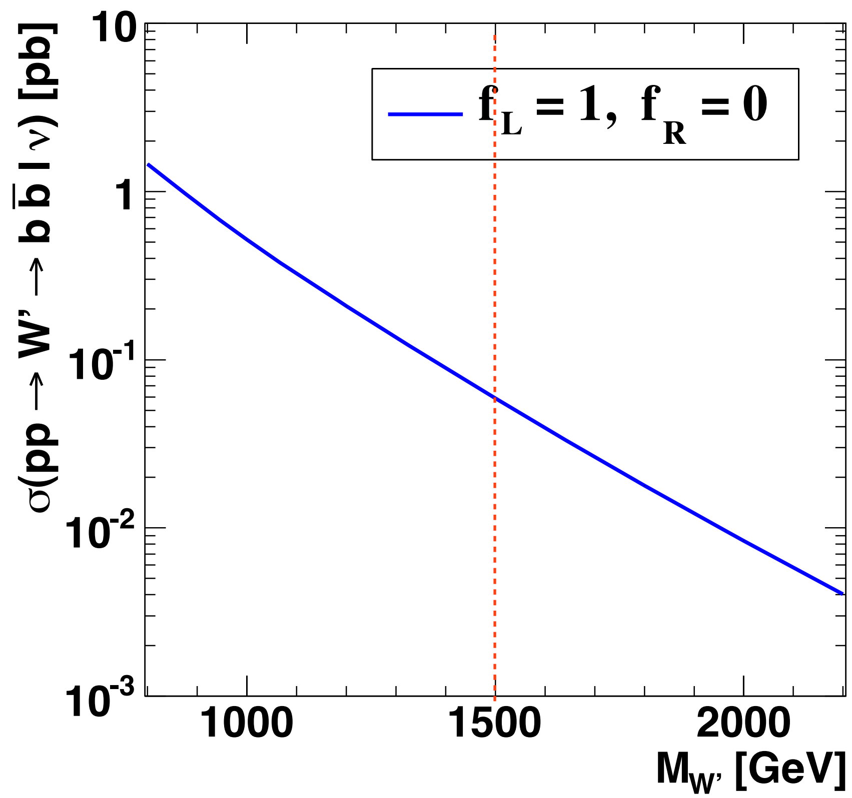
Top Quark Channel



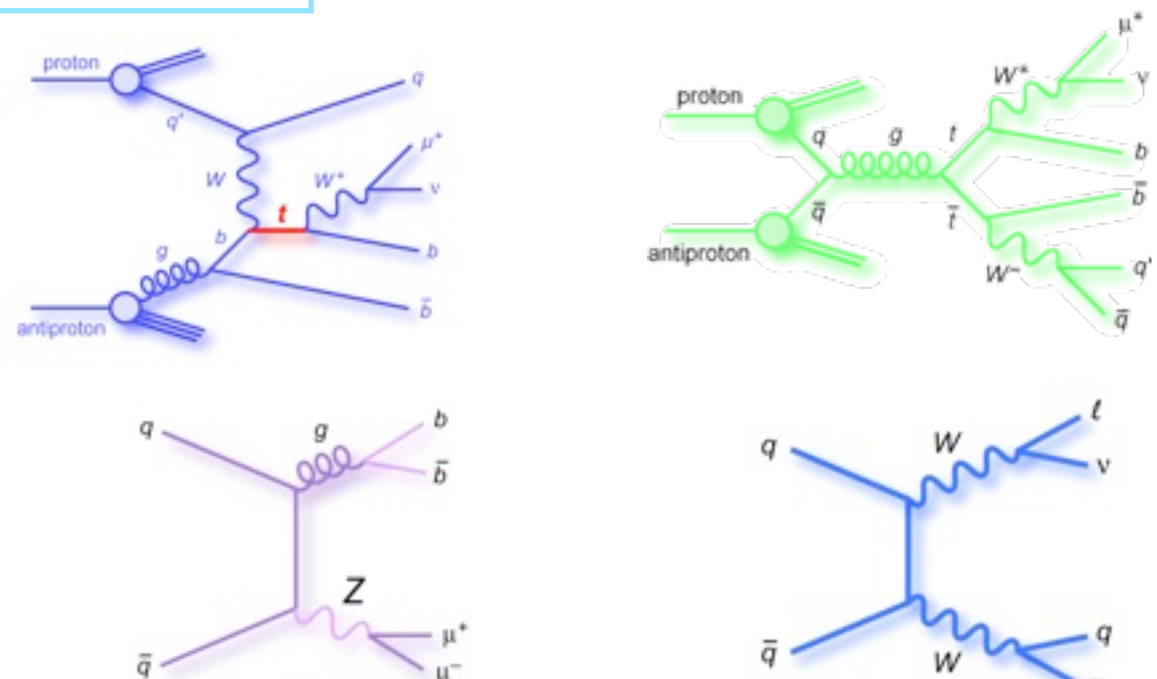
lepto-phobic model:
No hope to find W-prime in leptonic channel, discover W' in single top channel

