Randall-Sundrum graviton spin determination using azimuthal angular dependence

Vikram Rentala

(UC Berkeley & IPMU)

arXiv:0904.4561 [hep-ph]

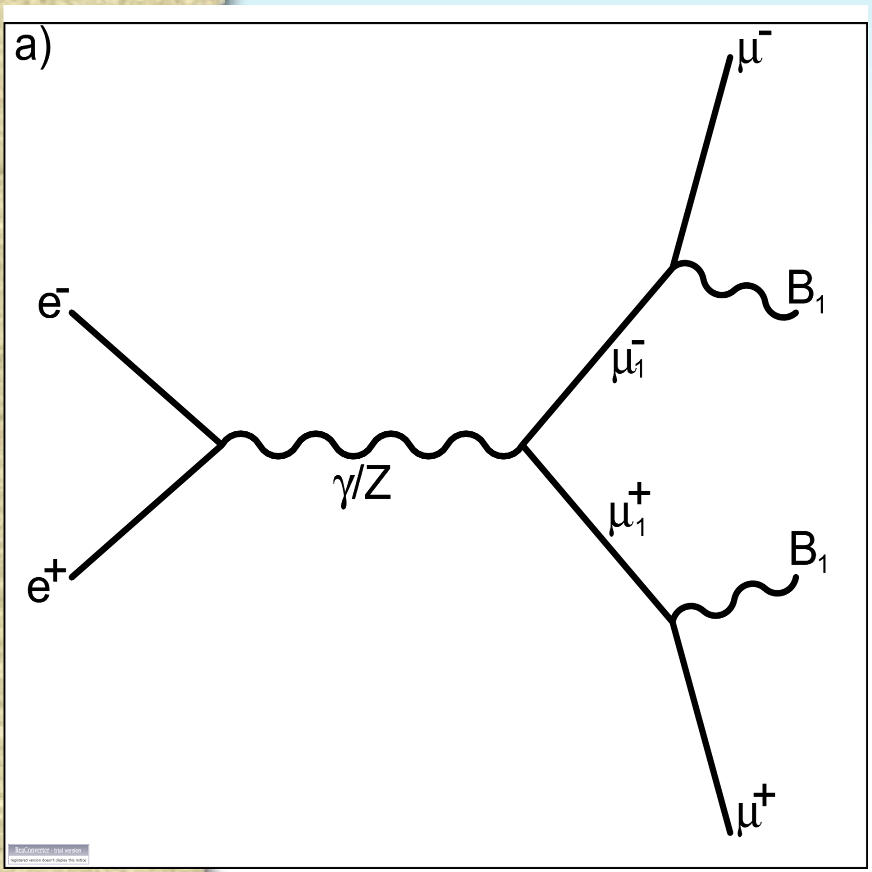
(with H. Murayama)

Presentation Outline

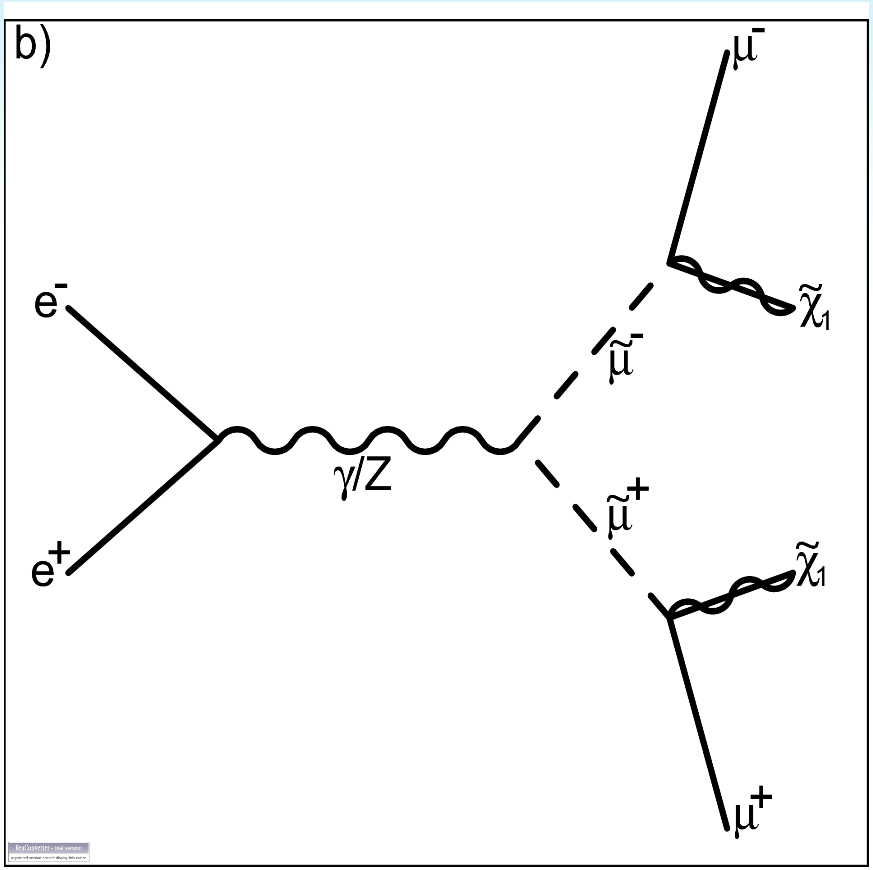
- Using Quantum Interference of Helicity Amplitudes to measure spin
- Challenge of spin measurement at the LHC
- Application of this technique to the RS graviton case at the LHC

Why measure spin?

