Detecting a Strongly Coupled Higgs sector at the LHC

Vikram Rentala

(U. Arizona/ UC Irvine)

With J. Shu and H. Murayama

arxiv/hep-ph 1105.xxxx

Strongly Coupled Higgs Sector

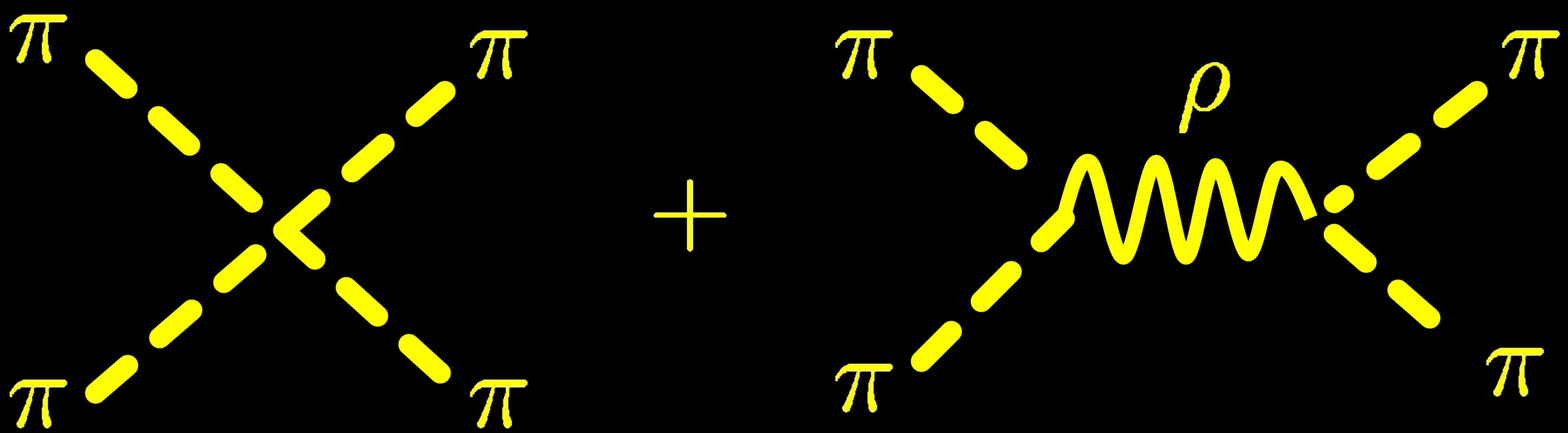
- EWSB similar to chiral symmetry breaking in QCD with 2 flavors
- $SU(2)_L \times SU(2)_R \rightarrow SU(2)_V$
- Chiral Lagrangian with gauged $SU(2)_L$ and hypercharge
- Longitudinal modes of the W,Z gauge bosons are the pseudo-goldstone bosons of chiral symmetry breaking i.e. the pions
- π - π scattering is unitarized through exchange of heavy resonances such at the ρ
- Resonance might be very broad / No visible peak in the W-Z invariant mass plot

Can we detect a strongly coupled Higgs sector without directly observing the resonance?

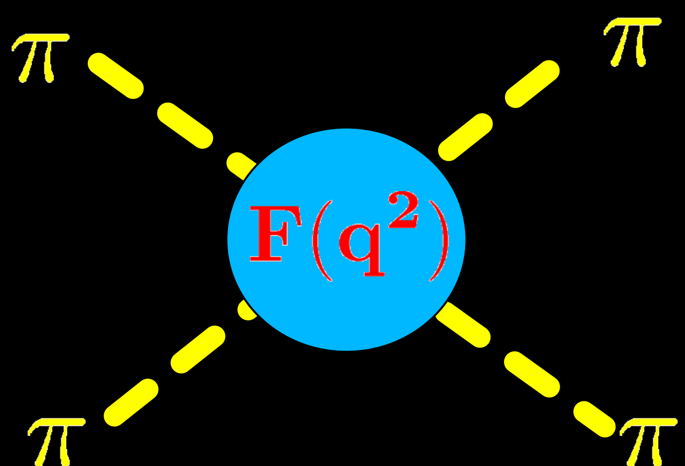
If we do observe a resonance can we discern some properties of its interactions with SM gauge bosons?

Look back at QCD

- π - π scattering picks up a phase shift!



- This can be parametrized as a form factor



Partial waves and unitarity

Quick review of elastic scattering

$$\pi\pi \to \pi\pi$$

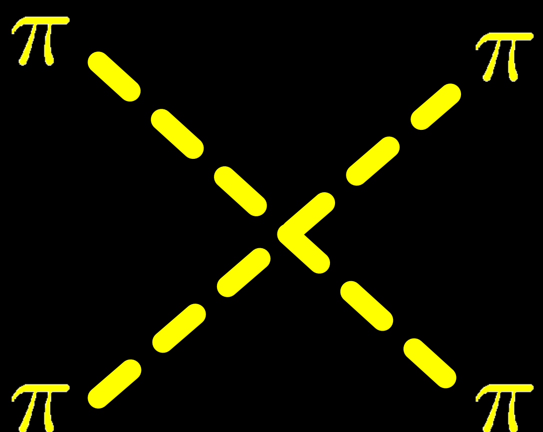
- Incoming partial wave
- Outgoing partial wave can only pick up a phase shift from unitarity $e^{i2\delta_J}$

$$\begin{aligned} \mathcal{T}_J &\propto e^{i2\delta_J} - 1 \\ &= \sin\delta_J e^{i\delta_J} \end{aligned}$$

What is the phase shift in QCD?