Top-flavor model:
Enhanced couplings to the top quark, larger chance to find W' in single top channel

All models, except FP and HP models:
probe the chiral structures of W'

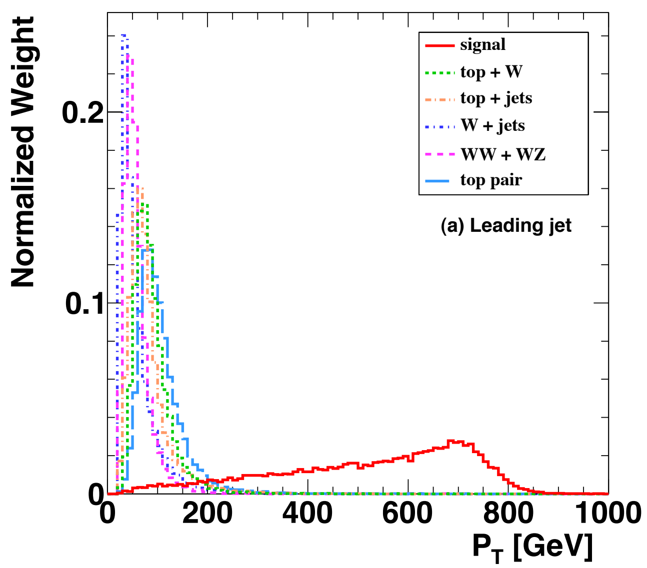


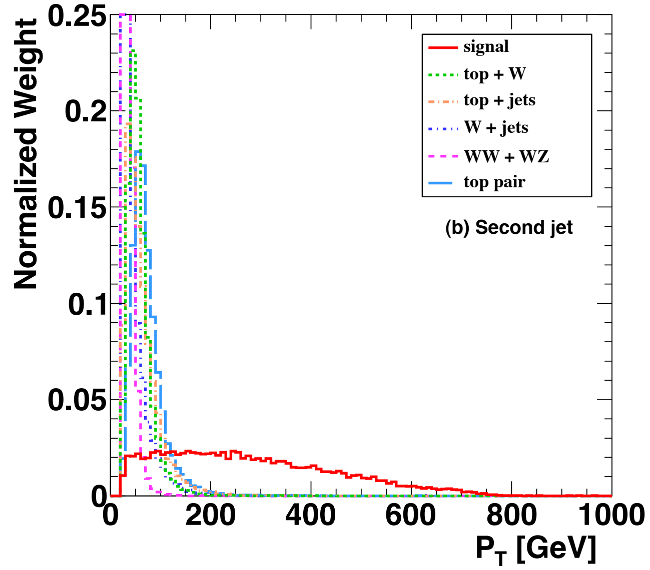
Backgrounds

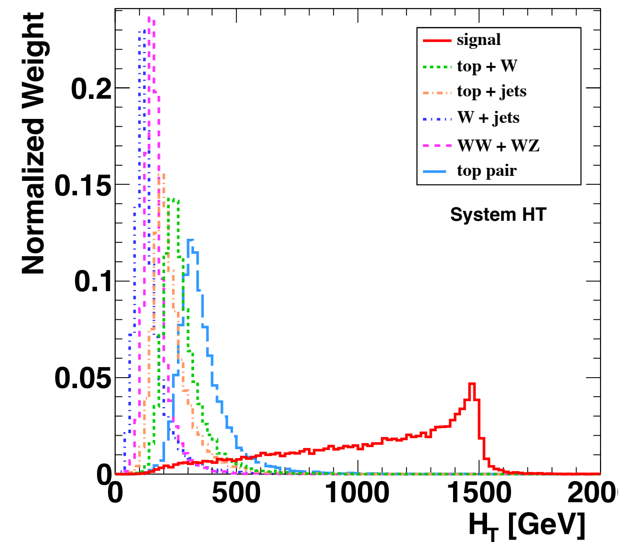


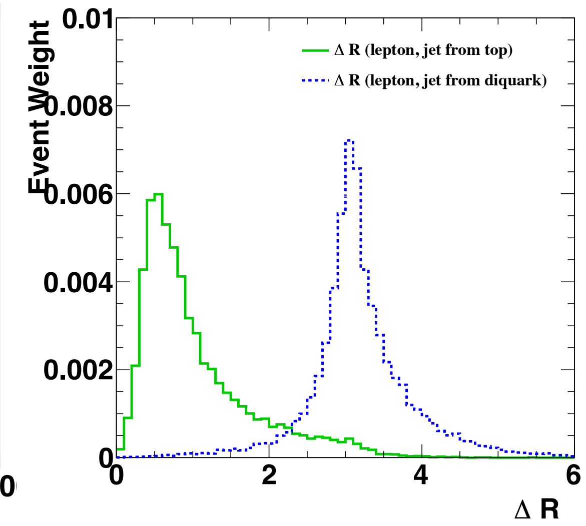
Monday, November 12, 2012

Cut Based Analysis









At least two jets with $p_T^j \geq 25\,\text{GeV}$, $|\eta_j| \leq 2.5$

