Discriminating Models of New Physics at the LHC

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Presentation Outline

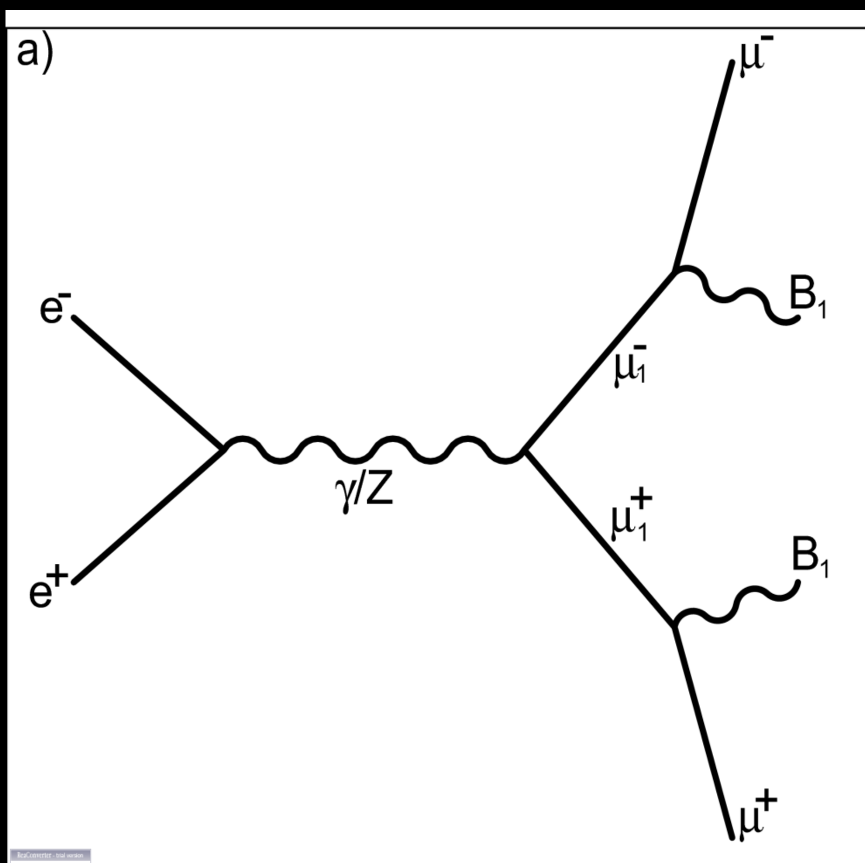
- Spin Measurement (SUSY/Extra Dimensions)
- Strongly coupled Higgs sector

Spin Measurement

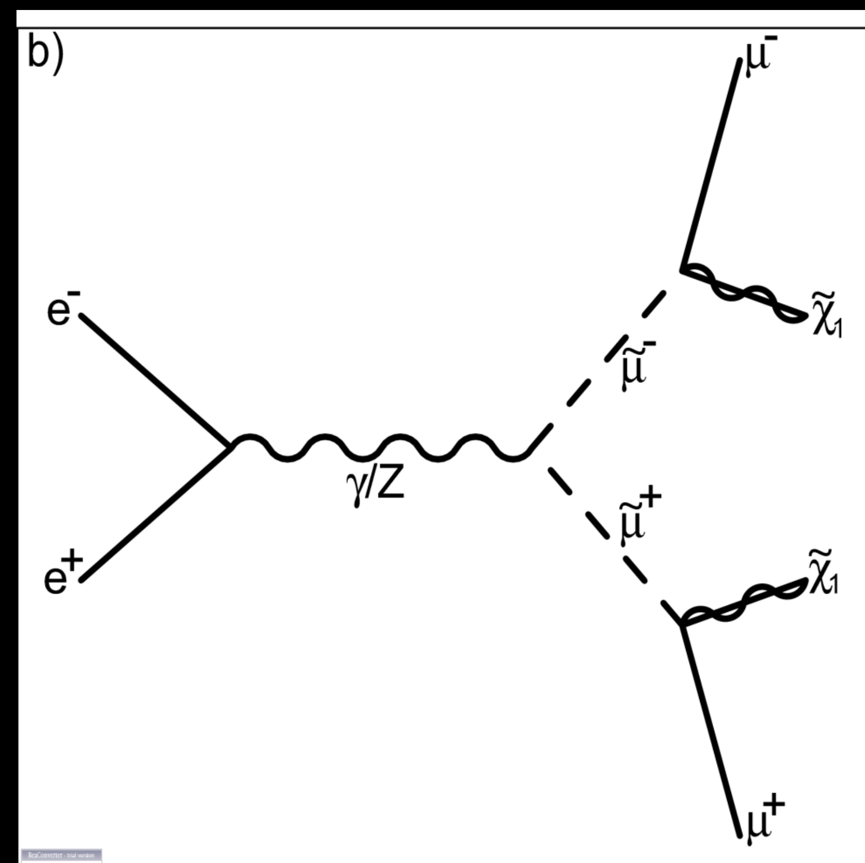
- Using Quantum Interference of Helicity Amplitudes to measure spin
- Challenge of spin measurement at the LHC
- Application of this technique to the RS graviton case at the LHC

Why measure spin?