LET – Low energy theorem $U = e^{i\frac{\pi^a T^a}{f_\pi}}$

$$\mathcal{L}_{\text{chiral}} = \frac{f_\pi^2}{4}\text{Tr}[\partial_\mu U \partial^\mu U^\dagger]$$



$$\sim \frac{1}{f_\pi^2}(\pi\partial_\mu\pi)^2$$

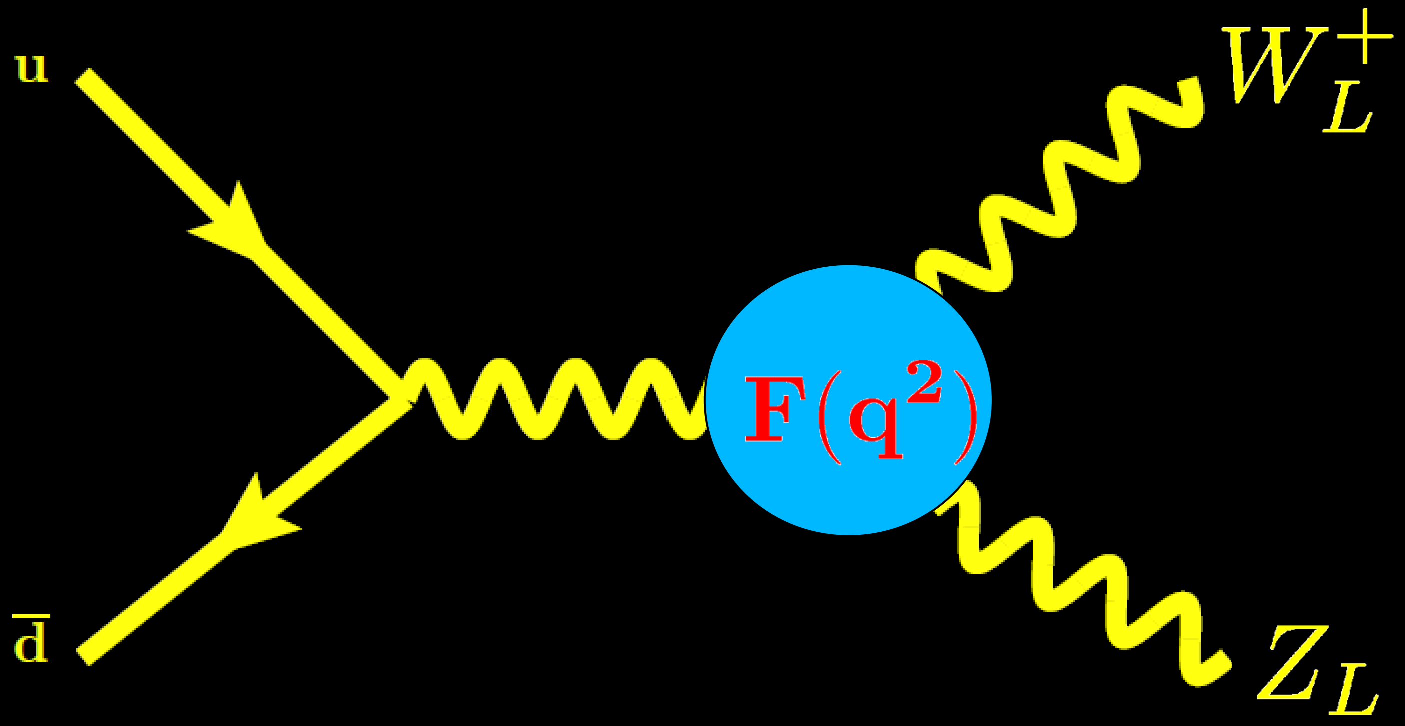
$$\sim \frac{s}{f_\pi^2}$$

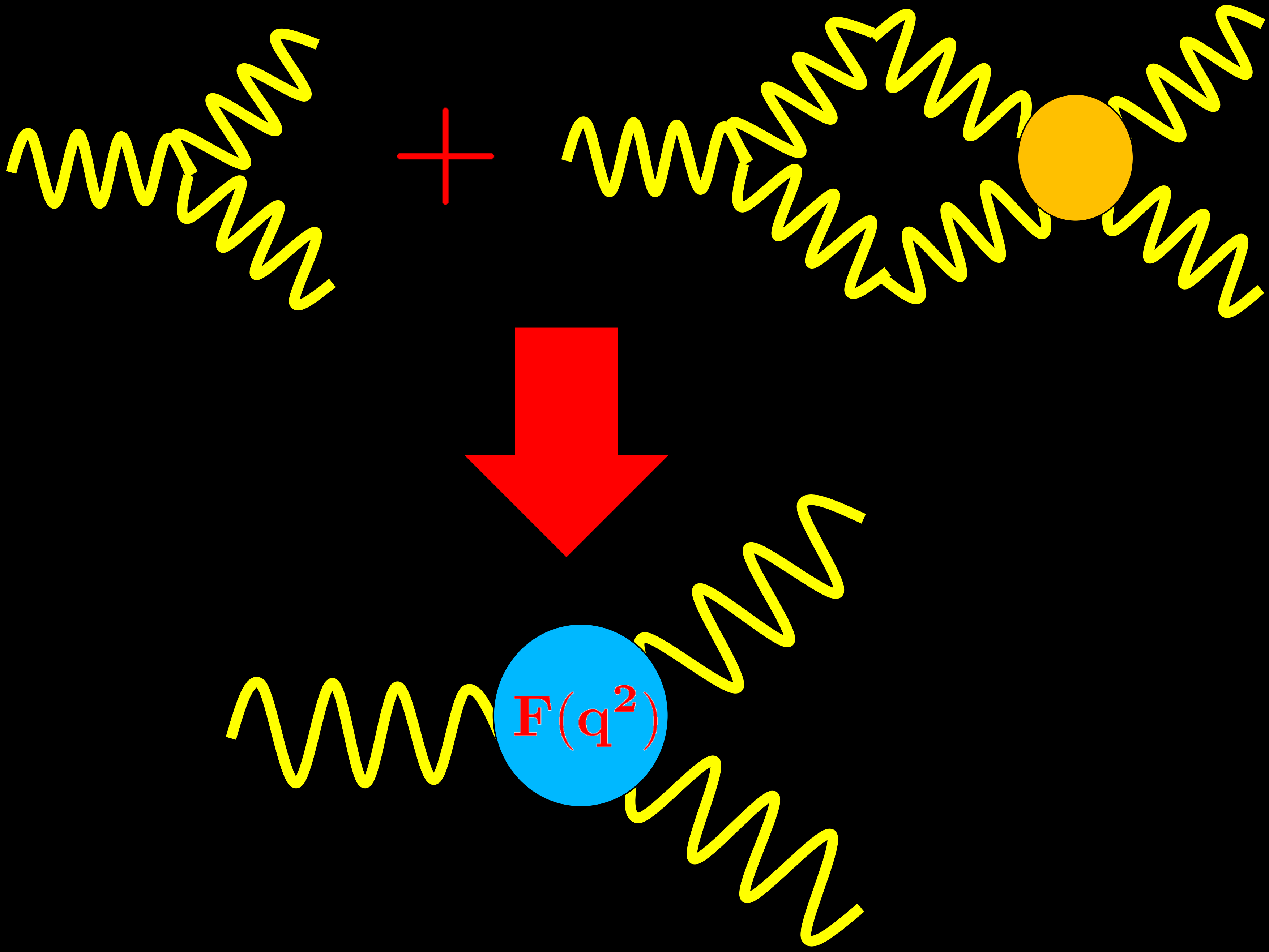
$$\Rightarrow \sin\delta_J \sim \delta_J \sim \#_J \frac{s}{f_\pi^2}$$