Exactly one lepton with $p_T^\ell \geq 25\,\text{GeV}$, $|\eta_\ell| \leq 2.5$,

Missing energy $\not{E}_T > 25$ GeV,

Separation with $\Delta R_{jj,j\ell} > 0.4$, $\Delta R_{\ell\ell} > 0.2$.

HT: scalar sum of all PTs/ met of final state particles

$$p_T^{j1st} \geq 200\,\text{GeV},$$

$$p_T^{j2st} \geq 80\,\text{GeV}.$$

$$H_T \geq 600\,\text{GeV}.$$

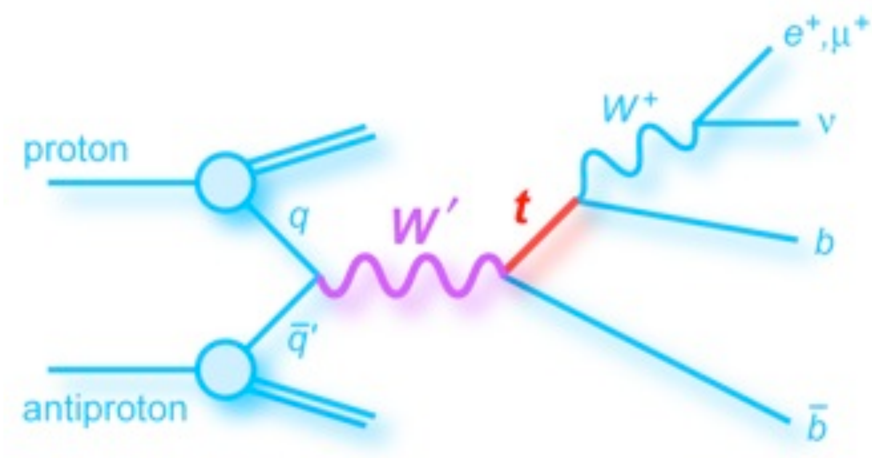
B-tagging efficiency: 60%, mis-tagging: 0.5%