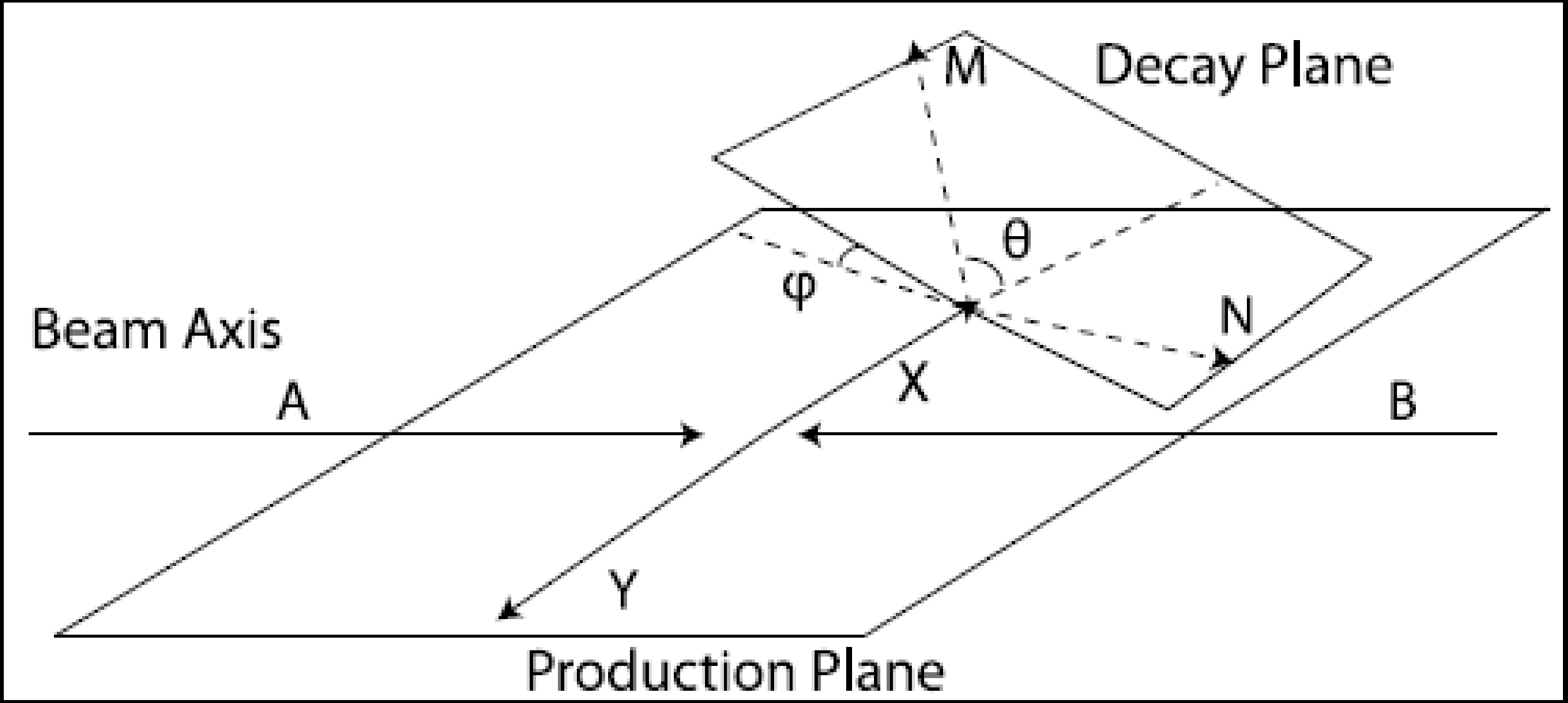
UED: Spin-1/2



Susy: Spin-0



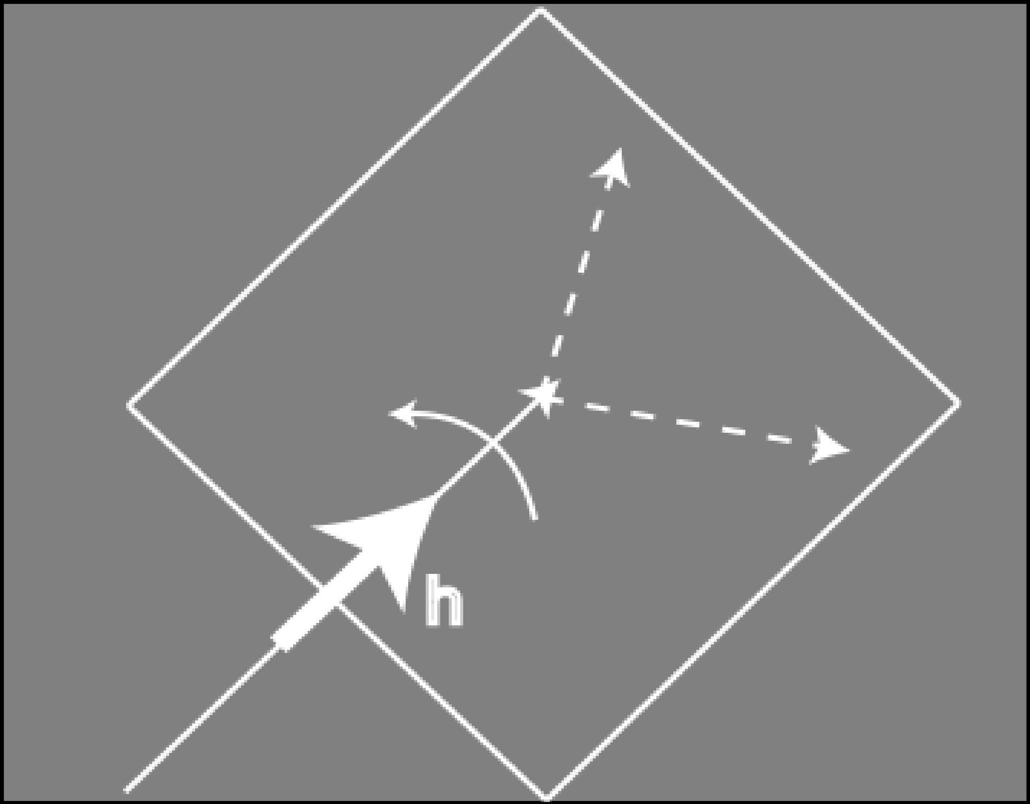
Collider Physics Angles



Back to Fundamentals

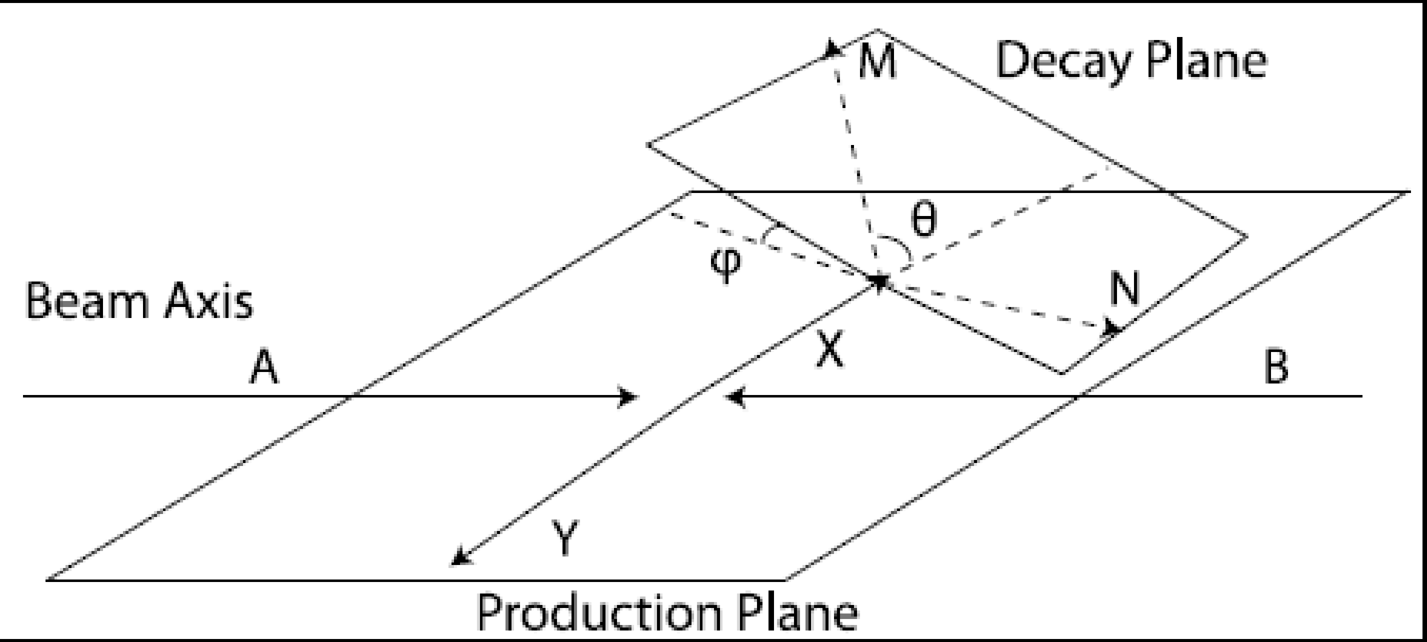
- Spin is a type of angular momentum
- Angular momentum generates rotations $U(\vec{n},\phi) = e^{i(\vec{J}.\vec{n})\phi}$
- We can isolate spin from orbital angular momentum by considering the component of angular momentum in the direction of motion of a particle

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



$$e^{ih\phi}$$

Model Independent Technique for Measuring Spins



- Production plane provides a reference orientation
- Rotating the decay plane by an angle φ → action of this rotation on the matrix element of the decay must be equivalent to the action of rotation on the parent particle by φ.

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

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

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 $n = h_{max} - h_{min} = 2s$.

The Bottom Line

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

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

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

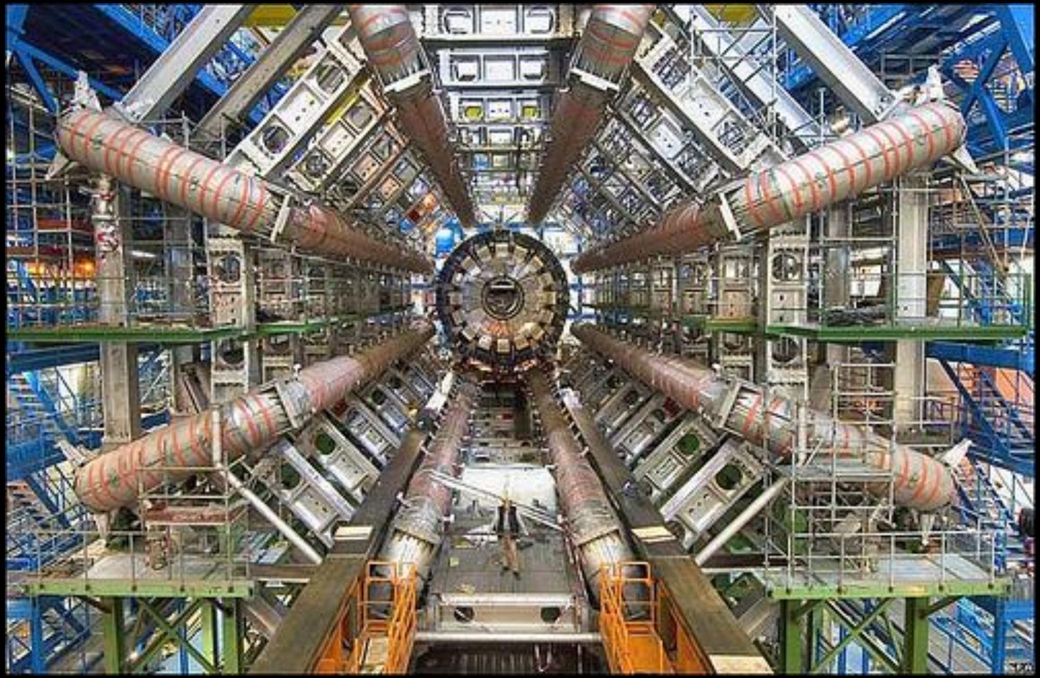
Tensor (spin-2): $$\frac{d\sigma}{d\phi} = A_0 + A_1 \cos\phi + A_2 \cos 2\phi + A_3 \cos 3\phi + A_4 \cos 4\phi$$

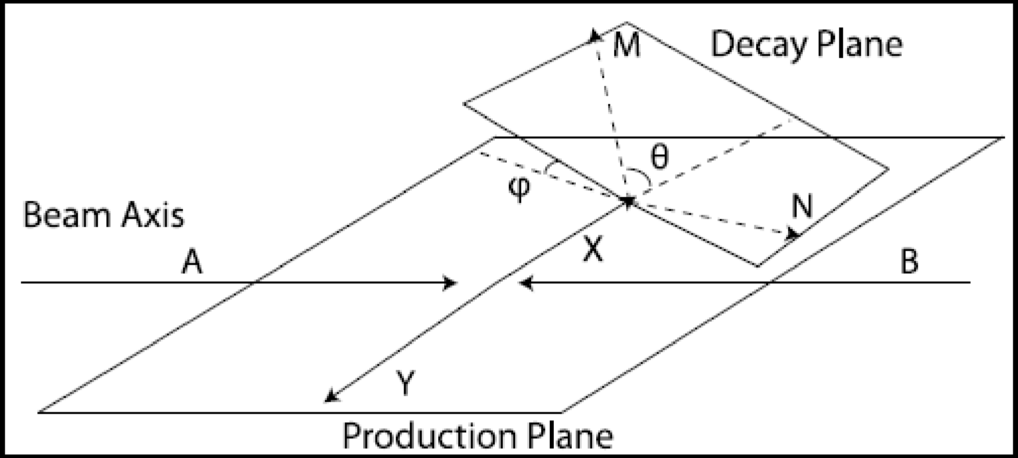
Look for the highest cosine mode to determine the spin!*

*(Can set a lower bound on the spin of a particle)

This argument is based entirely on Quantum Mechanical principles, to actually compute the coefficients requires Feynman diagrams!