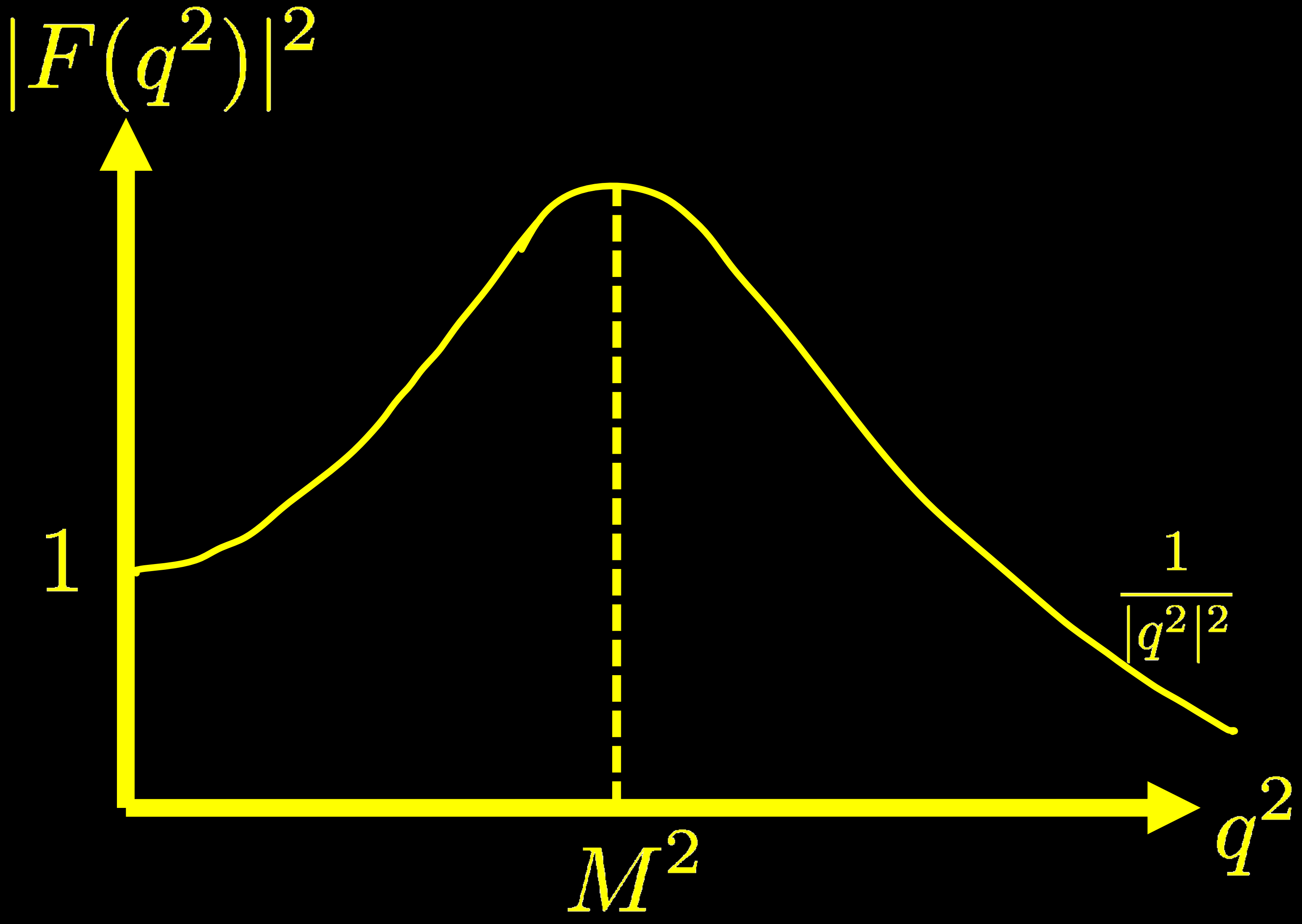
- Without a resonance amplitudes growing like ~ s would violate unitarity
- In QCD, resonances restore unitarity