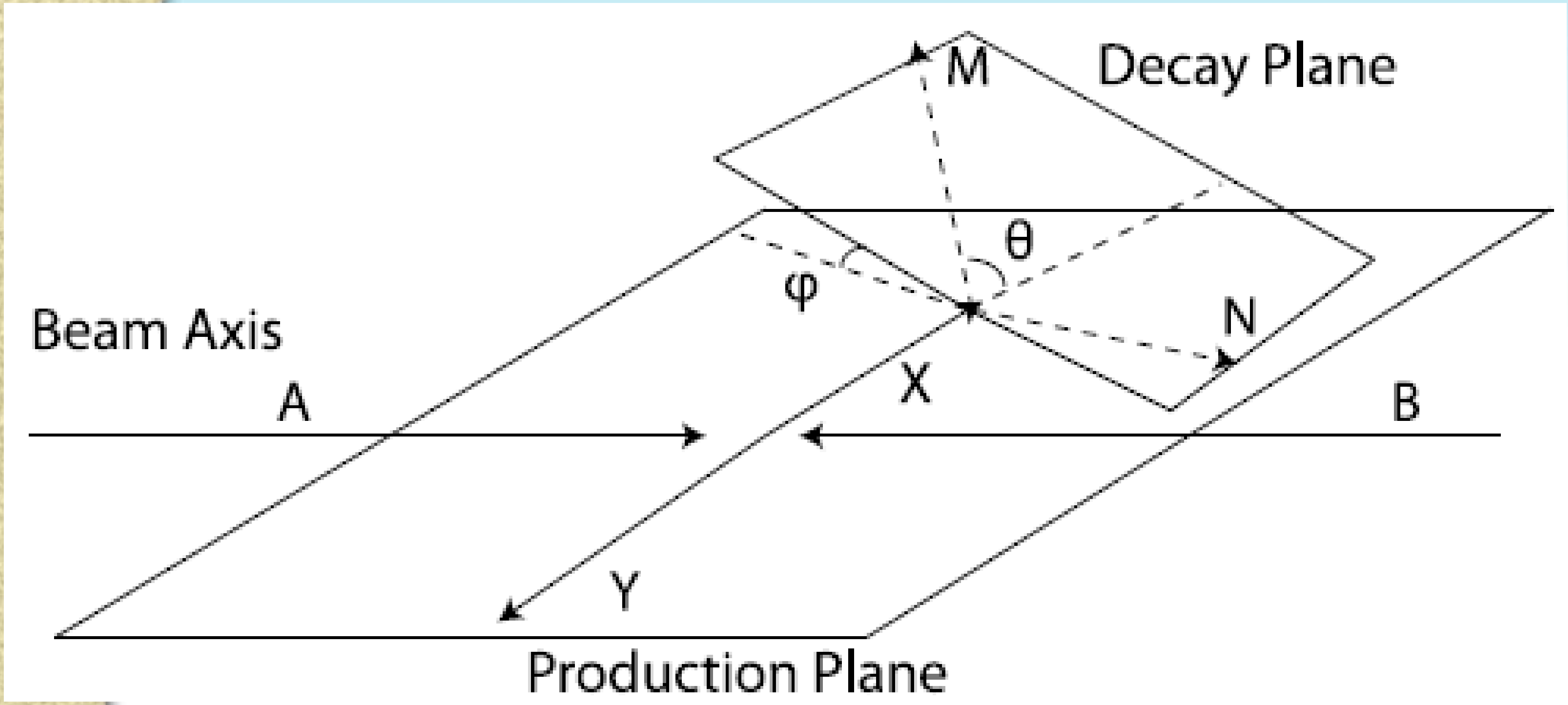
UED: Spin-1/2



Susy: Spin-0



Collider Physics Angles

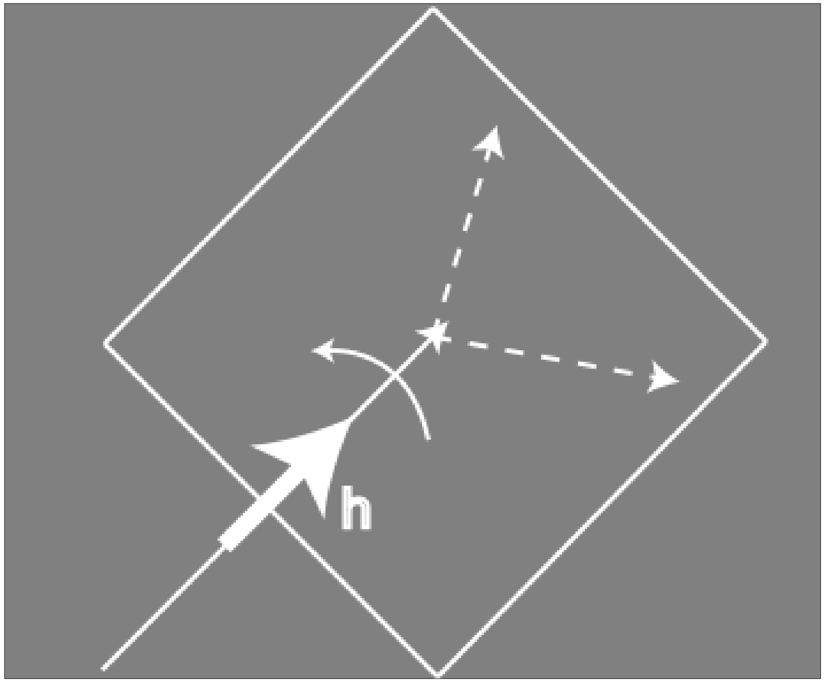


Model Independent Technique for Measuring Spins

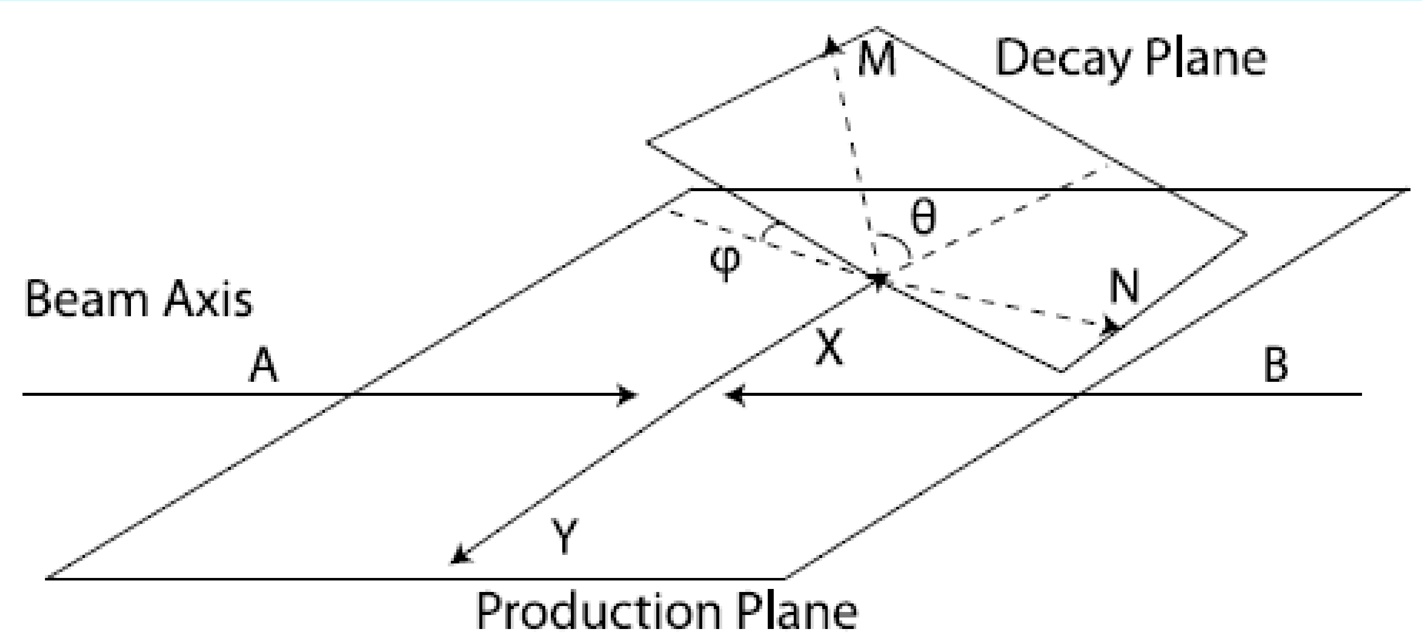
Back to Fundamentals

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

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



Model Independent Technique for Measuring Spins



- Production plane provides a reference orientation
- Rotating the decay plane about the +z axis 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. R. Buckley, H. Murayama, W. Klemm, V. Rentala (hep-ph/0711.0364)

Quantum Interference of Helicity States

Vector Boson

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

Spinor

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

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

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

- 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: $\frac{d\sigma}{d\varphi} = A_0$