σ(fb)	Signal	$t+$jets	$t+W$	$t\bar{t}$	WV	$W+$jets
no cuts	58.96	18877	2861	25840.	9888	4018600
basic cuts	33.38	4049.	833.	7206.7	2265	284516
+ smearing	33.83	4067.	815.	6878.6	2193	296371
+ hard cuts	28.65	158.5	11.1	232.56	3.67	7836.2
+ H_T cuts	26.45	59.80	5.69	137.6	3.51	3782.
+ b-tagging	22.26	44.79	3.44	115.7	0.19	61.98
+ mass window	21.59	7.80	0.13	3.97	0.03	16.02

Yu, Yuan

Jiang-Hao Yu (UT Austin & MSU)

Discovery and Chiral Structure



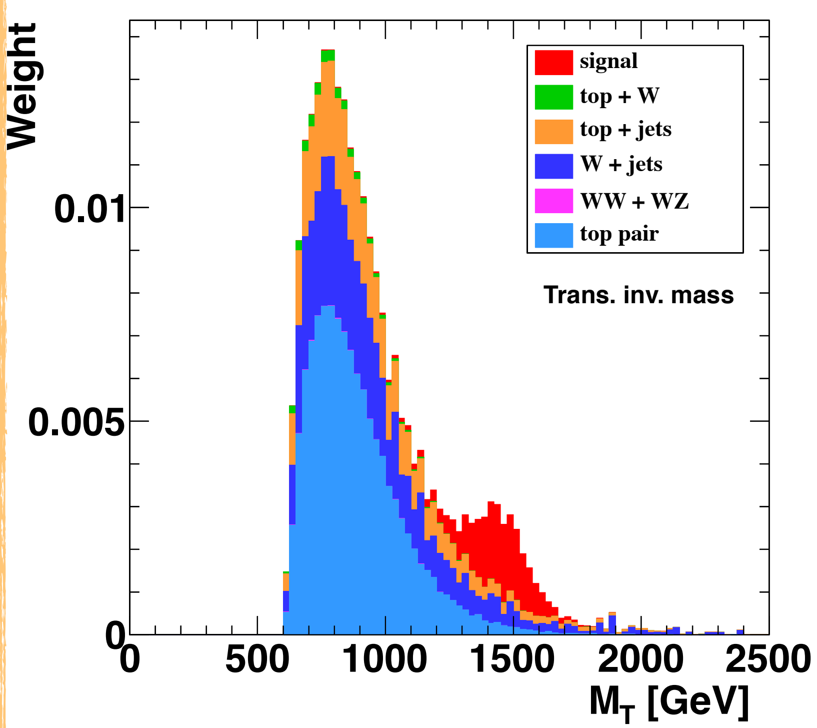
Top Quark reconstruction:
Require on-shell W, to get the solution of neutrino Pz (pick up the central one)