WZ scattering

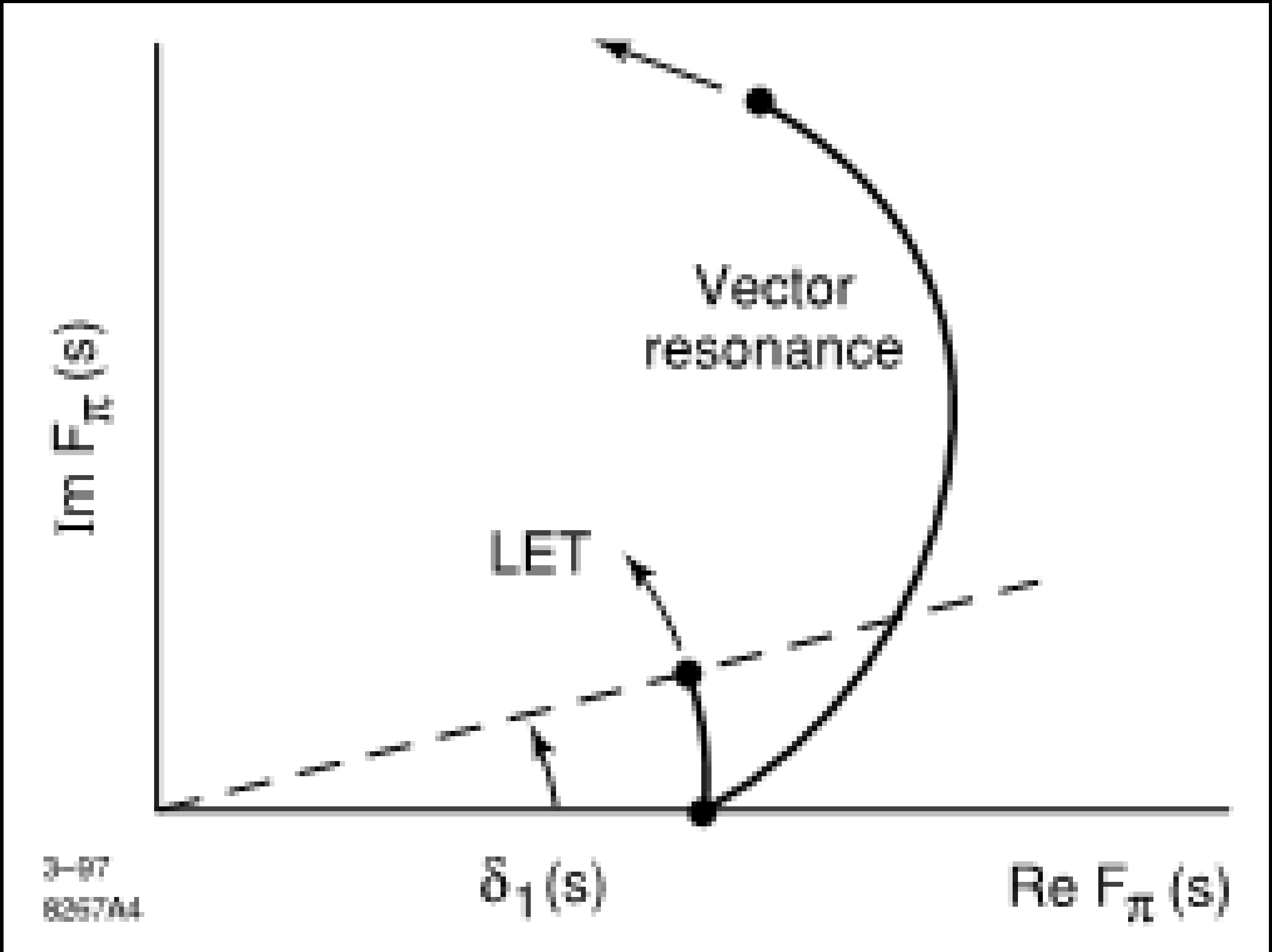
- What does this imply for WZ scattering?
- Only longitudinal modes pick up a phase from scattering in the high energy limit