Spinor: $\frac{d\sigma}{d\varphi} = A_0 + A_1 \cos(\varphi)$

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

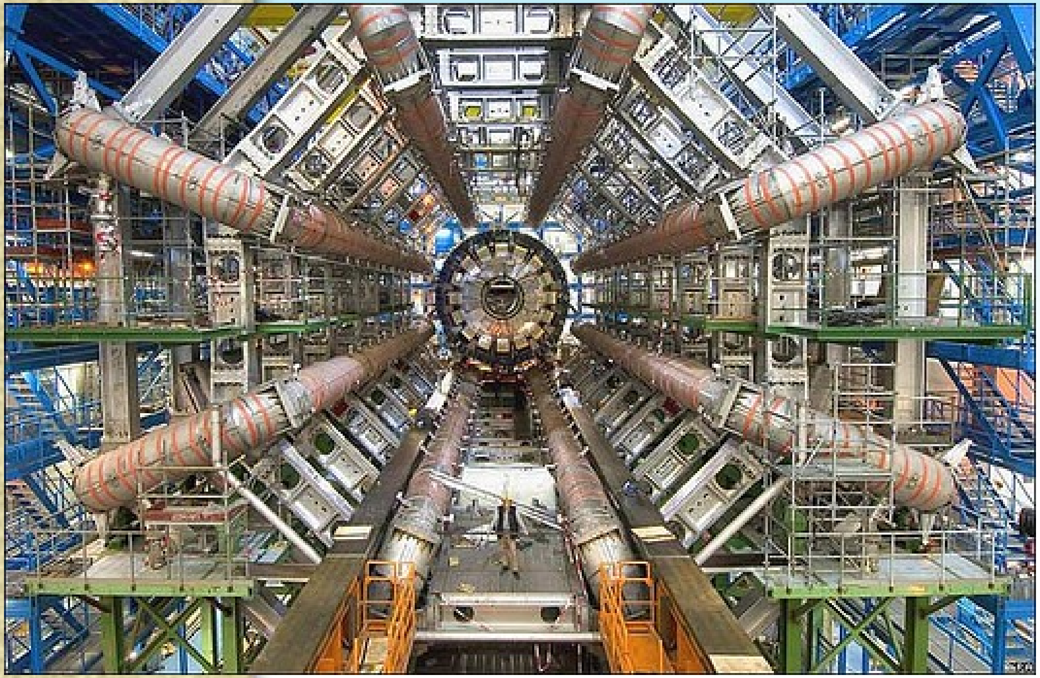
Tensor (spin-2): $\frac{d\sigma}{d\varphi} = A_0 + A_1 \cos(\varphi) + A_2 \cos(2\varphi) + A_3 \cos(3\varphi) + A_4 \cos(4\varphi)$

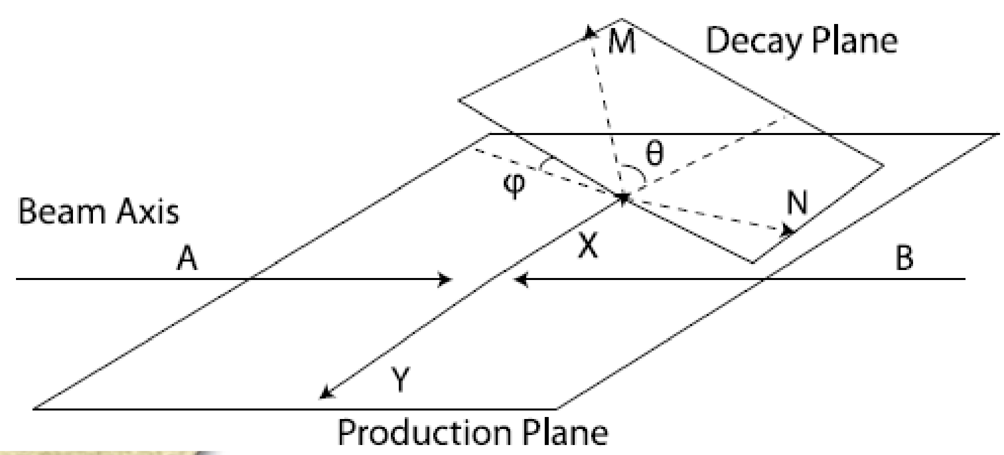
Look for the highest cosine mode to determine the spin!*

*(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

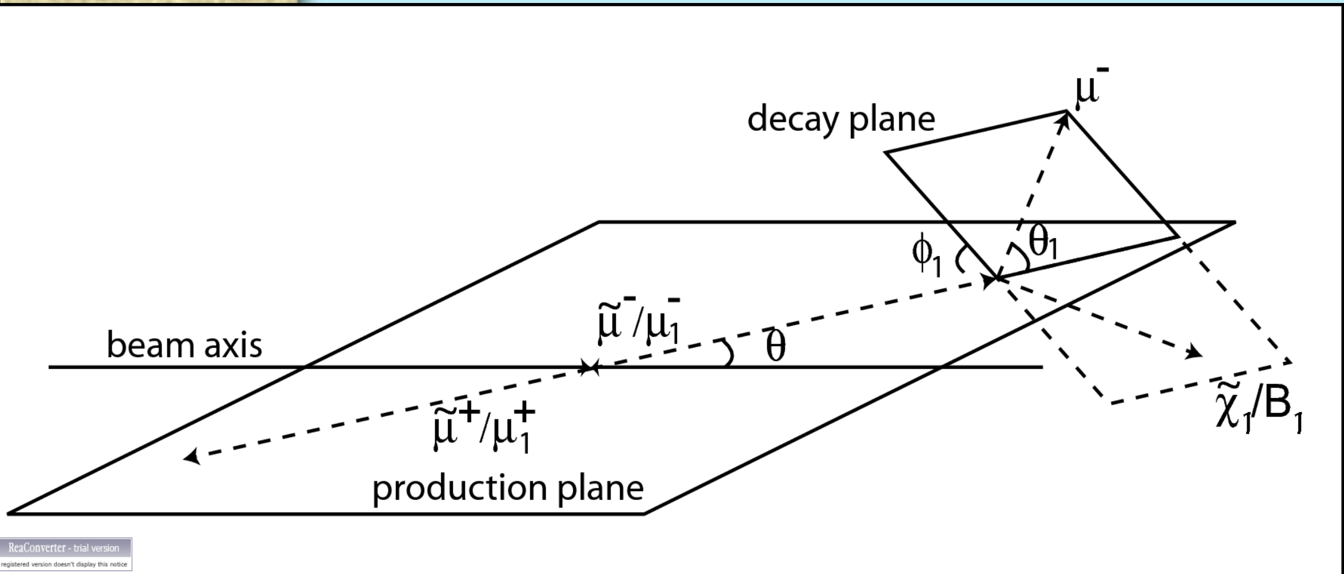




Applying this technique at the LHC

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

Many-fold ambiguity at LHC



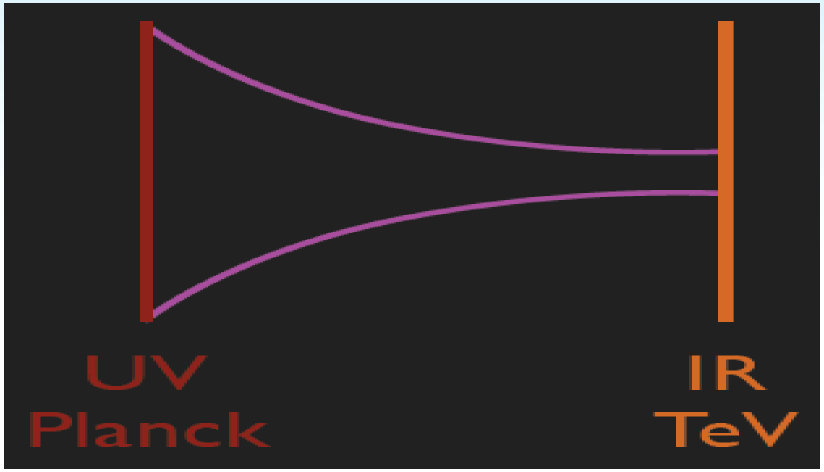
- Knowns: Outgoing lepton momenta, initial transverse momenta, masses of all particles
- Unknowns: Missing Particles 4-momentum for a total of 8 unknowns
  - CENTER OF MASS ENERGY AND MOMENTUM RELATIVE TO THE LAB FRAME

- Equations:
  - Overall energy momentum conservation: 4 equations
  - 4 mass shell constraints

8 equations and 8 unknowns + 2 MORE UNKNOWNS!

Randall-Sundrum Graviton spin?