The Large Hadron Collider

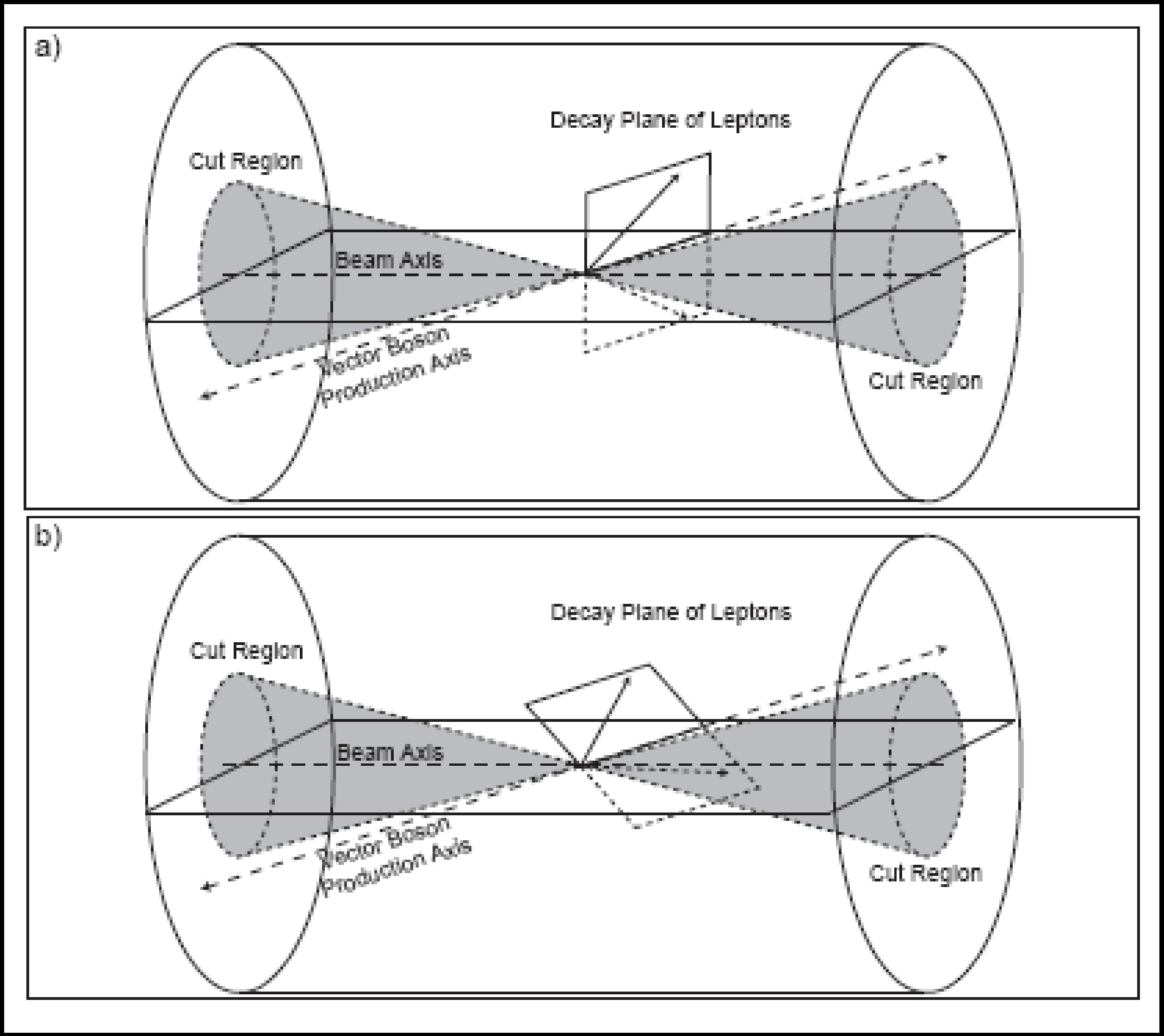




Applying this technique at the LHC

- Missing energy events are not reconstructible
- Odd modes disappear
- Have to adjust for detector cuts

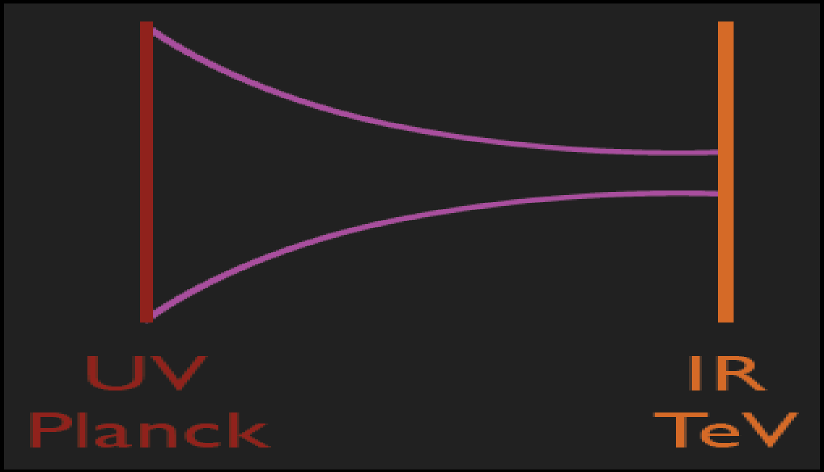
Cuts destroy Rotational Invariance!



Matthew R. Buckley Beate Heinemann William Klemm Hitoshi Murayama arXiv:0804.0476 [hep-ph]

Randall-Sundrum Graviton spin?

RS case: Fully reconstructible! No missing energy. Spin measurement easier.

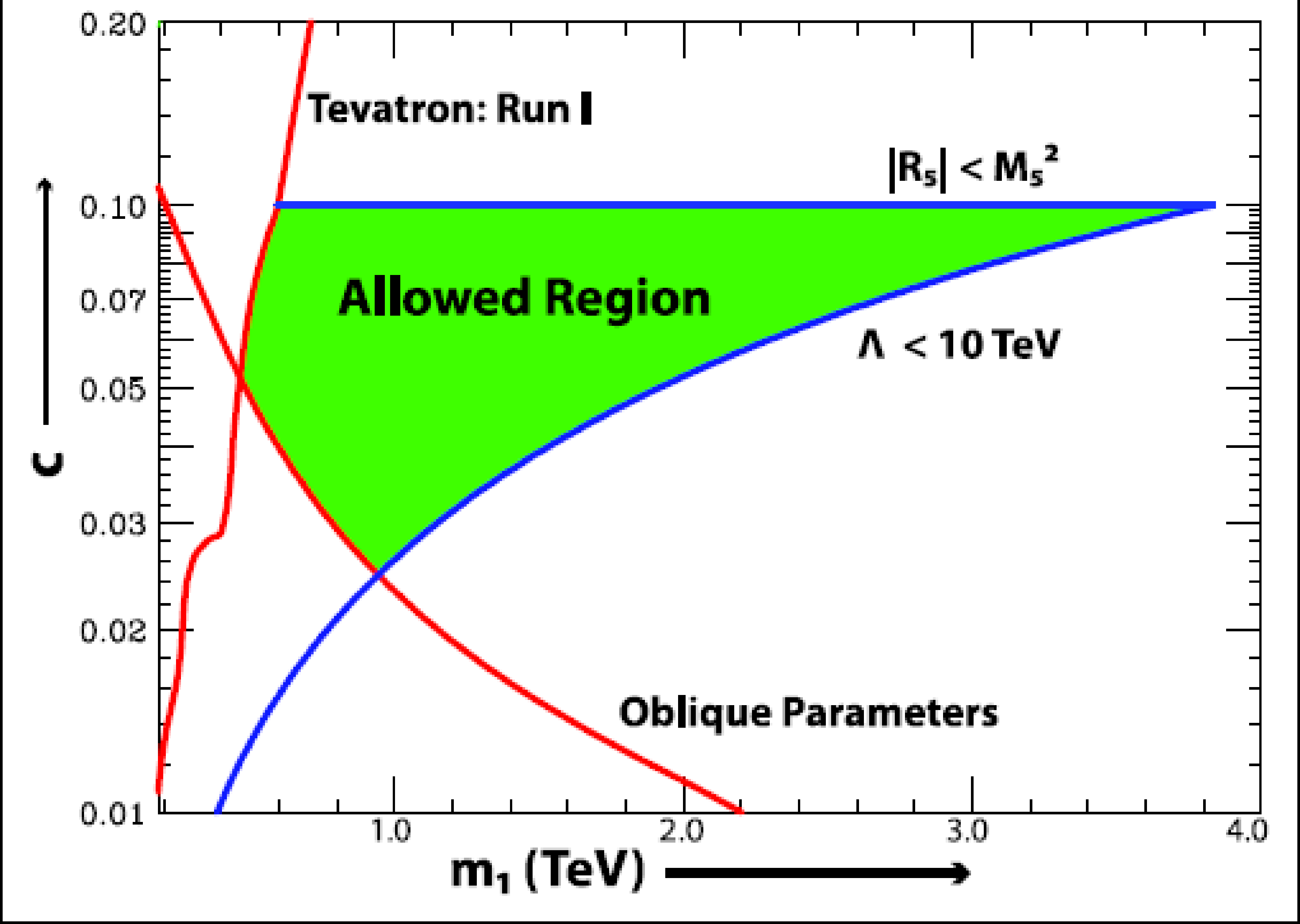


Unique signature! → cos(4ø) mode

$$\frac{d\sigma}{d\phi} = A_0 + A_1 \cos\phi + A_2 \cos 2\phi + A_3 \cos 3\phi + A_4 \cos 4\phi$$

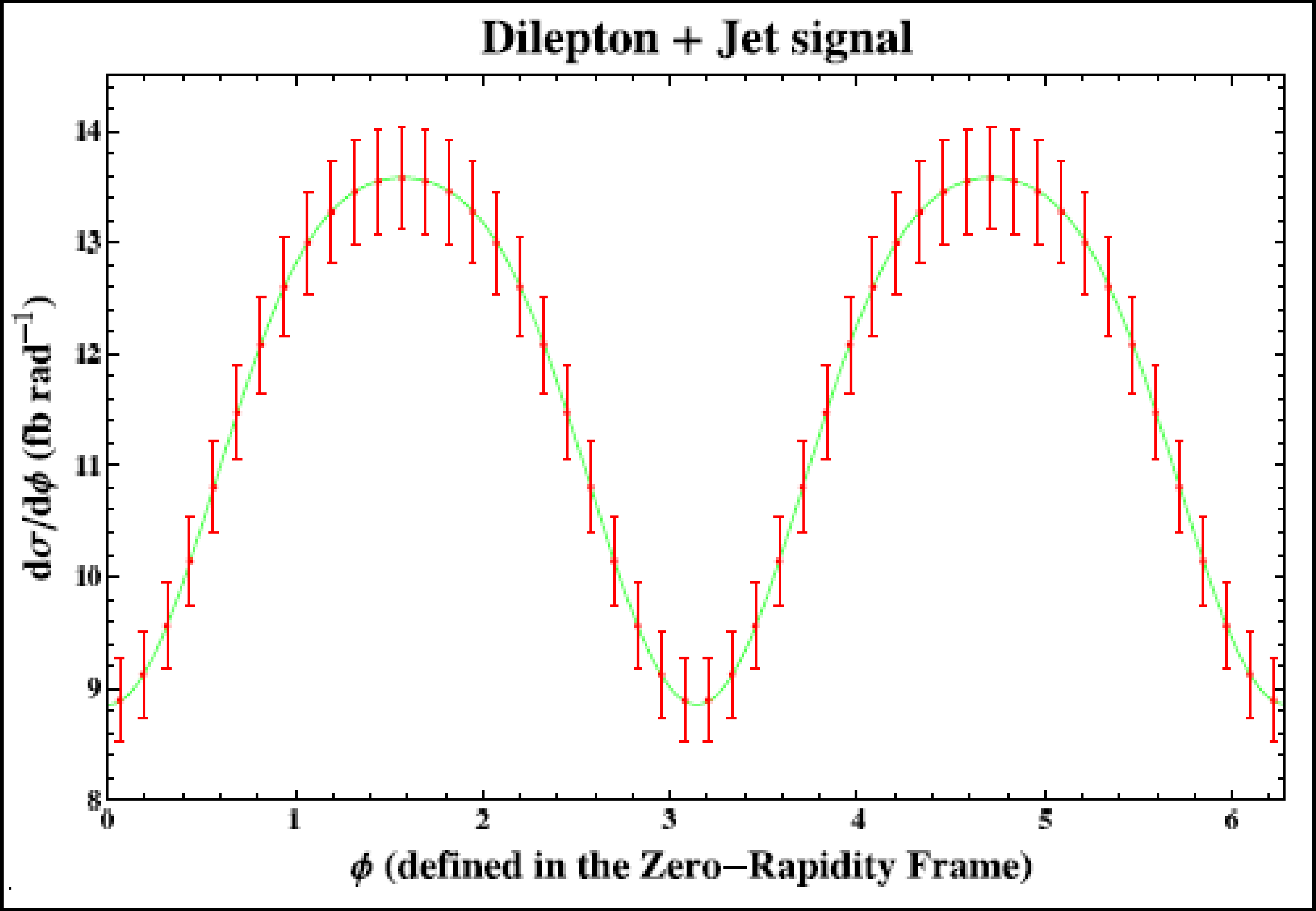
Background is from spin-1 particles. No contribution to the 4-mode! ... but contributes to the overall normalization of the cross-section.