$F(q^2)$



Ansatz: $F(q^2) = \dfrac{-M^2 + iM\Gamma}{q^2 - M^2 + iM\Gamma}$

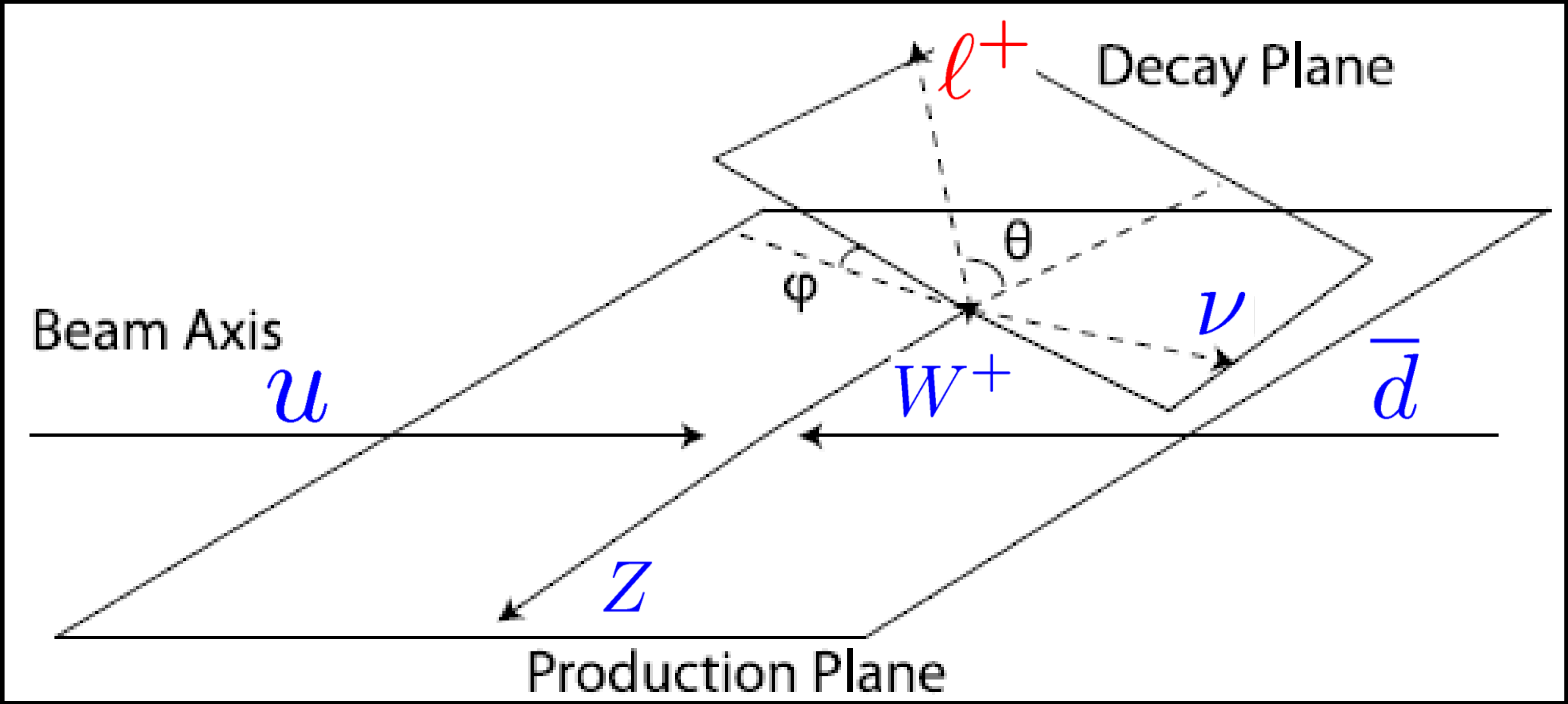


T. Barklow, G. Burdman, Chivakula, Dobrescu … hep-ph/9704217

Longitudinal WZ modes pick up this phase shift!

Is this phase shift observable?

WZ production at LHC



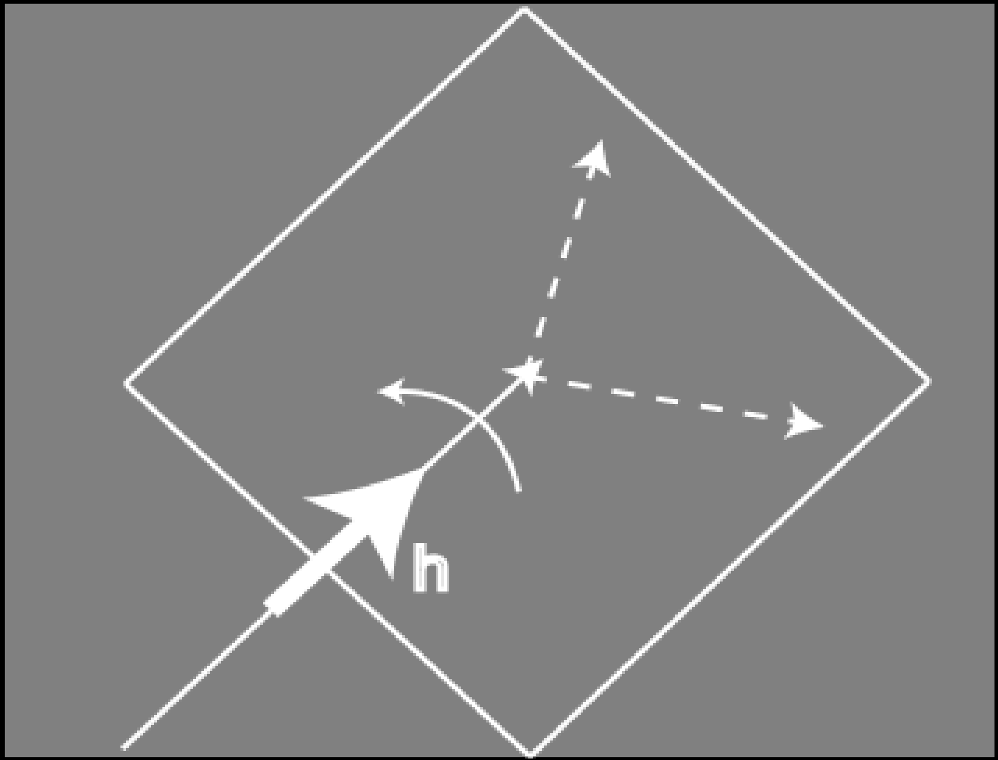
Look for W^+Z fully leptonic modes

Rotating the Decay Plane

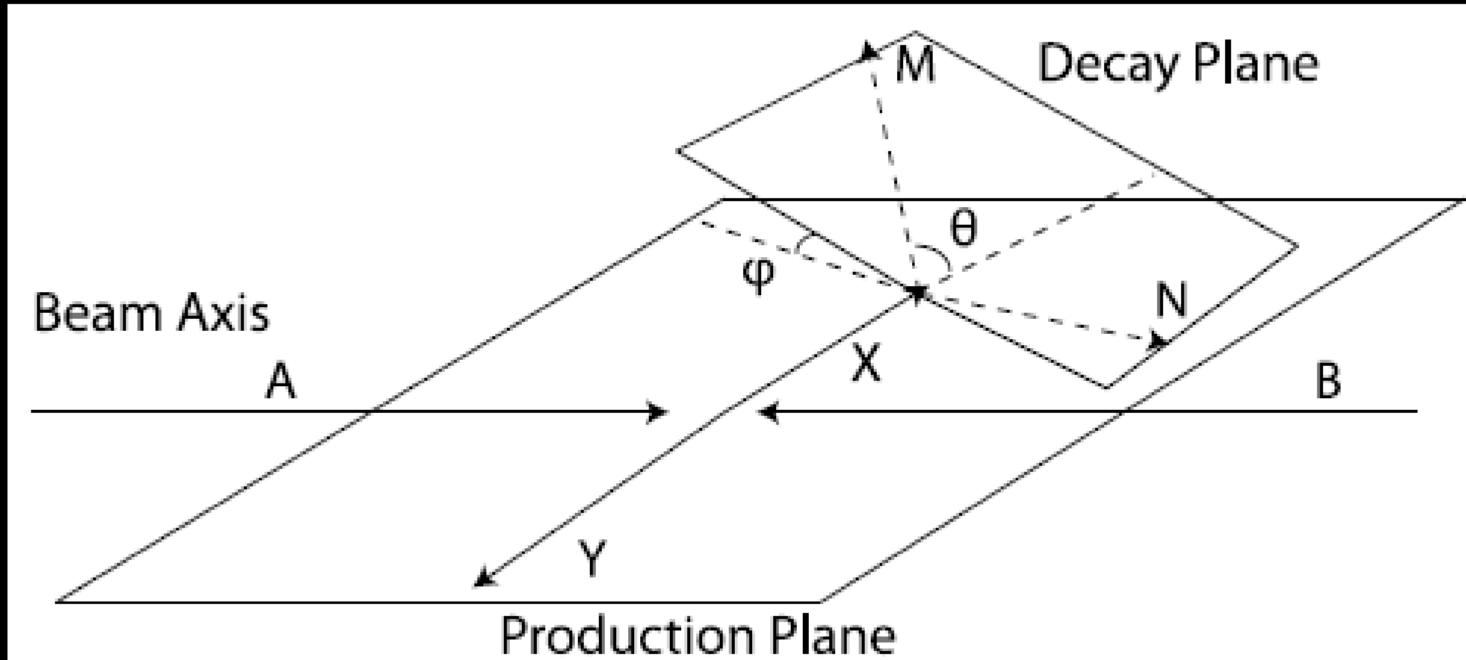
- All orientations of the decay plane are related by an application of the operator $U(\vec{n}, \phi) = e^{i(\vec{J}.\vec{n})\phi}$