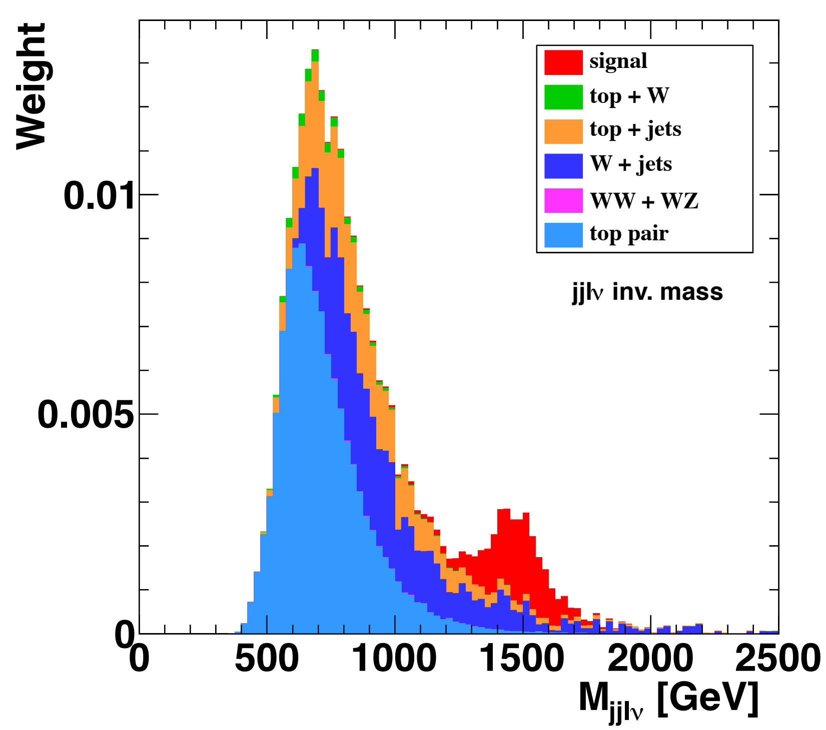
reconstruct the whole system

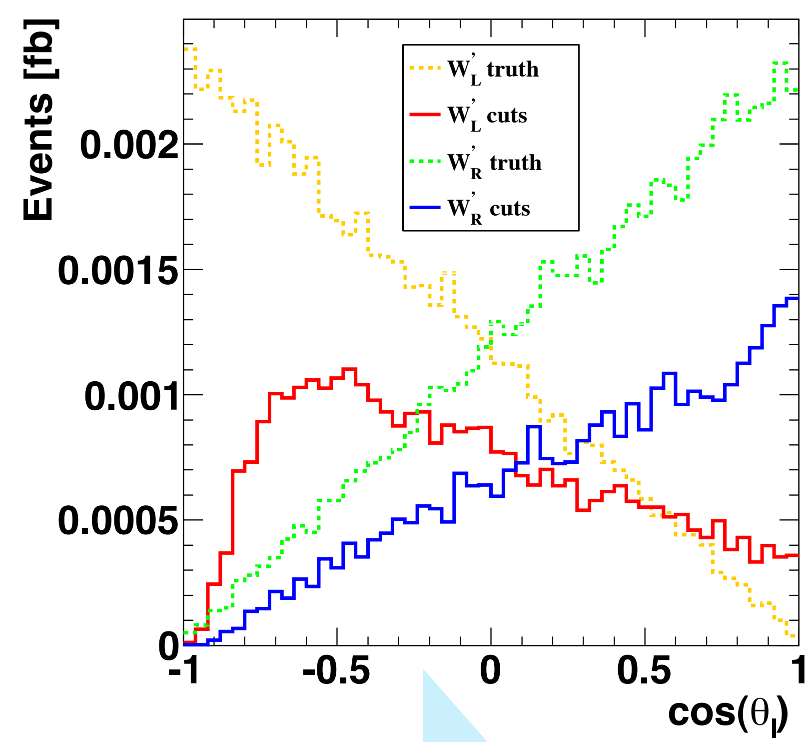
boost back to top rest frame

No reconstruction is needed

JHY, Yuan







Different luminosity

Summary of G221 W' Discovery

els

		Constraints	Discovery Potential (lepton channel)	W' Discovery
Breaking Pattern I	left-right (LRD)	1.7 TeV	3.2 - 5 TeV	Lepton Channel
	lepto-phobic (LPD)	0.55 TeV	No improve	Top Channel
	hadro-phobic (HPD)	0.5 TeV	0.55 TeV	Di-boson Channel
	fermio-phobic (FPD)	0.5 TeV	No improve	Di-boson Channel
Breaking Pattern II	Seqential (SQD)	1.4 TeV	3.5 - 5 TeV	Lepton Channel
	Top-flavor (TFD)	1.7 TeV	2 - 5 TeV	Lepton/Top Channel
	Un-unified (UUD)	3.1 TeV	4.6 - 5 TeV	Lepton Channel

After discovery, all models, except FP and HP models: probe the chiral structures of W'!