Parameter Space

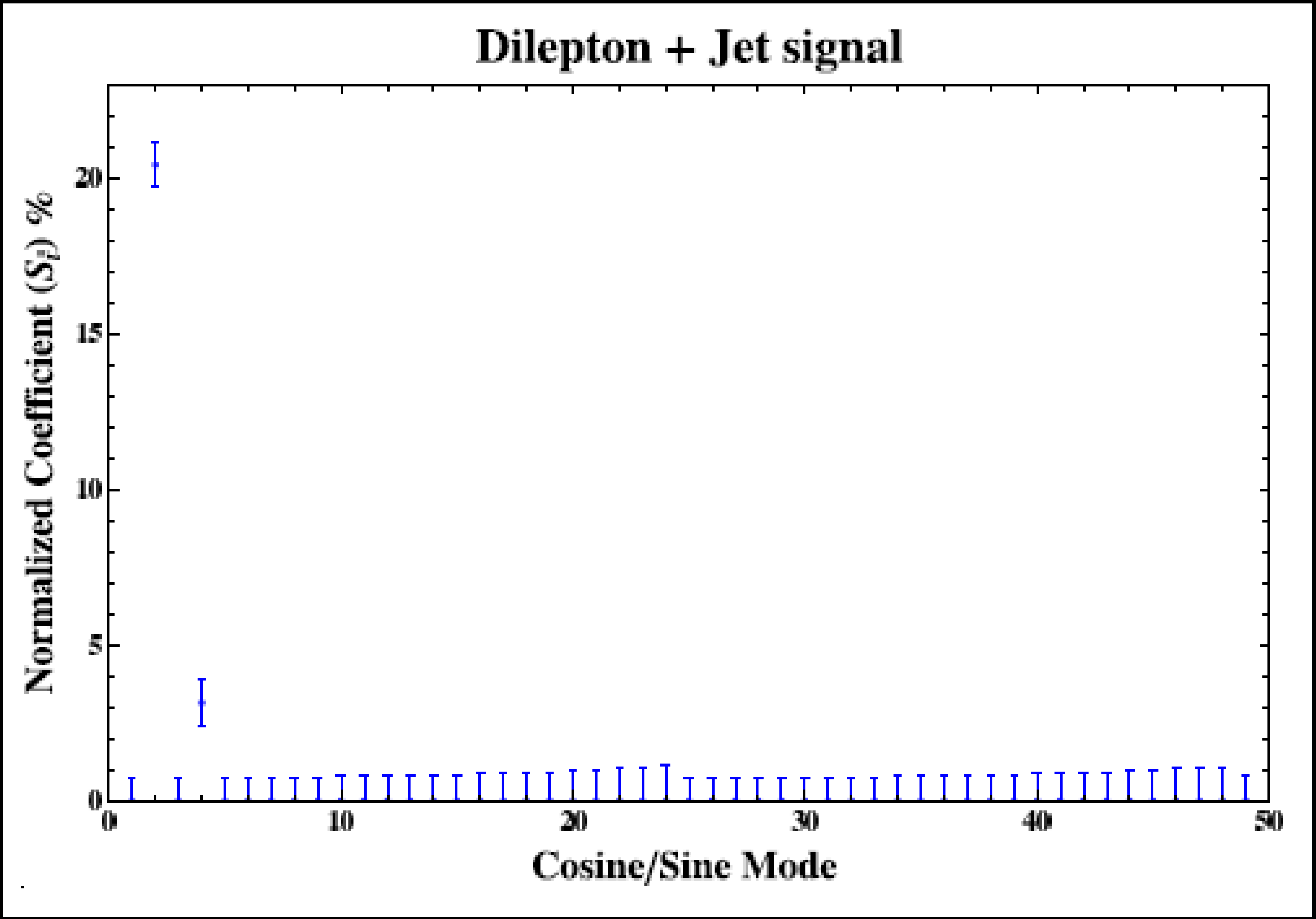


hep-ph/0006041 H. Davoudiasl J.L. Hewett T.G. Rizzo

Results from Simulation



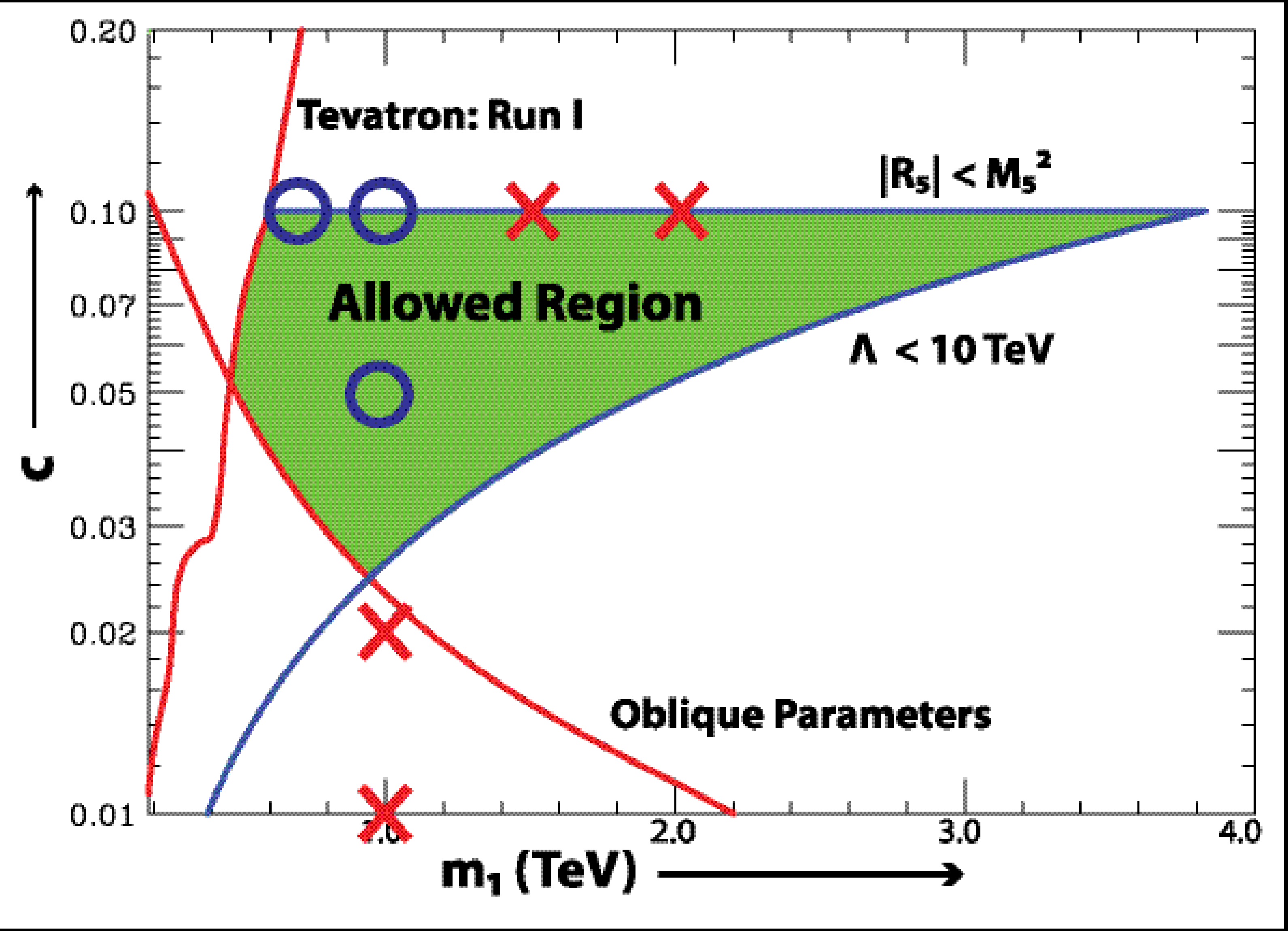
- The green curve shows the differential distribution
- 2-mode is easily visible. Is there a 4-mode?
- How do we extract information about it?



Can see a cos(4Ø) mode in addition to the cos(2Ø) mode! (with about 3% strength)