- Rotating the decay plane about the axis of motion of the parent particle

$$J_z = \vec{J}.\hat{p} = (\vec{s} + \vec{r} \times \vec{p}).\hat{p} = \vec{s}.\hat{p} = h$$



$$e^{ih\phi}$$



$$\mathcal{M}_{decay}(\phi) = e^{+ih\phi}\mathcal{M}_{decay}(\phi = 0)$$

Quantum Interference of Helicity States

Vector Boson

$$\mathcal{M}_+ \propto e^{i\phi_1}$$
$$\mathcal{M}_0 \propto 1$$
$$\mathcal{M}_- \propto e^{-i\phi_1}$$

Spinor

$$\mathcal{M}_\uparrow \propto e^{i\phi_1/2}$$
$$\mathcal{M}_\downarrow \propto e^{-i\phi_1/2}$$

- If multiple helicity states are produced this phase dependence is observable

$$\frac{d\sigma}{d\phi} \propto \left|\sum_h \mathcal{M}_{prod} e^{ih\phi} \mathcal{M}_{decay}(\phi = 0)\right|^2$$

- True within the validity of the narrow width approximation ("weakly coupled" physics)
- As a result of interference the differential cross-section develops a cos(nφ) dependence, where $n = h_{max} - h_{min} = 2s$.

Spin Measurement

Scalar: $$\frac{d\sigma}{d\phi} = A_0$$

Spinor: $$\frac{d\sigma}{d\phi} = A_0 + A_1 \cos\phi$$

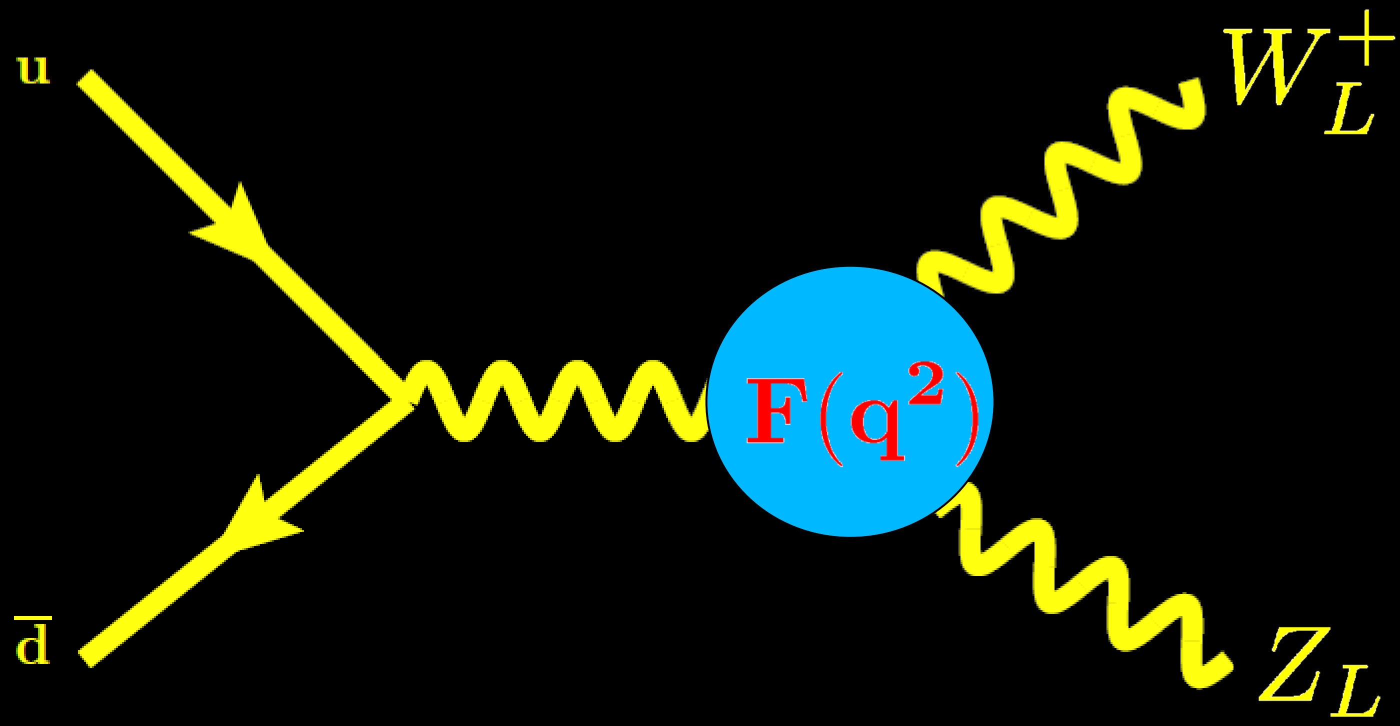
Vector boson: $$\frac{d\sigma}{d\phi} = A_0 + A_1 \cos\phi + A_2 \cos 2\phi$$

Tensor (spin-2): $$\frac{d\sigma}{d\phi} = A_0 + A_1 \cos\phi + A_2 \cos 2\phi + A_3 \cos 3\phi + A_4 \cos 4\phi$$

Look for the highest cosine mode to determine the spin!