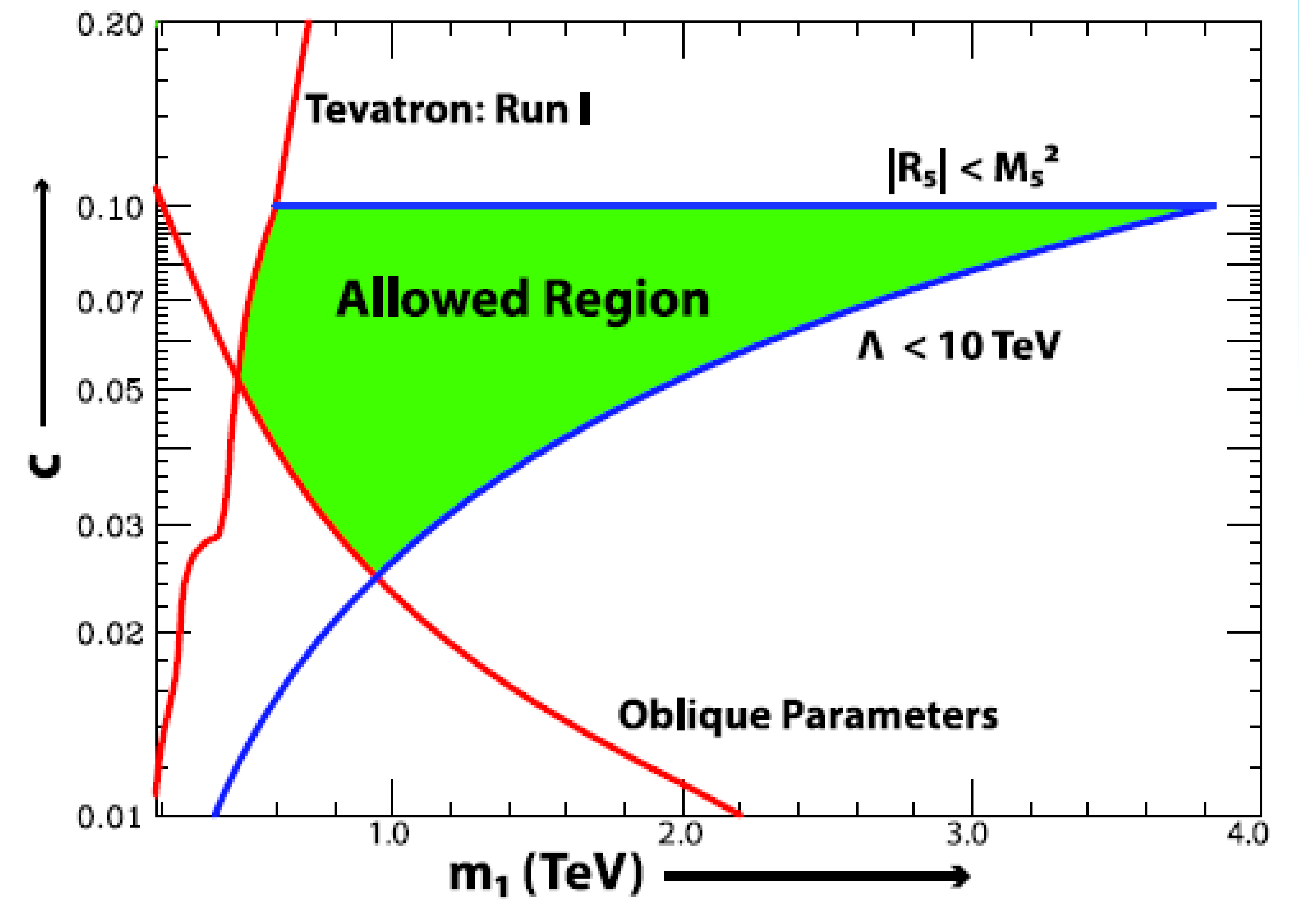
- RS case: Fully reconstructible! No missing energy. Spin measurement easier.



- Unique signature! → cos(4ø) mode

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

Parameter Space



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

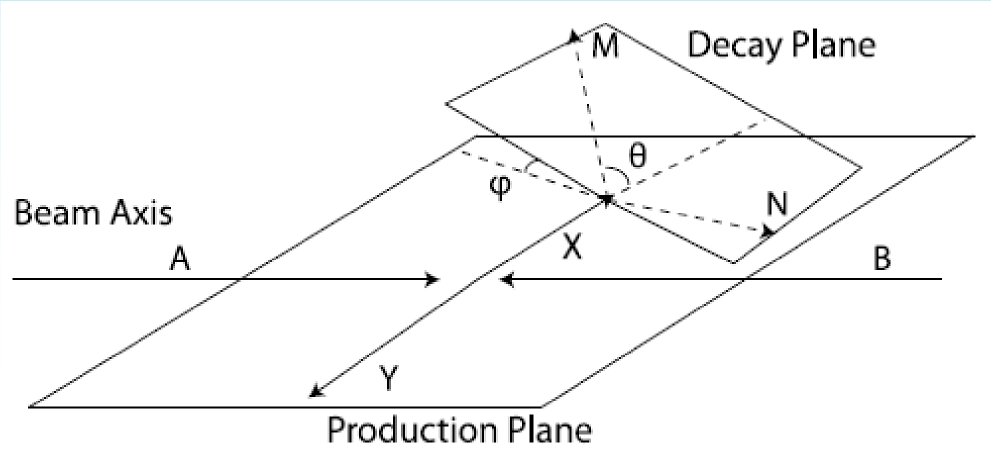
Partonic Processes

- Process

$$gg \longrightarrow Gg$$

$$q(\bar{q})\, g \rightarrow G\, q(\bar{q})$$

$$q\,\bar{q} \longrightarrow G\, g.$$



- SM background

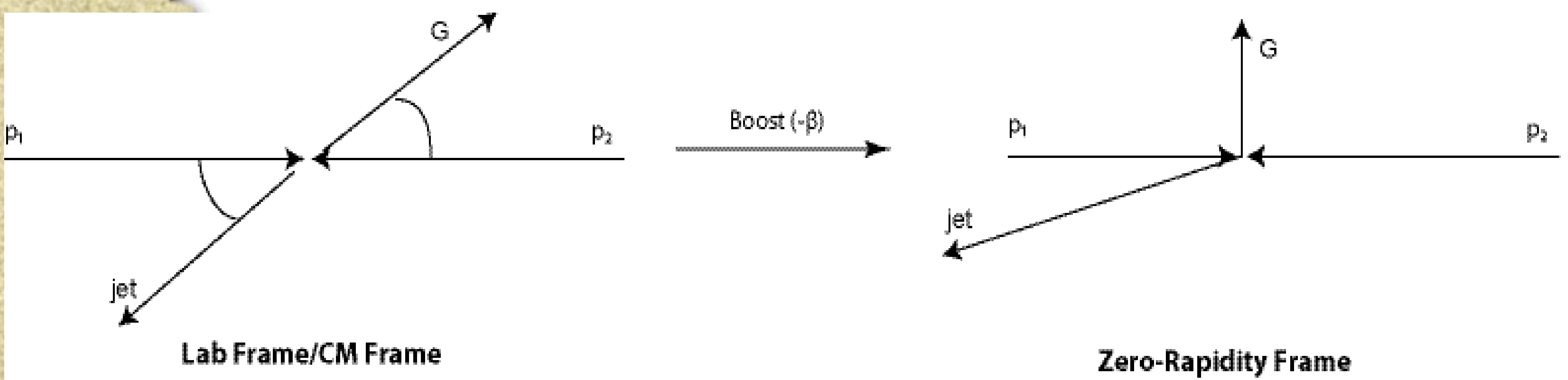
  Through an offshell Z, γ

- Finally decay to $e^+ e^-$ pair

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

Zero-Rapidity Frame

- Choose a frame which maximizes $S_4 \equiv |A_4/A_0|$
- CM frame found to have a larger value than lab frame, but error in reconstruction dependent on jet resolution
- Use ZR frame instead. Signal found to be even better!