Error in $|A_4/A_0|$ in this example is ~ 20%

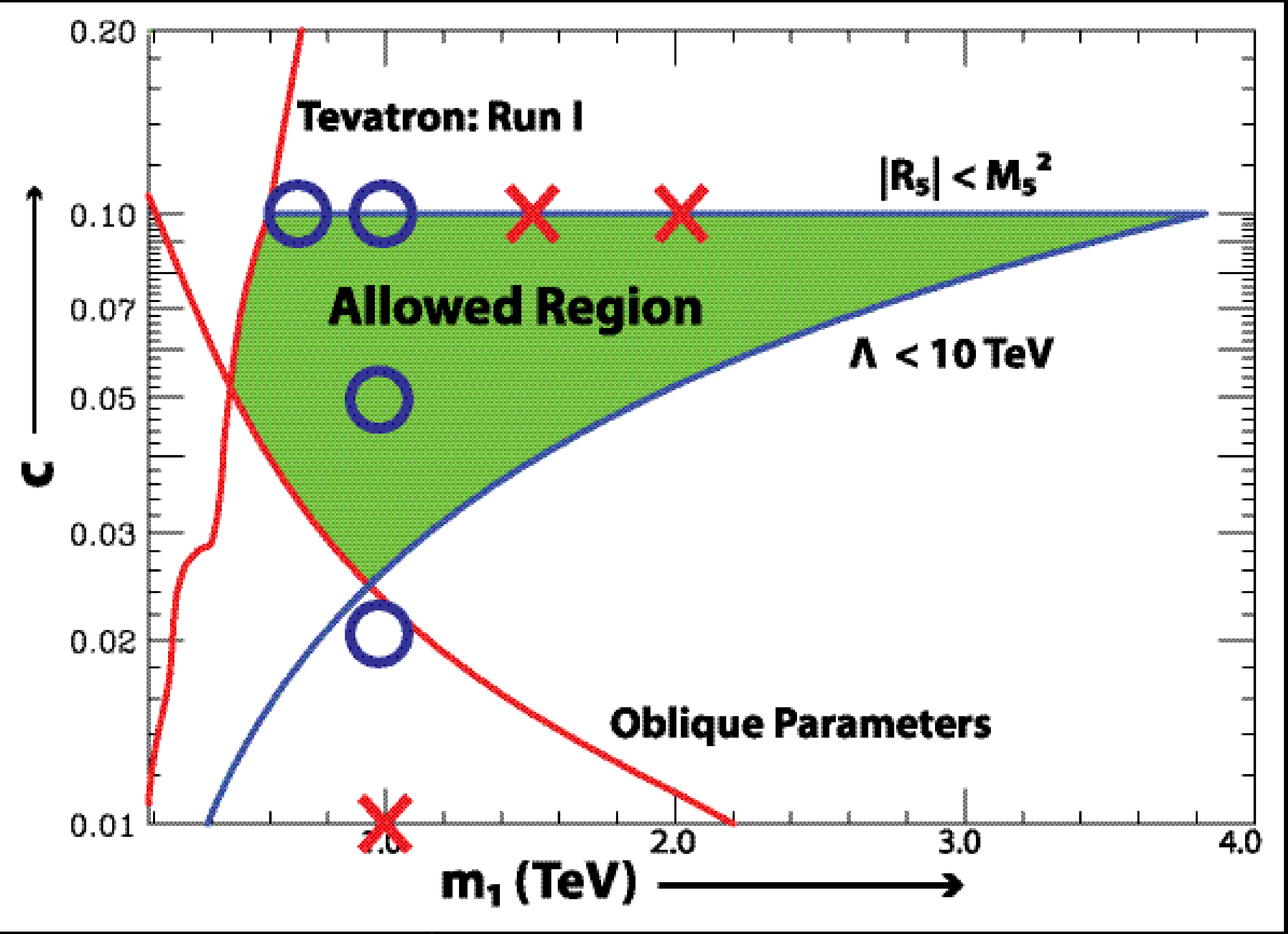
2-σ determination of Graviton spin



for 100 fb^{-1} Integrated Luminosity

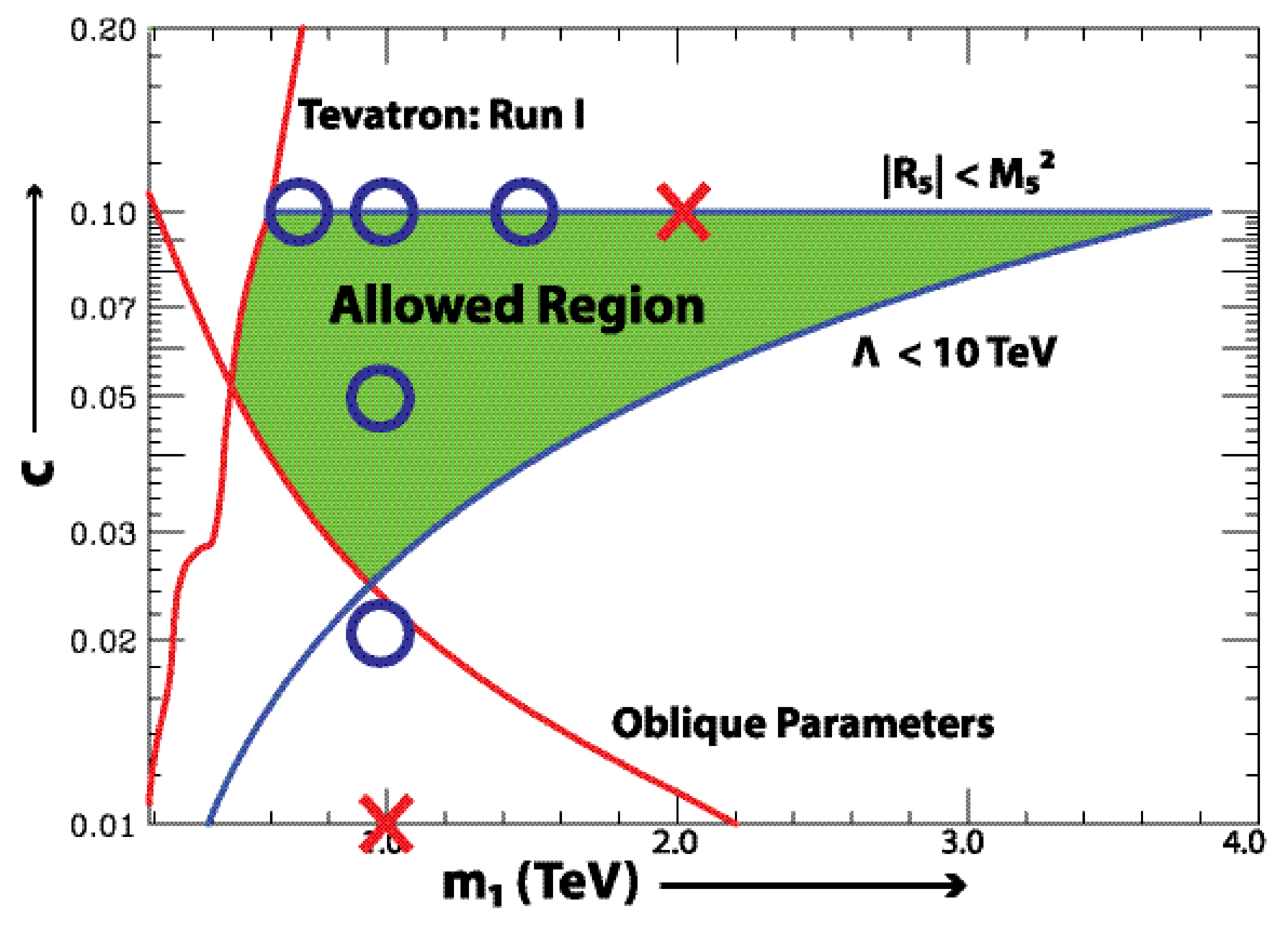
H. Murayama, VR   arXiv:0904.4561

2-σ determination of Graviton spin



for 500 fb^{-1} Integrated Luminosity

2-σ distinction from scalar



for **10 fb⁻¹** Integrated Luminosity

Conclusions and Summary

- **Spin measurement** at LHC is a challenge, but for **RS gravitons looks quite feasible**
- ~3% signal in $|A_4/A_0|$ for values of $m_1 < 1$ TeV and large values of the coupling $c \sim 0.1$.
- Can distinguish scalars from spin-2 objects easily even with low luminosities! (Look at $|A_2/A_0|$)
- Error in measurement only dependent on statistics but cross-section drops rapidly
- Important complementary, <u>model-independent</u> determination of spin possible with large integrated luminosity

Strongly Coupled Higgs Sector

(with H. Murayama and J.Shu)

Strongly Coupled Higgs Sector

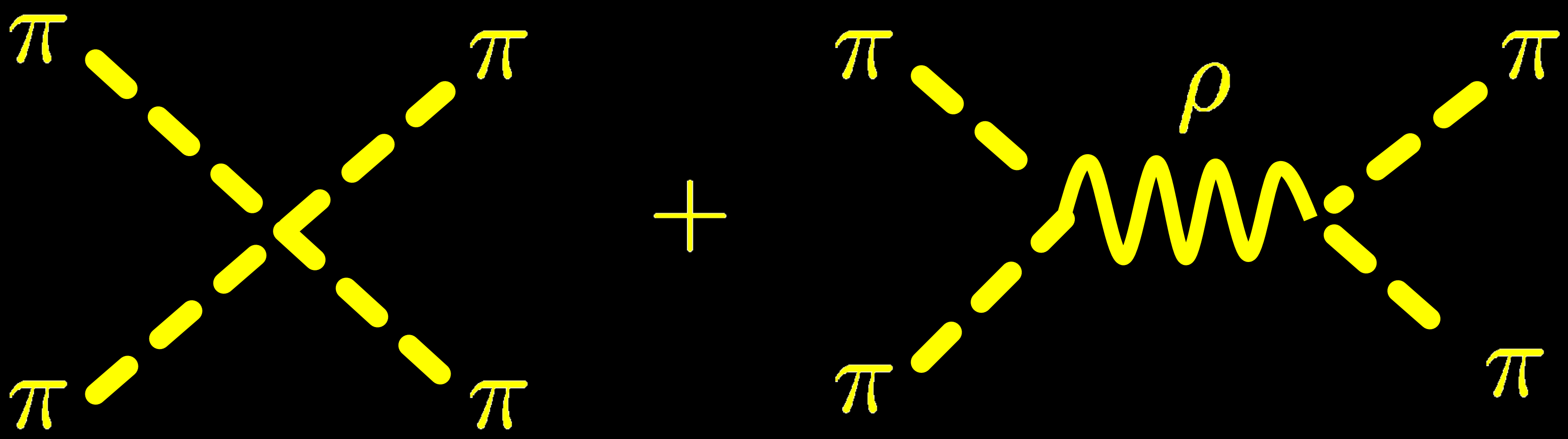
- EWSB similar to chiral symmetry breaking in QCD with 2 flavors
- $SU(2)_L \times SU(2)_R \rightarrow SU(2)_V$
- Chiral Lagrangian with gauged $SU(2)_L$ and hypercharge
- Longitudinal modes of the W,Z gauge bosons are the pseudo-goldstone bosons of chiral symmetry breaking i.e. the pions
- π - π scattering 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?

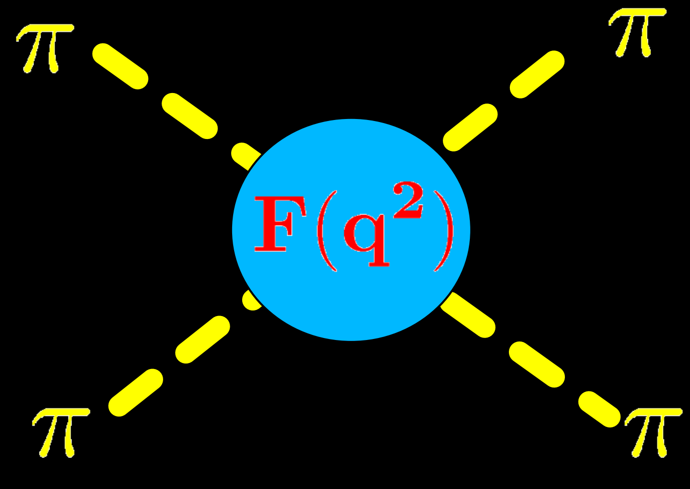
If we do observe a resonance can we discern some properties of its interactions with SM gauge bosons?

Look back at QCD

- π - π scattering picks up a phase shift!