M.Buckley, W. Klemm, H. Murayama and VR hep-ph/0711.0364
H. Murayama, VR hep-ph/0904.4561

Back to WZ …



$$F(q^2) = \frac{-M^2 + iM\Gamma}{q^2 - M^2 + iM\Gamma}$$

Interference of helicity states

New phase shift in the longitudinal modes!

$$\mathcal{M}_{\uparrow} \propto e^{i\phi_1}$$
$$\mathcal{M}_{0} \propto F(q^2) = Ae^{i\delta(s)}$$
$$\mathcal{M}_{\downarrow} \propto e^{-i\phi_1}$$

$$\frac{d\sigma}{d\phi} \propto \left|\sum_h \mathcal{M}_{prod} e^{ih\phi} \mathcal{M}_{decay}(\phi = 0)\right|^2$$

$$\frac{d\sigma}{d\phi} = A_0 + A_1 \cos(\phi + \delta) + A_2 \cos 2\phi$$

$$= A_0 + A_1 \cos\phi + B_1 \sin\phi + A_2 \cos 2\phi$$

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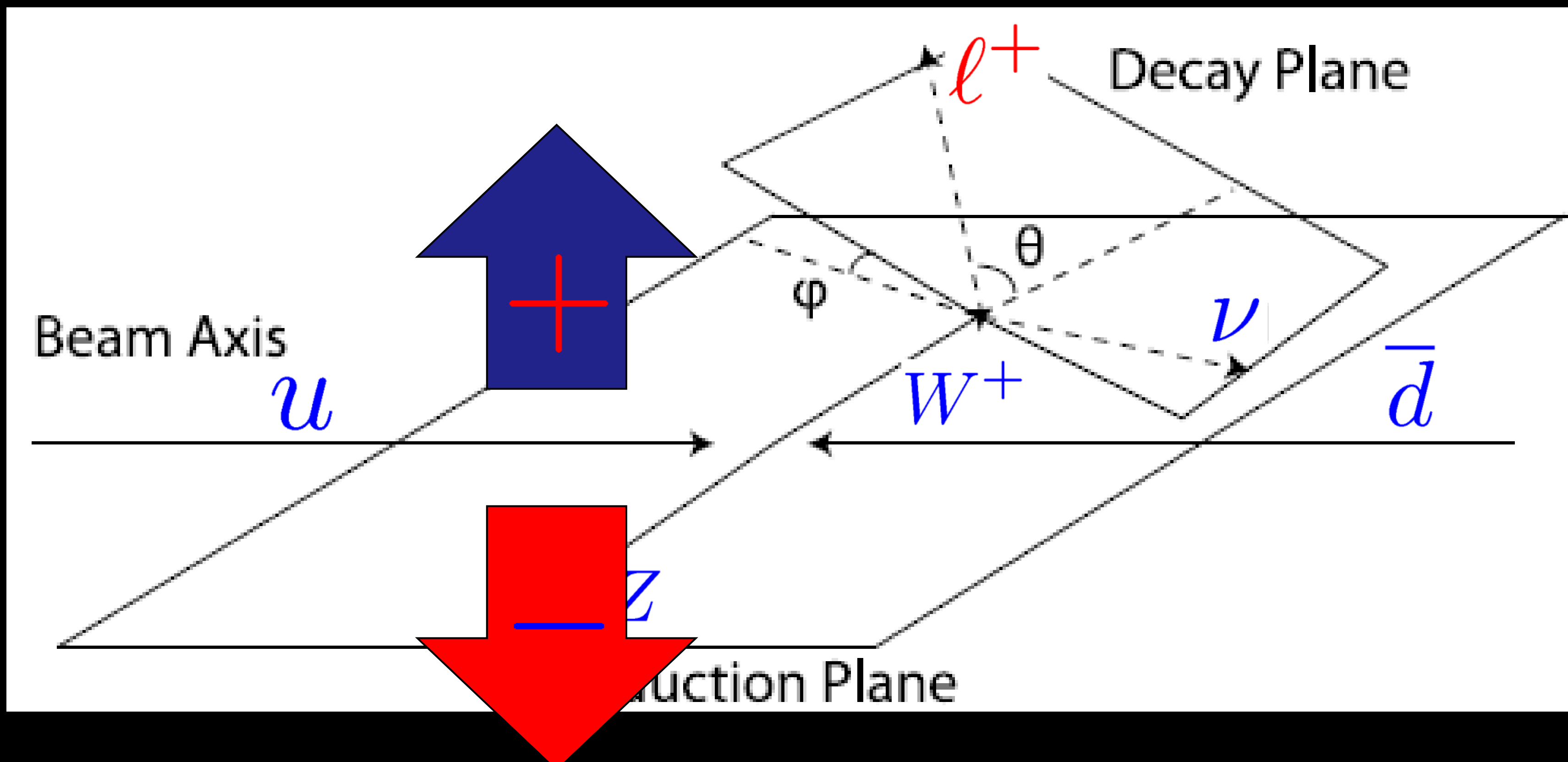
$$\frac{d\sigma}{d\phi} \propto \left| \sum \mathcal{M}_{prod} e^{ih\phi} \mathcal{M}_{decay}(\phi = 0) \right|^2$$

NEW NEW

$$\frac{d\sigma}{d\phi} = A_0 + A_1 \cos(\phi - \delta) + A_2 \cos 2\phi$$
$$= A_0 + A_1 \cos\phi + B_1 \sin\phi + A_2 \cos 2\phi$$

Look for sin φ mode to tell you if the Higgs sector is strongly coupled !