Cuts

- Cuts on the jet: $|\eta| < 2.5$ GeV, $p_T > 20$ GeV
- Mass window cut (from ATLAS e+e- resolution)

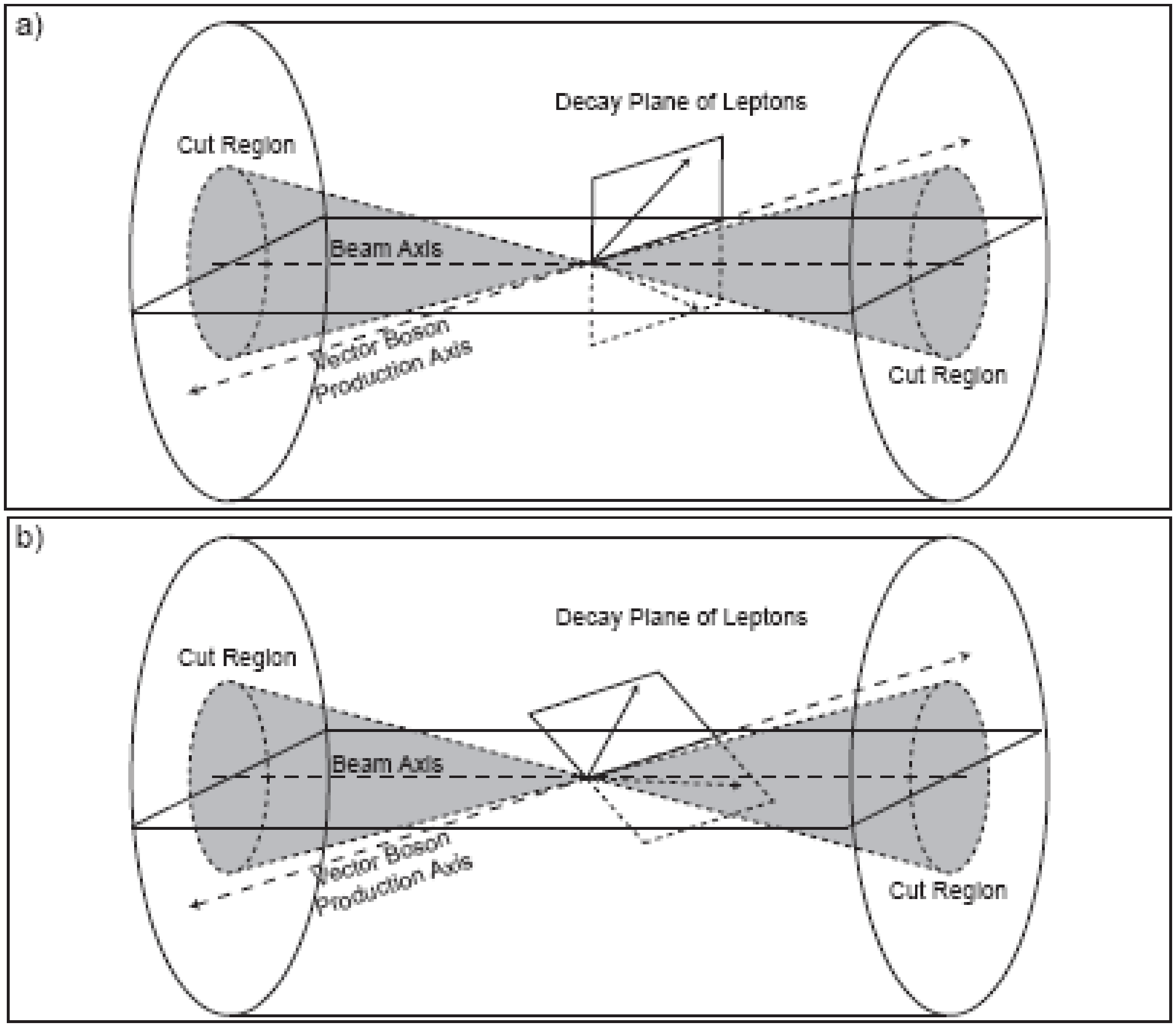
$$\Delta M = 24\,(0.625M + M^2 + 0.0056)^{1/2}\,\mathrm{GeV}.$$

- Cuts on the leptons: $p_{T1} > 10$ GeV and $p_{T2} > 20$ GeV
- Lepton isolation cut:

$$\Delta r \equiv \sqrt{(\Delta\eta)^2 + \Delta\phi^2} > 0.7$$

- These cuts are not rotationally invariant!

Cuts destroy Rotational Invariance!



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

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

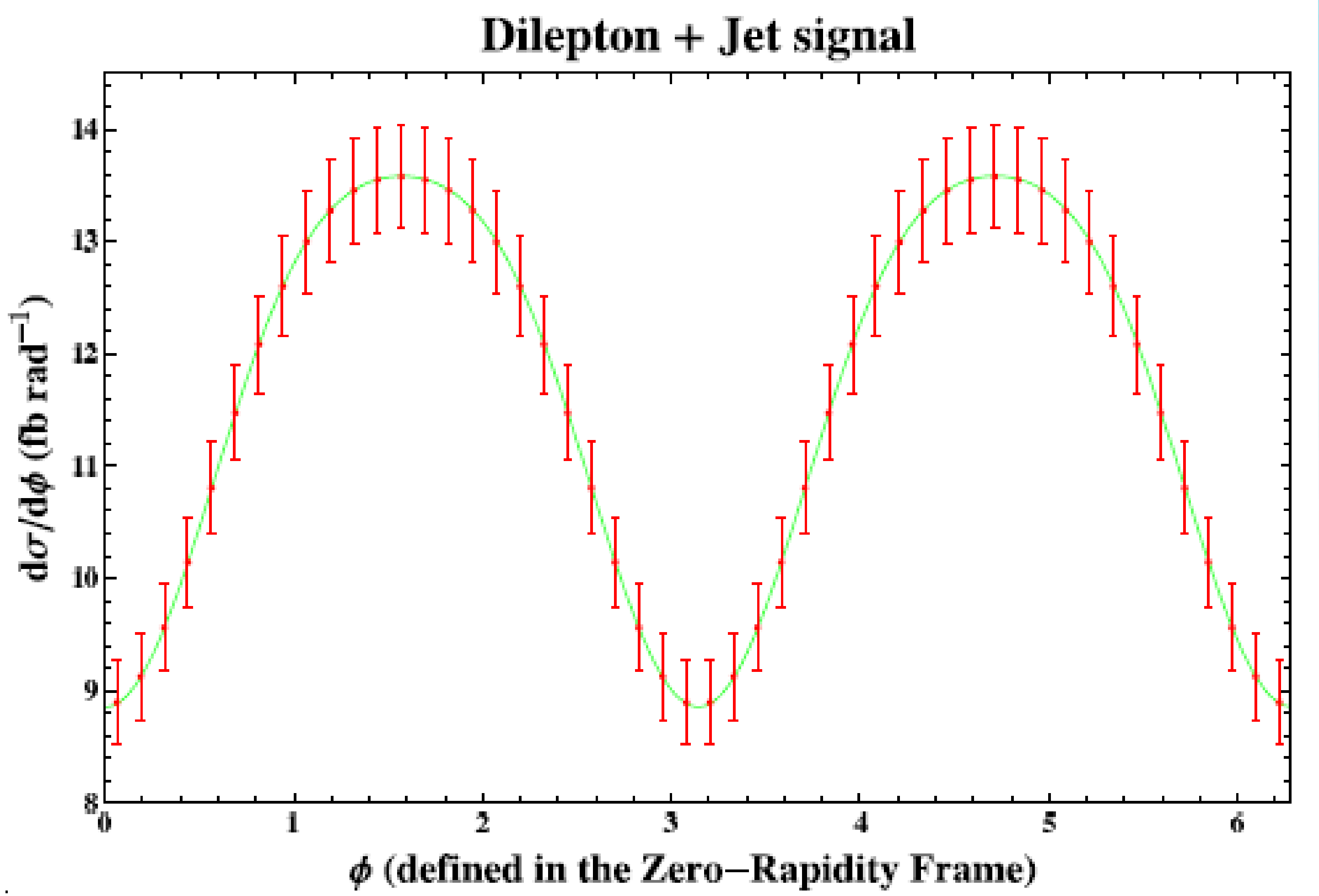
  K. Hagiwara, J. Kanzaki, Q. Li, K. Mawatari, 2008