- This is parametrized as a form factor



Partial waves and unitarity

Quick review of elastic scattering

$$\pi\pi \rightarrow \pi\pi$$

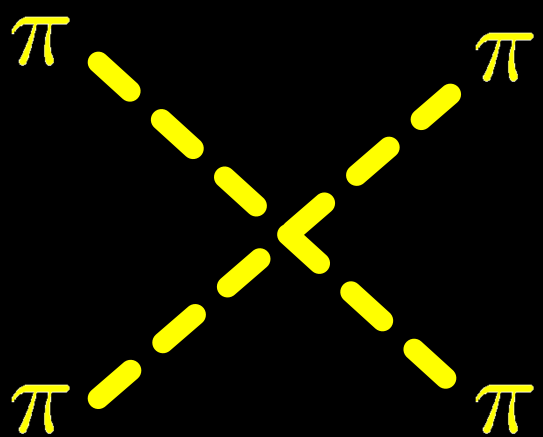
- Incoming partial wave
- Outgoing partial wave can only pick up a phase shift from unitarity $e^{i2\delta_J}$

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

What is the phase shift in QCD?

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

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



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

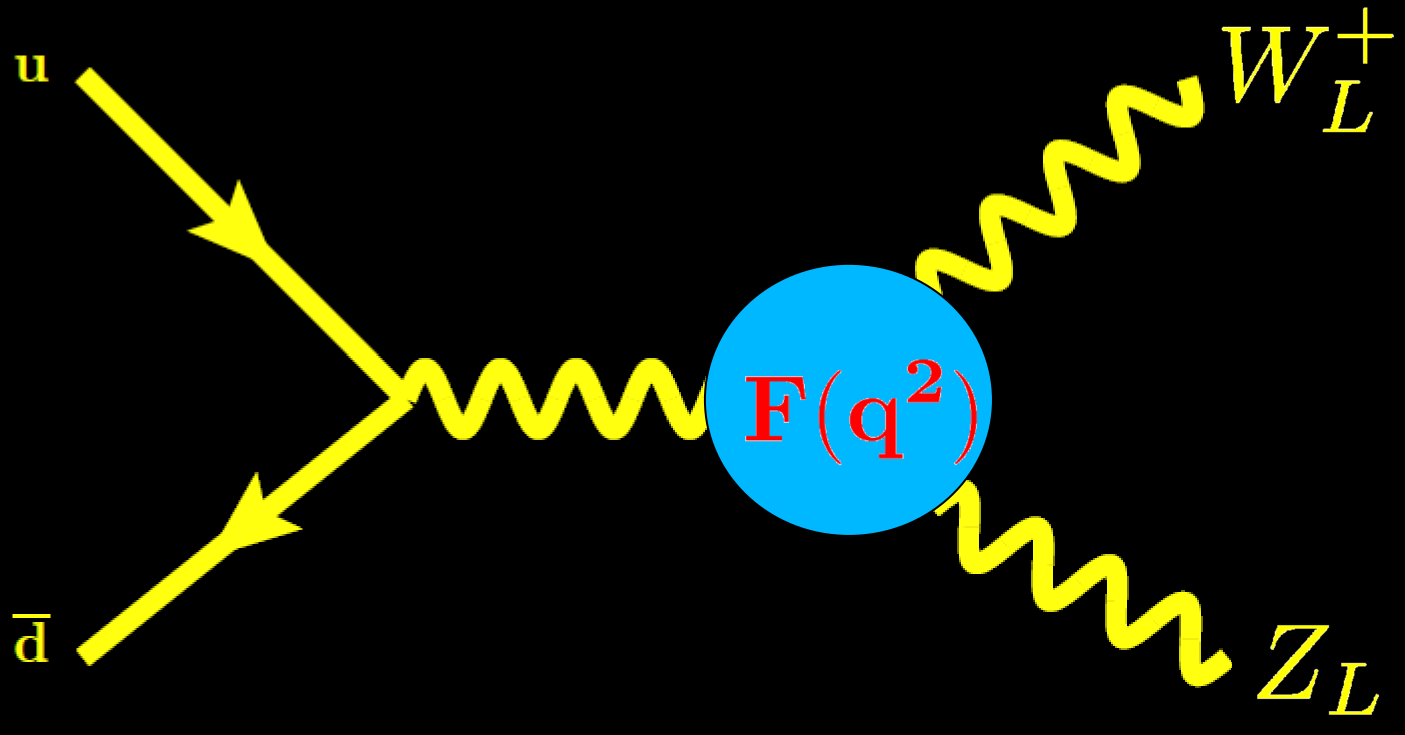
$$\sim \frac{s}{f_\pi^2}$$

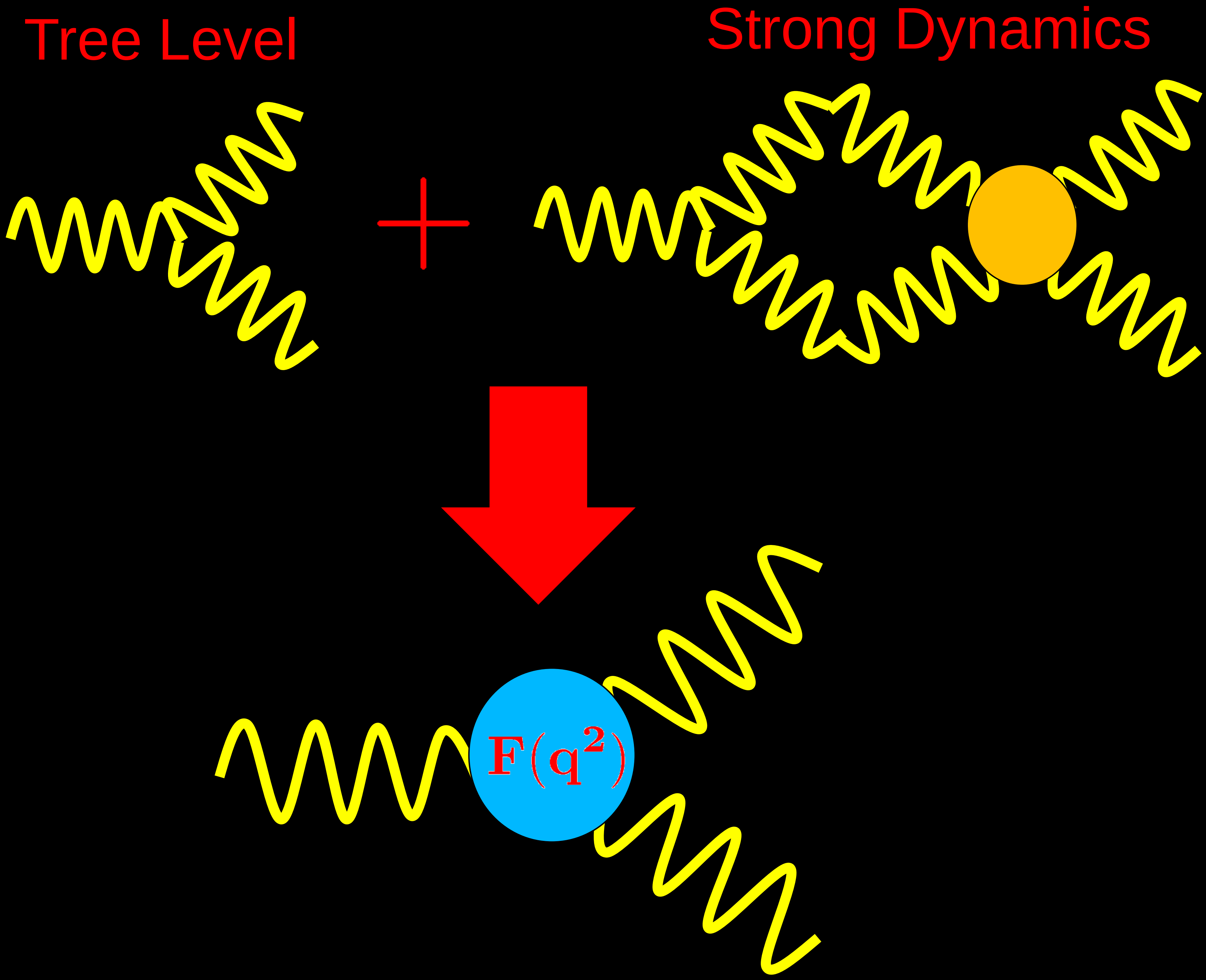
$$\Rightarrow \sin\delta_J \sim \delta_J \sim \#_J \frac{s}{f_\pi^2}$$