The sign of sin φ



- If the lepton is moving upwards $\sin\phi > 0$
- If the lepton is moving downwards $\sin\phi < 0$

Define a new observable

$$AS = \frac{N^+ - N^-}{N^+ + N^-}$$

- N^+ is the number of leptons going above the plane
- N^- is the number of leptons going below the plane

Counting Experiment

$$AS = \frac{N^+ - N^-}{N^+ + N^-}$$

- The error in AS is from counting
- Background is negligible* and zero at tree level
- Can calculate ΔAS for a given integrated luminosity
- Significance is defined as $S = \frac{AS}{\Delta AS}$

* after cuts

Cuts

- $\Delta r > 0.4$ between leptons or lepton and jet
- p_t >20 GeV and $\eta < 2.5$ cuts on the leptons and jets
- Invariant mass cut on the W Z system between M - 3Γ and M + 3Γ
- Cos θ cut (0.4 – 0.6) on the W in the CM frame to maximize the interference

Significance with $\sqrt{s} = 14\ \mathrm{TeV}$ (500 fb^{-1} integrated luminosity)

Γ/M \ Mass	10%	20%	30%	40%
800 GeV	6.56	6.84	4.46	4.72
1 TeV	3.59	3.89	2.1	2.4
1.2 TeV	1.54	2.21	1.08	1.48

$$S = \frac{AS}{\Delta AS}$$

$$AS = \frac{N^+ - N^-}{N^+ + N^-}$$

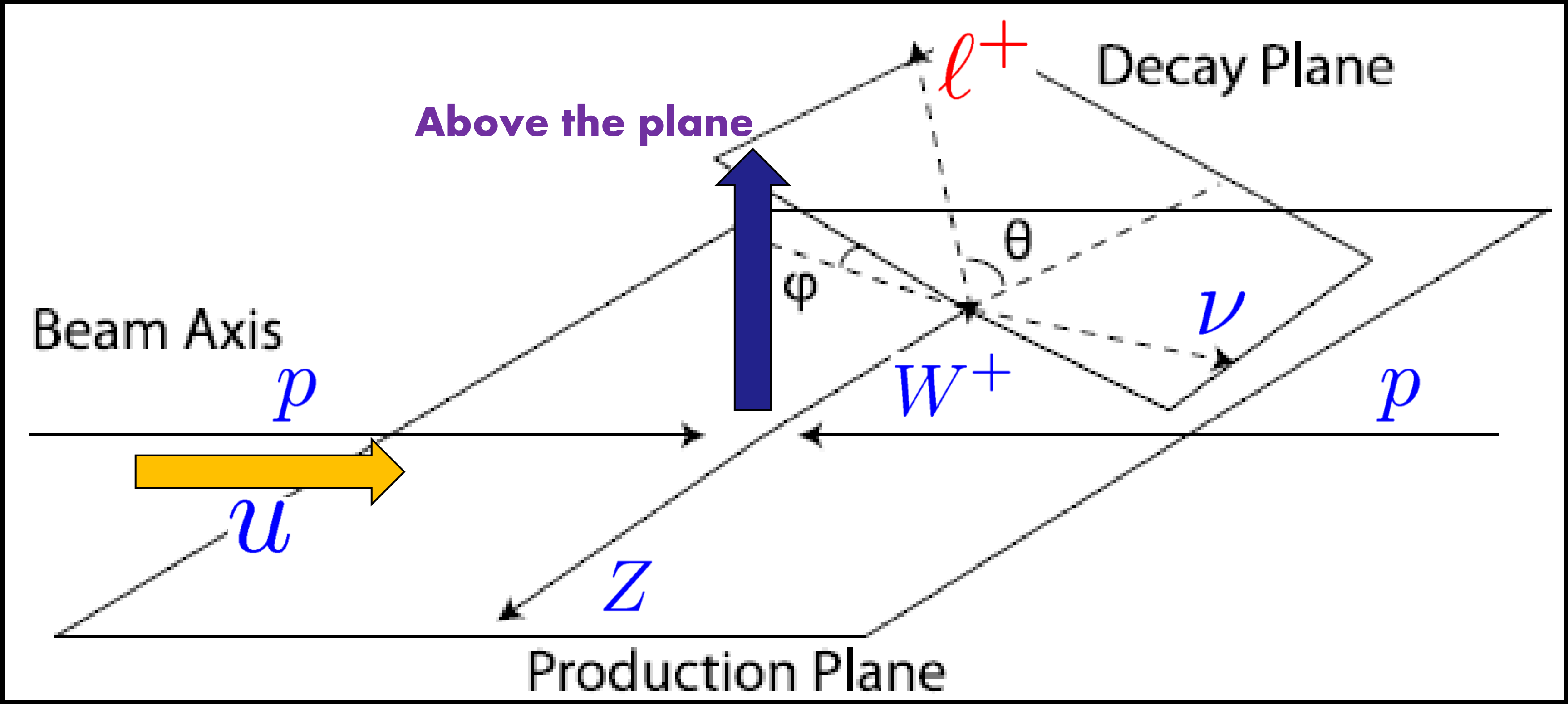
Conclusions

- Looking for up-down asymmetry can be a good probe of a strongly coupled Higgs sector in the absence of a resonance
- Even when a resonance can be observed, AS is a probe of the nature of interactions
- Need large integrated luminosity, large phase shift and enhancement in longitudinal modes (Best case Form factor)
- Need to optimize cuts
- Need to compute the SM background at loop level


QUESTIONS, COMMENTS, SUGGESTIONS?

Backup Slides

Orientation of the plane



- W^+ preferentially emitted in the direction of the u-quark
- Use this to guess the direction of the u-quark

Practical Issues at the LHC

- Cuts
- Orientation of the plane
- True and False solution (asymmetry does not depend on this)

THEORY ISSUES

- Really should look at phi1-phi2
- WZ fusion more dominant