Conclusion and Outlook

CONCLUSION AND OUTLOOK

- One sentence:

Classified the G221 Moose model, and discussed constraints, discovery channels, LHC potential and chiral properties.

- More information:

(1) In BP-I(right-handed W′), Z′ is heavier than W′, and in Phobic models observing a Z′ in lepton channel alone doesn't mean no W′;

(2) In BP-II(left-handed W′), degenerate W′ and Z′ mass, and observing W′ and Z′ at the same timescale of LHC.

(3) Top quark channel to discover lepto-phobic and top-flavor W′, and to probe the chiral structure using the top polarization.

- Outlook:

Di-boson channel, and associate production channel are promising to probe symmetry breaking sectors.

Thank you!

Back up

TimeLine of Charged Gauge Bosons

Fermi theory of Weak interaction
1934

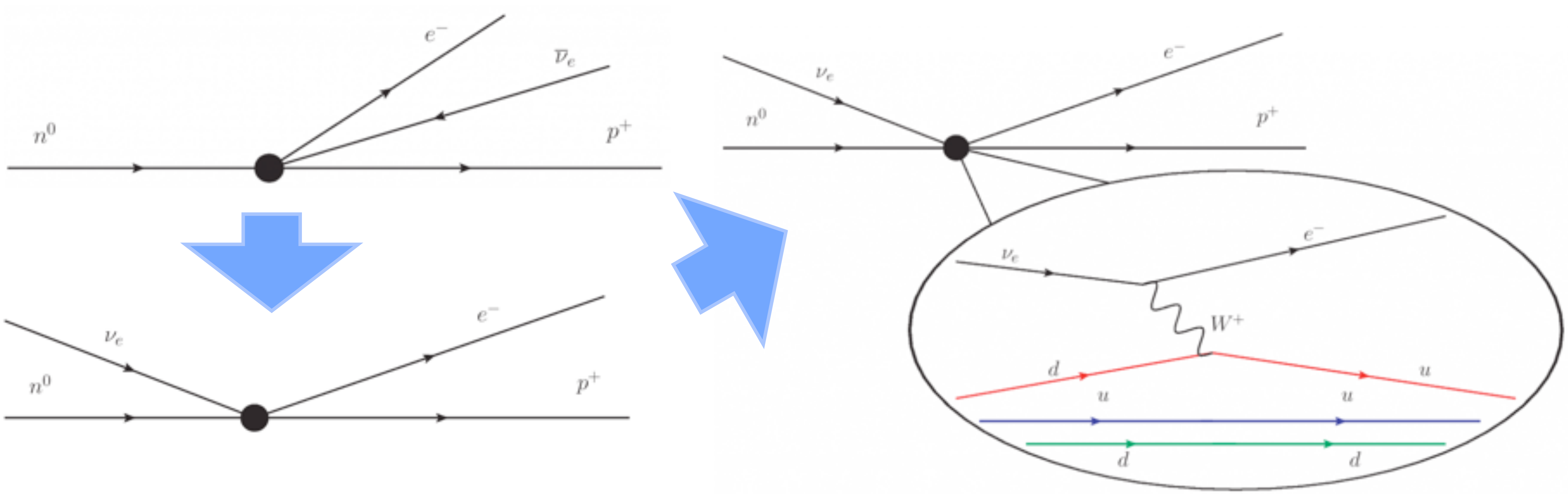
V-A current in Fermi theory
1956

Unitarity violation in Fermi Theory
1950s

Phenomenological Intermediate Weak Boson Model
1957

Glashow Weinberg Salam Model
1967

Charged Gauge Boson Discovery
1983 (CERN)