- BASES: adaptive Monte Carlo package to integrate the differential distributions

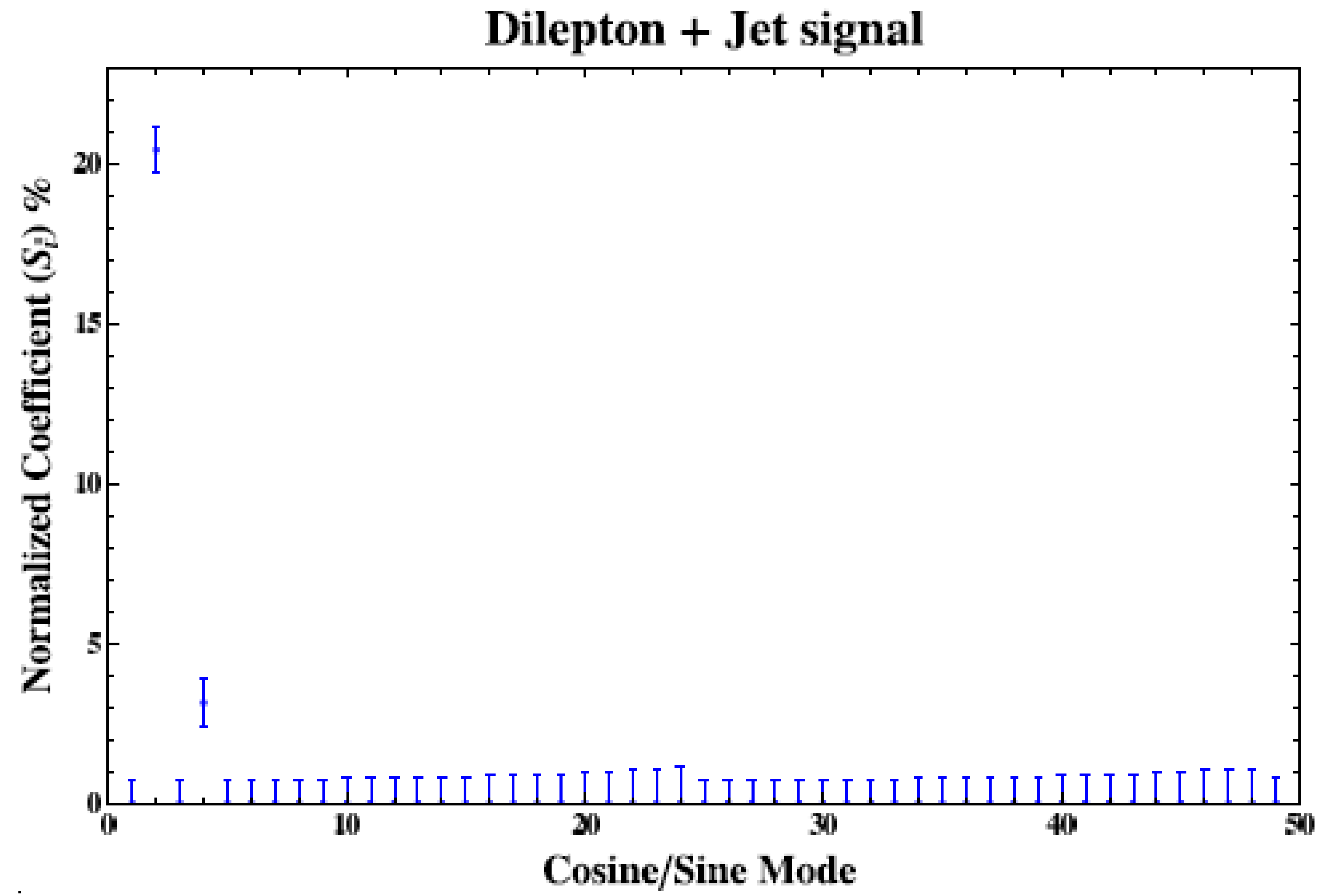
  (S. Kawabata, 1986)

- LHApdf (CTEQ6l)

Results from Simulation

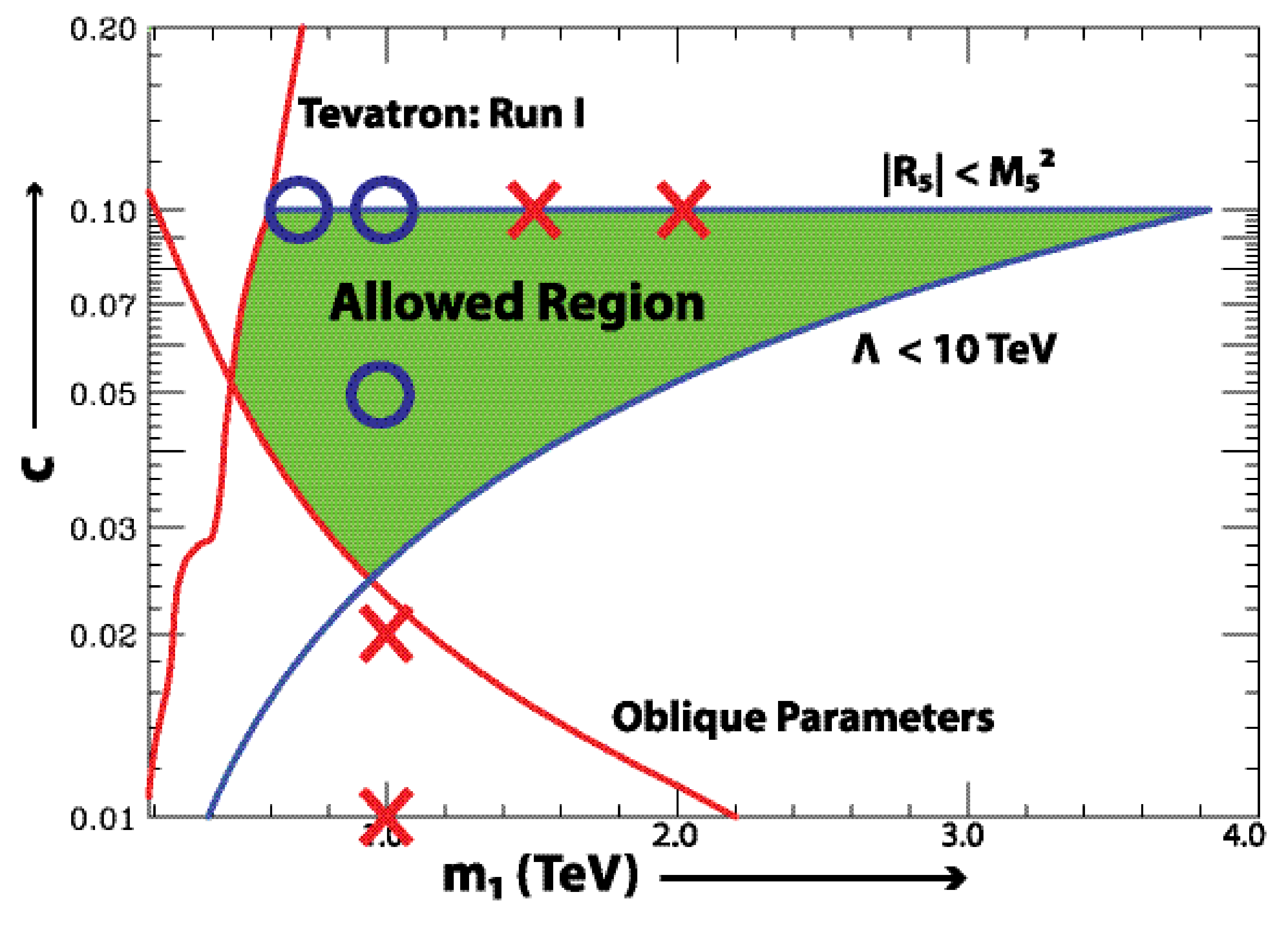


- The green curve shows the differential distribution
- 2-mode is easily visible. Is there a 4-mode?
- How do we extract information about it?