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

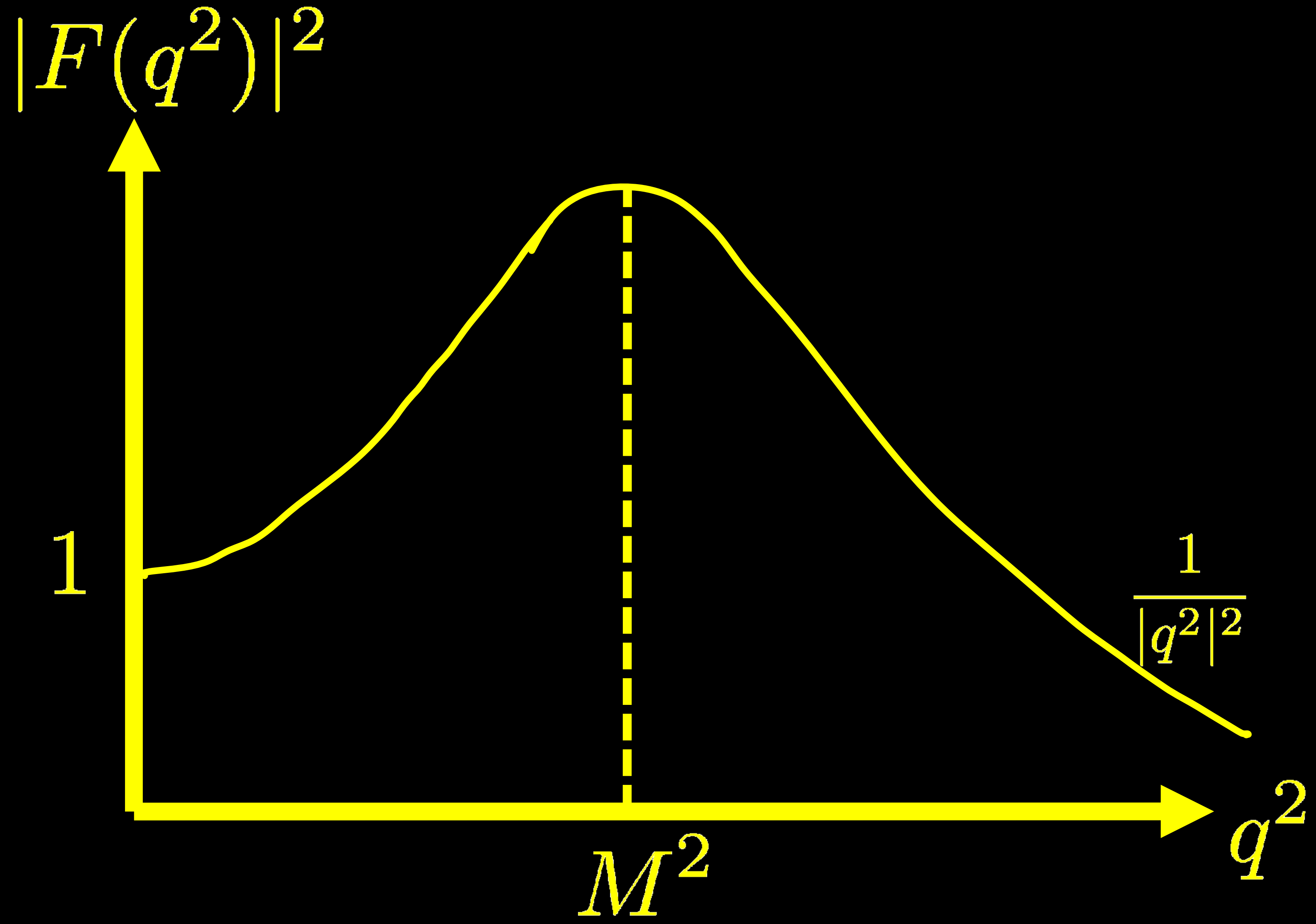
WZ scattering

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

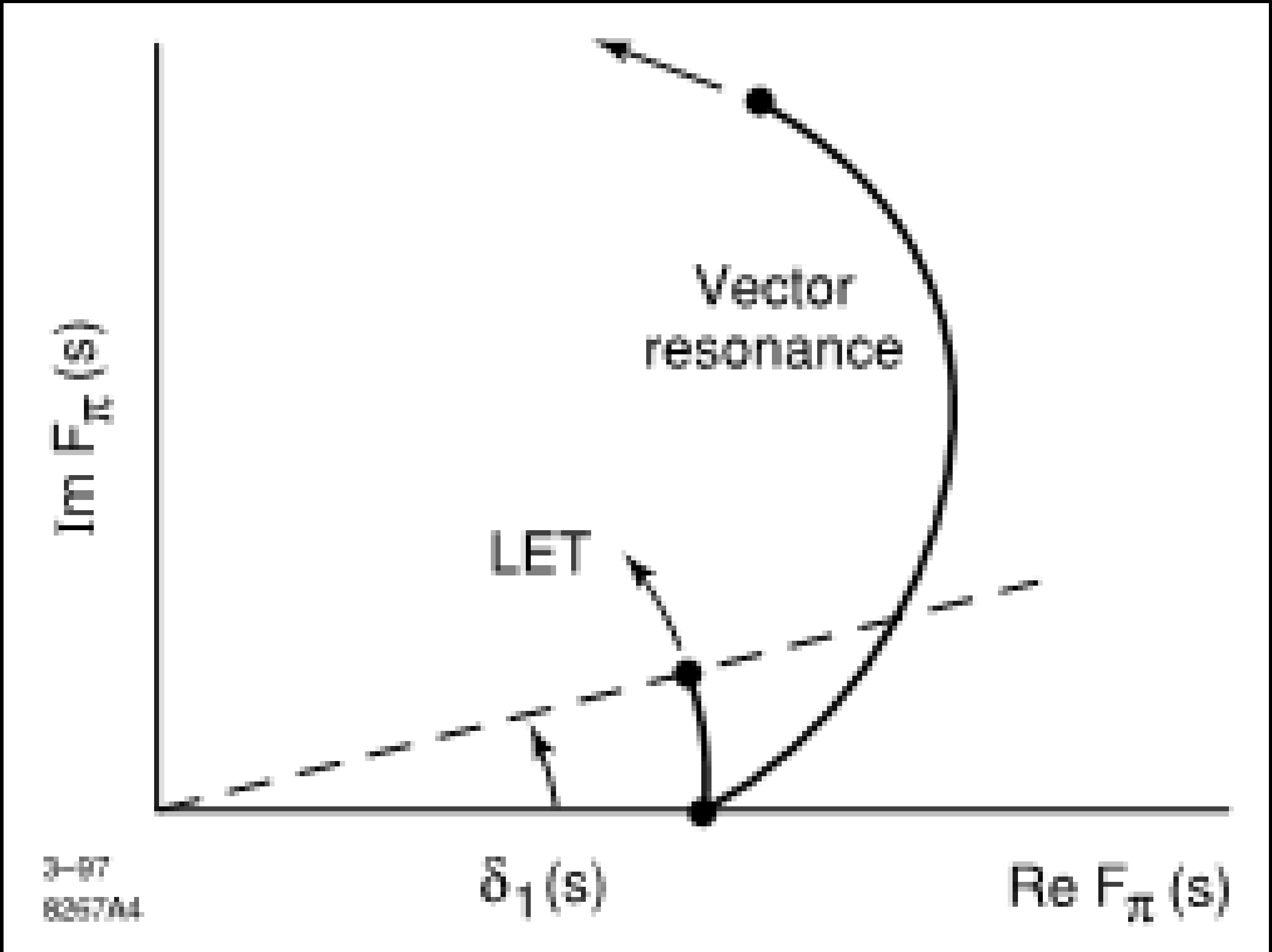




Tree Level
Strong Dynamics
+
$F(q^2)$



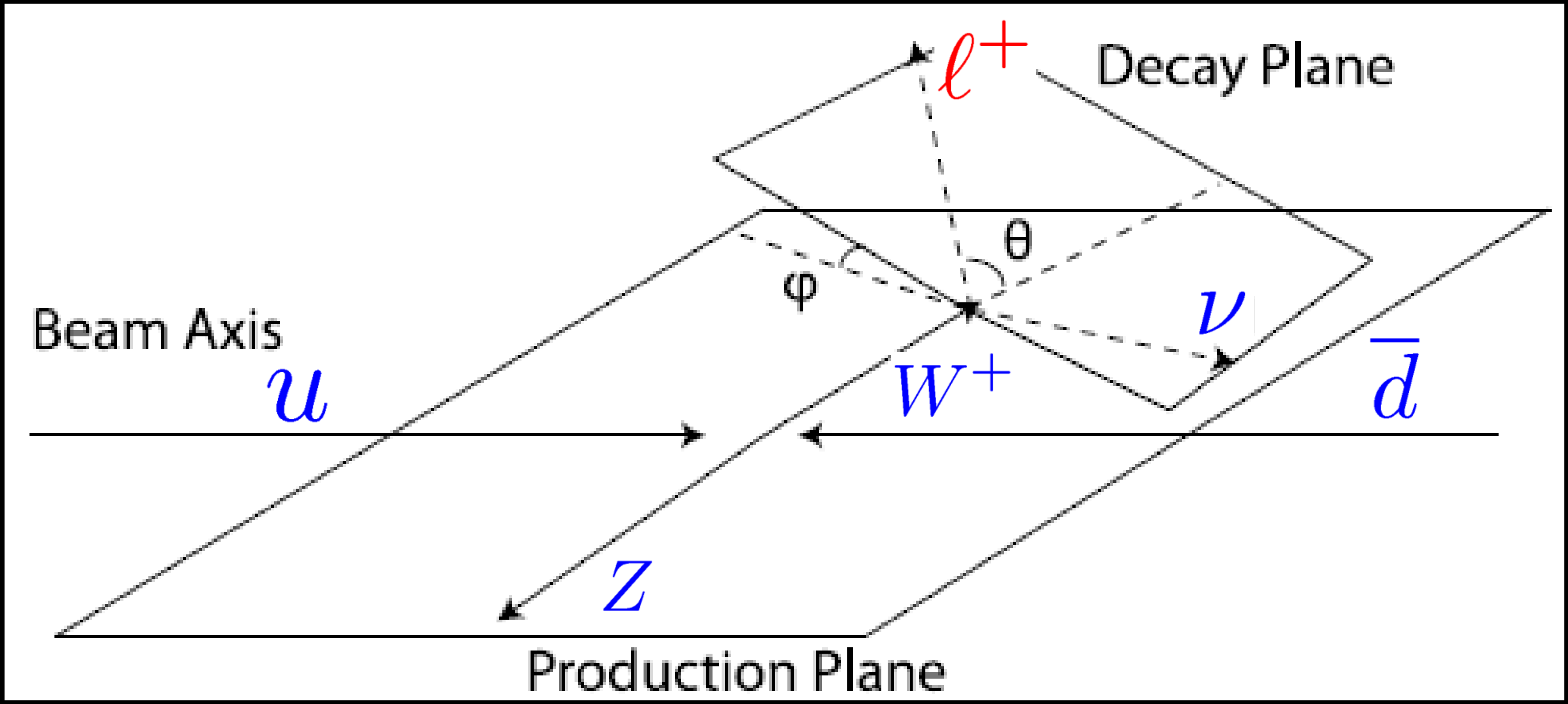
Ansatz: $F(q^2) = \dfrac{-M^2 + iM\Gamma}{q^2 - M^2 + iM\Gamma}$



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

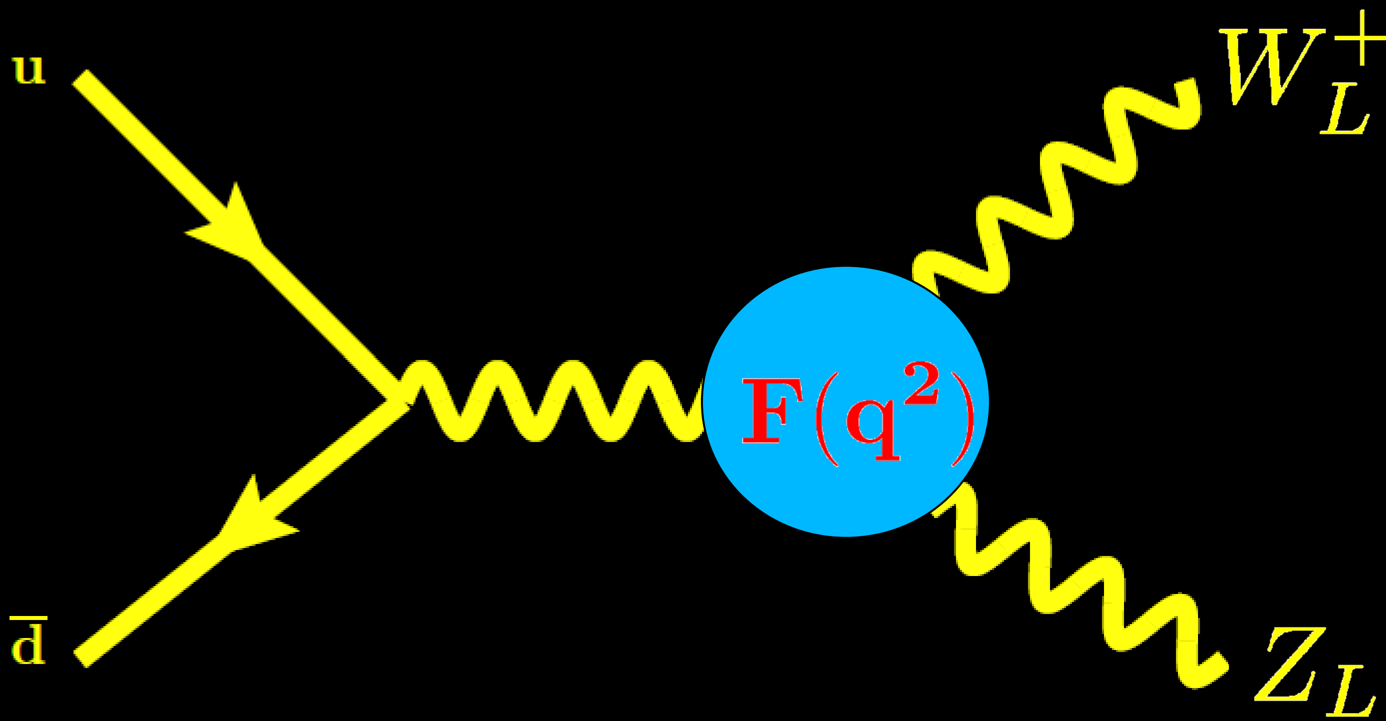
Longitudinal WZ modes pick up this phase shift!