Feynman Rules in G221

Couplings	g_L	g_R
$W'^{+\mu}\bar{f}f'$ (BP-I)	$-\frac{e_m}{\sqrt{2}s_W^2}\gamma_\rho T_L^+ \frac{c_W s_{2\beta} s_\phi}{x}$	$\frac{e_m}{\sqrt{2}c_W s_\phi}\gamma_\rho T_R^+$
$Z'\bar{f}f$ (BP-I)	$\frac{e_m}{c_W c_\phi s_\phi}\gamma_\rho \left[(T_{3L} - Q)\, s_\phi^2 - \frac{c_\phi^4 s_\phi^2 \left(T_{3L} - Q s_W^2\right)}{x s_W^2} \right]$	$\frac{e_m}{c_W c_\phi s_\phi}\gamma_\rho \left[(T_{3R} - Q s_\phi^2) + Q\frac{c_\phi^4 s_\phi^2}{x} \right]$
$W'^{\pm\mu}\bar{f}f'$ (BP-II)	$-\frac{e_m s_\phi}{\sqrt{2}s_W c_\phi}\gamma^\mu T_l^\pm \left(1 + \frac{s_\phi^2 c_\phi^2}{x}\right)$	0
$W'^{\pm\mu}\bar{F}F'$ (BP-II)	$\frac{e_m c_\phi}{\sqrt{2}s_W s_\phi}\gamma^\mu T_h^\pm \left(1 - \frac{s_\phi^4}{x}\right)$	0
$Z'\bar{f}f$ (BP-II)	$-\frac{e_m}{s_W}\gamma^\mu \left[\frac{s_\phi}{c_\phi} T_{3l} \left(1 + \frac{s_\phi^2 c_\phi^2}{x c_W^2}\right) - \frac{s_\phi}{c_\phi}\frac{s_\phi^2 c_\phi^2}{x c_W^2} s_W^2 Q \right]$	$\frac{e_m}{s_W}\gamma^\mu \left(\frac{s_\phi}{c_\phi}\frac{s_\phi^2 c_\phi^2}{x c_W^2} s_W^2 Q \right)$
$Z'\bar{F}F$ (BP-II)	$\frac{e_m}{s_W}\gamma^\mu \left[\frac{c_\phi}{s_\phi} T_{3h} \left(1 - \frac{s_\phi^4}{x c_W^2}\right) + \frac{c_\phi}{s_\phi}\frac{s_\phi^4}{x c_W^2} s_W^2 Q \right]$	$\frac{e_m}{s_W}\gamma^\mu \left(\frac{c_\phi}{s_\phi}\frac{s_\phi^4}{x c_W^2} s_W^2 Q \right)$

Couplings	BP-I	BP-II
$H\ W_\nu\ W'_\rho$	$-\frac{i}{2}\frac{e_m^2 s_{2\beta}}{c_W s_W s_\phi} v g_{\nu\rho} \left[1 + \frac{\left(c_W^2 s_\phi^2 - s_W^2\right)}{x s_W^2} \right]$	$-\frac{i}{2}\frac{e_m^2 s_\phi}{s_W^2 c_\phi} v g_{\nu\rho} \left[1 + \frac{s_\phi^2 \left(c_\phi^2 - s_\phi^2\right)}{x} \right]$
$H\ Z_\nu\ Z'_\rho$	$-\frac{i}{2}\frac{e_m^2 c_\phi}{c_W^2 s_W s_\phi} v g_{\nu\rho} \left[1 - \frac{c_\phi^2 \left(c_\phi^2 s_W^2 - s_\phi^2\right)}{x s_W^2} \right]$	$-\frac{i}{2}\frac{e_m^2 s_\phi}{c_W s_W^2 c_\phi} v g_{\nu\rho} \left[1 - \frac{s_\phi^2 \left(s_\phi^2 c_W^2 - c_\phi^2\right)}{x c_W^2} \right]$
$W_\mu^+\ W_\nu'^-\ Z_\rho$	$i\frac{e_m s_{2\beta} s_\phi}{x s_W^2}$	$i\frac{e_m c_\phi s_\phi^3}{x s_W c_W}$
$W_\mu'^+\ W_\nu^-\ Z'_\rho$	$i\frac{e_m s_\phi c_W c_\phi^3}{x s_W^2}$	$i\frac{e_m c_\phi s_\phi^3}{x s_W}$

|j=1\rangle = \frac{1}
{2} (1+ \cos\theta) |

FPD and UUD Models