- 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%

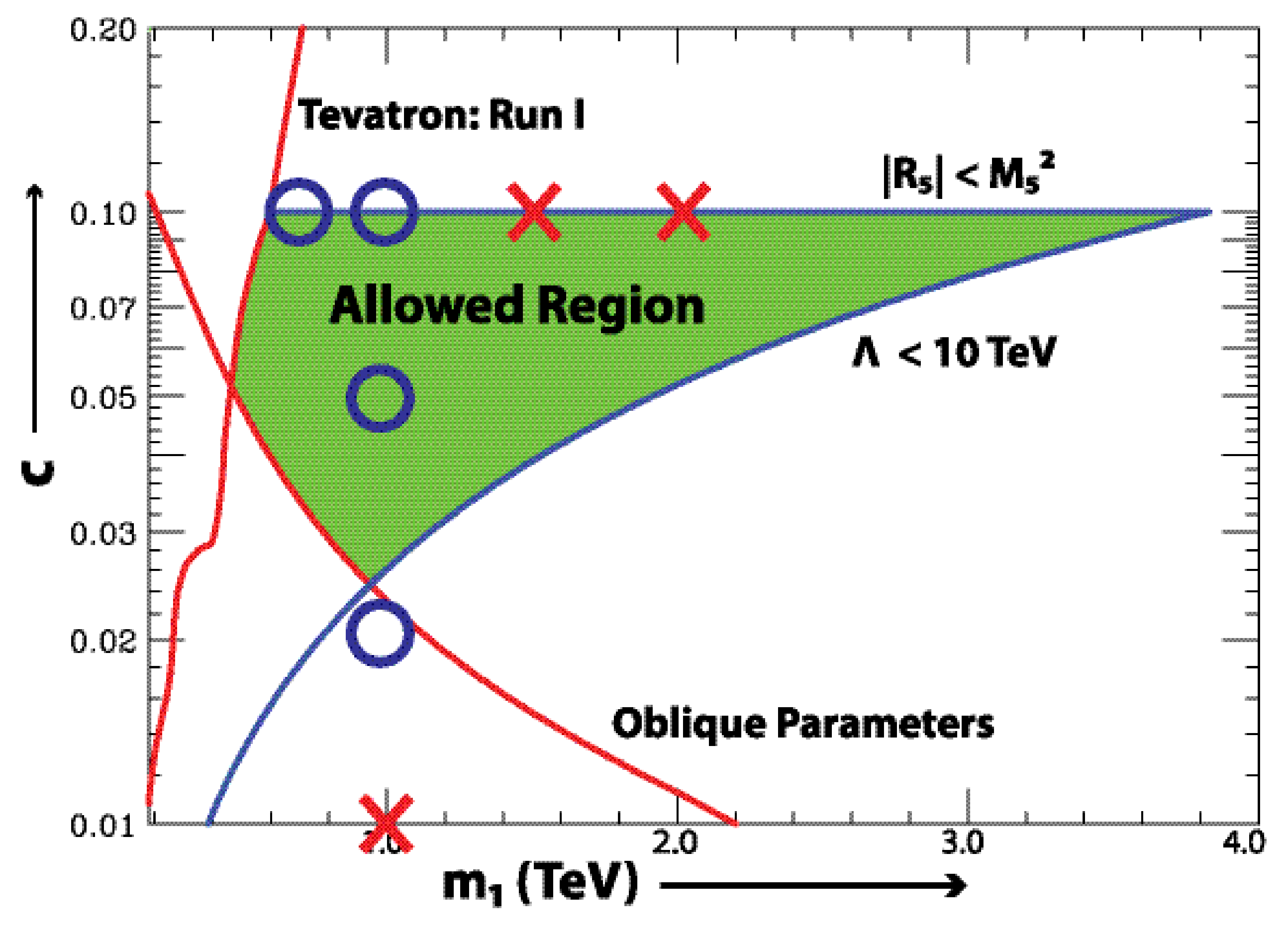
2-σ determination of Graviton spin



for 100 fb^{-1} Integrated Luminosity

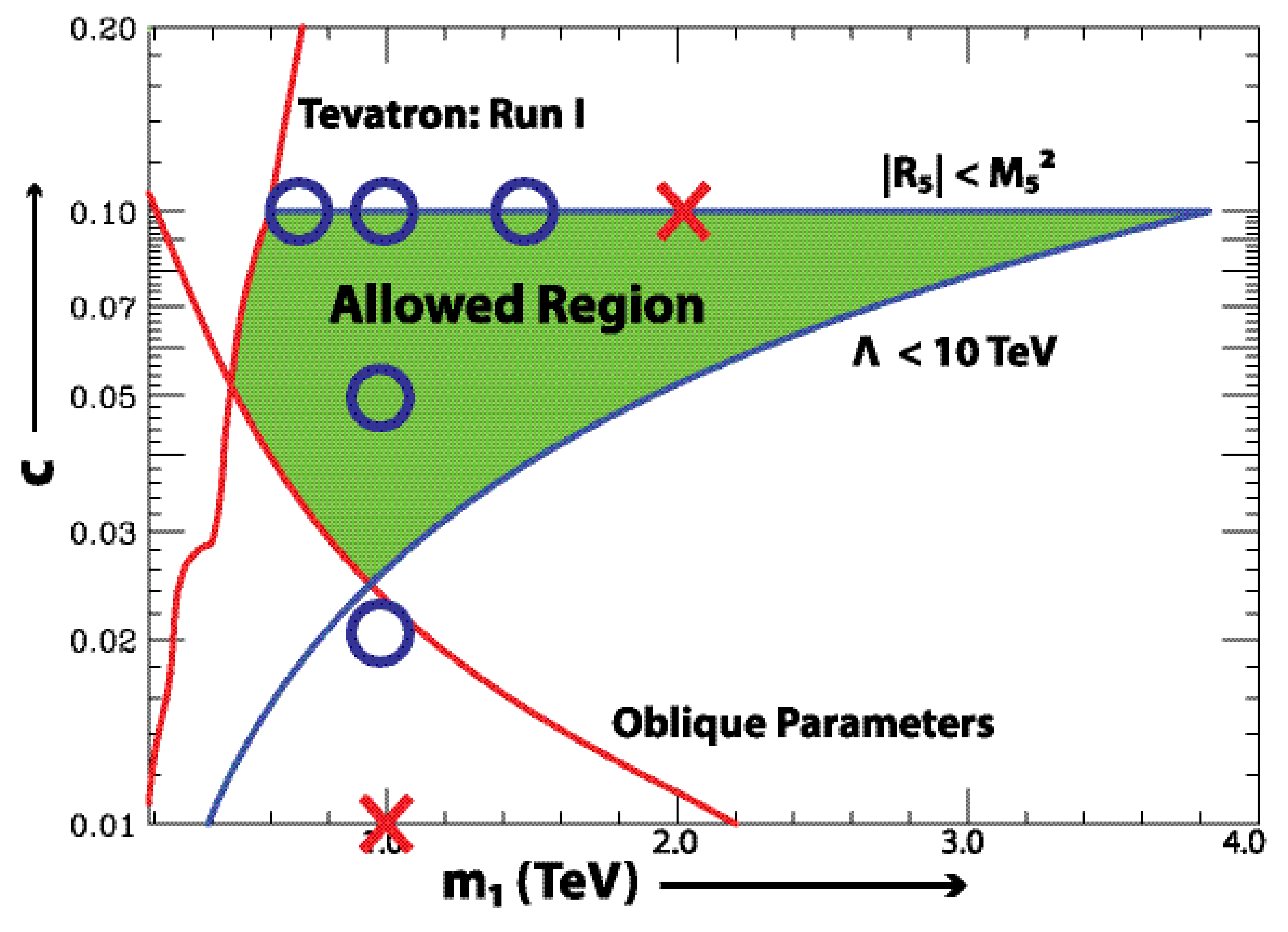
H. Murayama, V. Rentala arXiv:0904.4561 [hep-ph]