WZ production at LHC



Look for W^+Z fully leptonic modes

Only the Longitudinal modes pick up the phase shift from Strong dynamics



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

Interference of helicity states

New phase shift in the longitudinal modes!

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

$$\begin{aligned}\frac{d\sigma}{d\phi} &\propto \left|\sum_h \mathcal{M}_{prod} e^{ih\phi} \mathcal{M}_{decay}(\phi = 0)\right|^2\\ \frac{d\sigma}{d\phi} &= A_0 + A_1 \cos(\phi + \delta) + A_2 \cos 2\phi\\ &= A_0 + A_1 \cos\phi + B_1 \sin\phi + A_2 \cos 2\phi\end{aligned}$$

Interference of helicity states

New phase shift in the longitudinal modes!

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

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

NEW

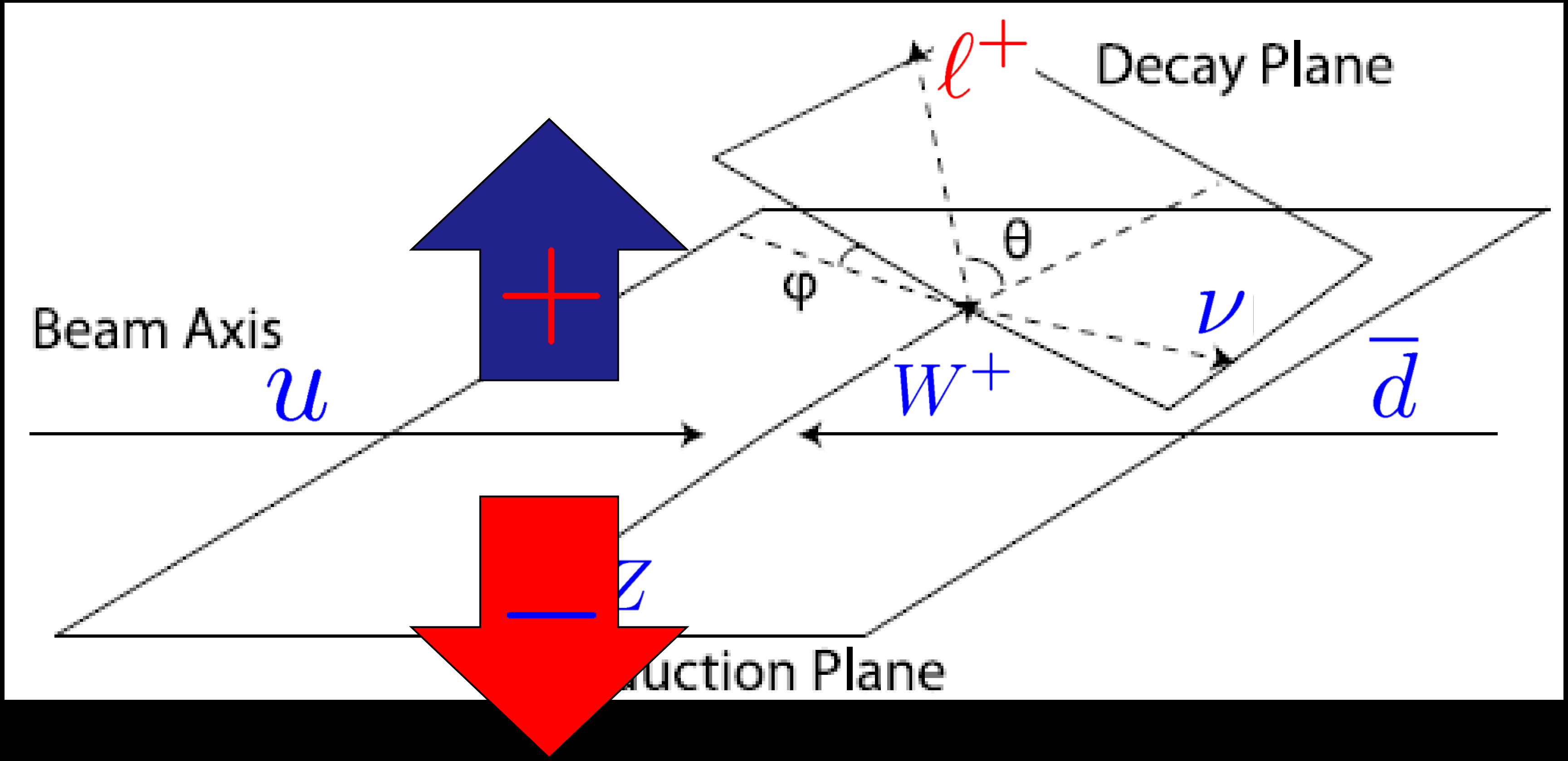
NEW

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

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

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

Define a new observable

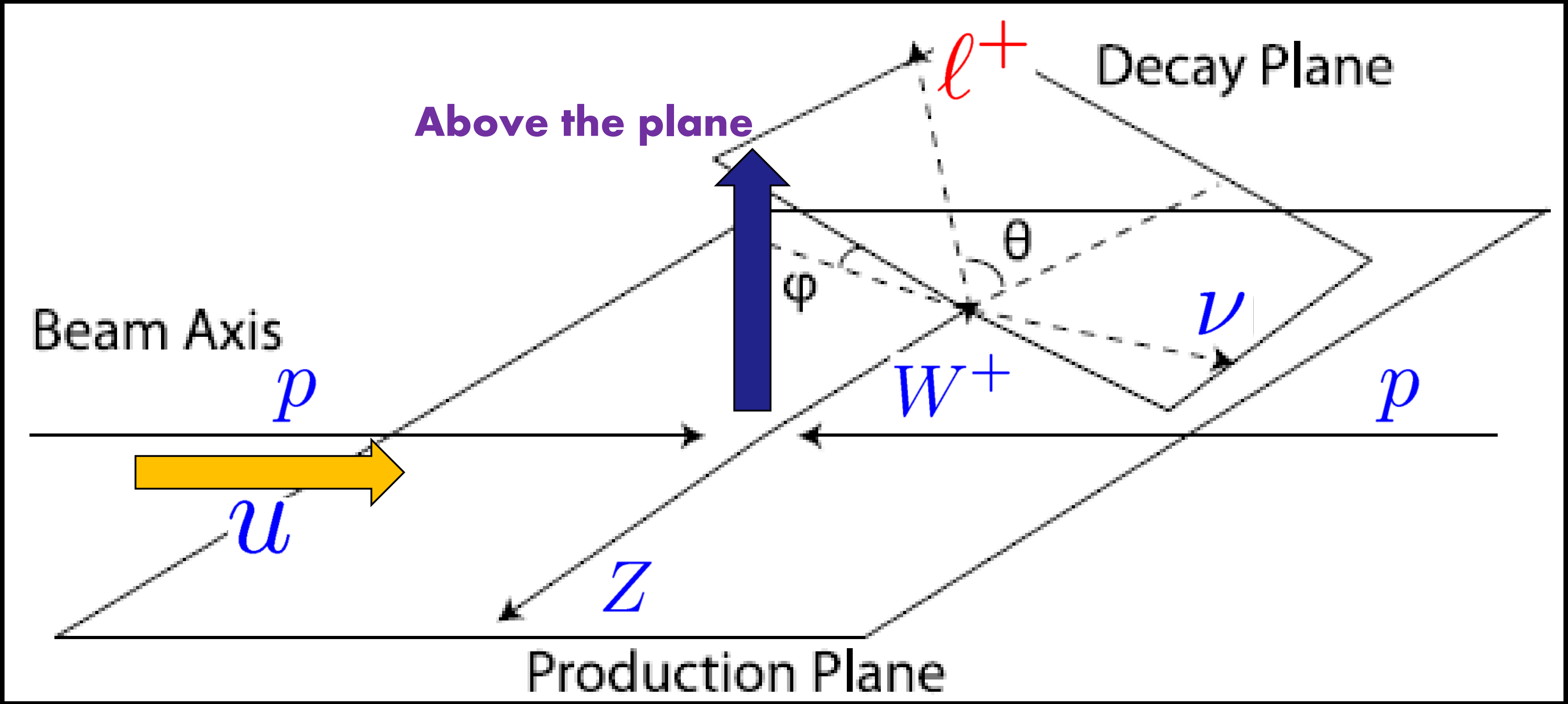
$$A_S = \frac{N^+ - N^-}{N^+ + N^-}$$

WAIT...

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

WHAT DEFINES ABOVE THE PLANE AND BELOW THE PLANE WHEN THE BEAMS ARE IDENTICAL?

Orientation of the plane



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

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

Mass \ Γ/M	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

$$S = \frac{AS}{\Delta AS} \qquad AS = \frac{N^+ - N^-}{N^+ + N^-}$$

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 strong 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

Software Tools used

- HELAS: “HELicity Amplitude Subroutines for Feynman diagram calculation” used to get differential cross-section
  - (H. Murayama, I. Watanabe, Kaoru Hagiwara, 1992)
- HELAS with spin 2-particles
  - K. Hagiwara, J. Kanzaki, Q. Li, K. Mawatari, 2008
- BASES: adaptive Monte Carlo package to integrate the differential distributions
  - (S. Kawabata, 1986)
- LHApdf (CTEQ6l)