2-σ determination of Graviton spin



for 500 fb^{-1} Integrated Luminosity

2-σ distinction from scalar



for **10 fb⁻¹** Integrated Luminosity

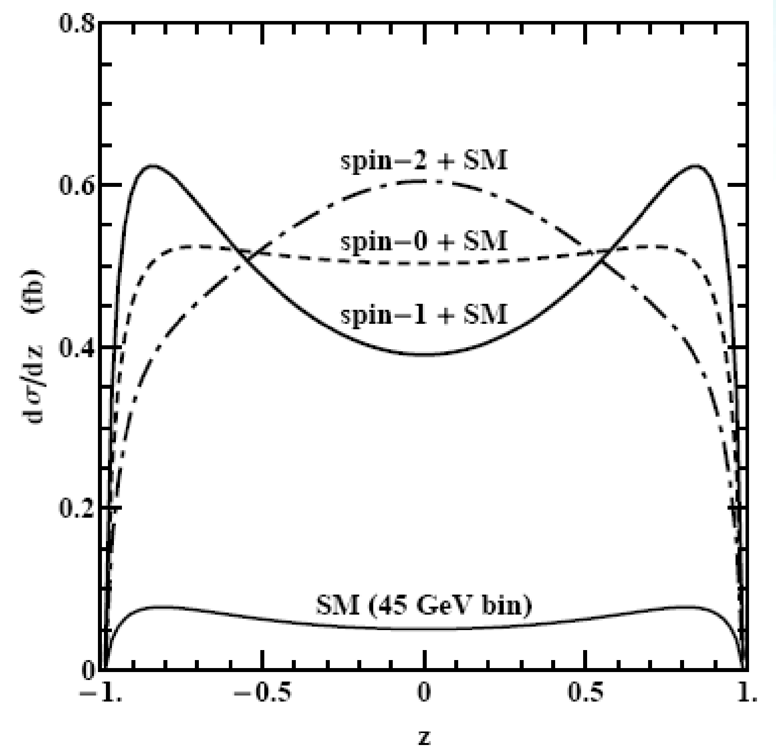
Current Technique (Center-Edge Asymmetry)

- Consider resonant graviton production followed by decay into a lepton pair

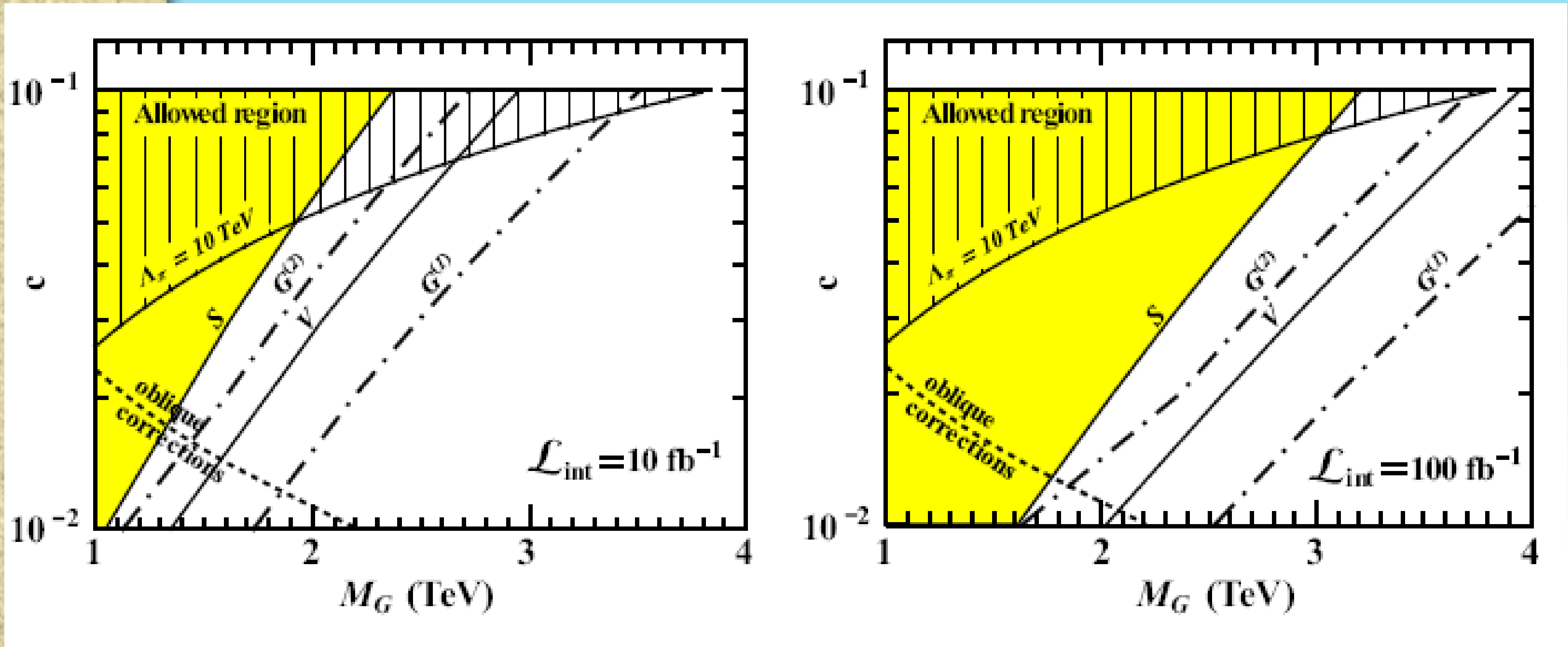
$$q\bar{q} \to G \to l^+l^-$$

$$gg \to G \to l^+l^-$$

$$\frac{d\sigma}{d\cos\theta} = A\cos^4\theta + B\cos^2\theta + C$$



arXiv:0805.2734 P. Osland, A.A. Pankov, N. Paver, A.V. Tsytrinov



	Discovery		Identification	
$\mathscr{L}_{int}$	$c = 0.01$	$c = 0.1$	$c = 0.01$	$c = 0.1$
10 fb^{-1}	1.7 TeV	3.5 TeV	1.1 TeV	2.4 TeV
100 fb^{-1}	2.5 TeV	4.6 TeV	1.6 TeV	3.2 TeV

arXiv:0805.2734 P. Osland, A.A. Pankov, N. Paver, A.V. Tsytrinov

arXiv:0805.2734 P. Osland, A.A. Pankov, N. Paver, A.V. Tsytrinov

Conclusions and Summary

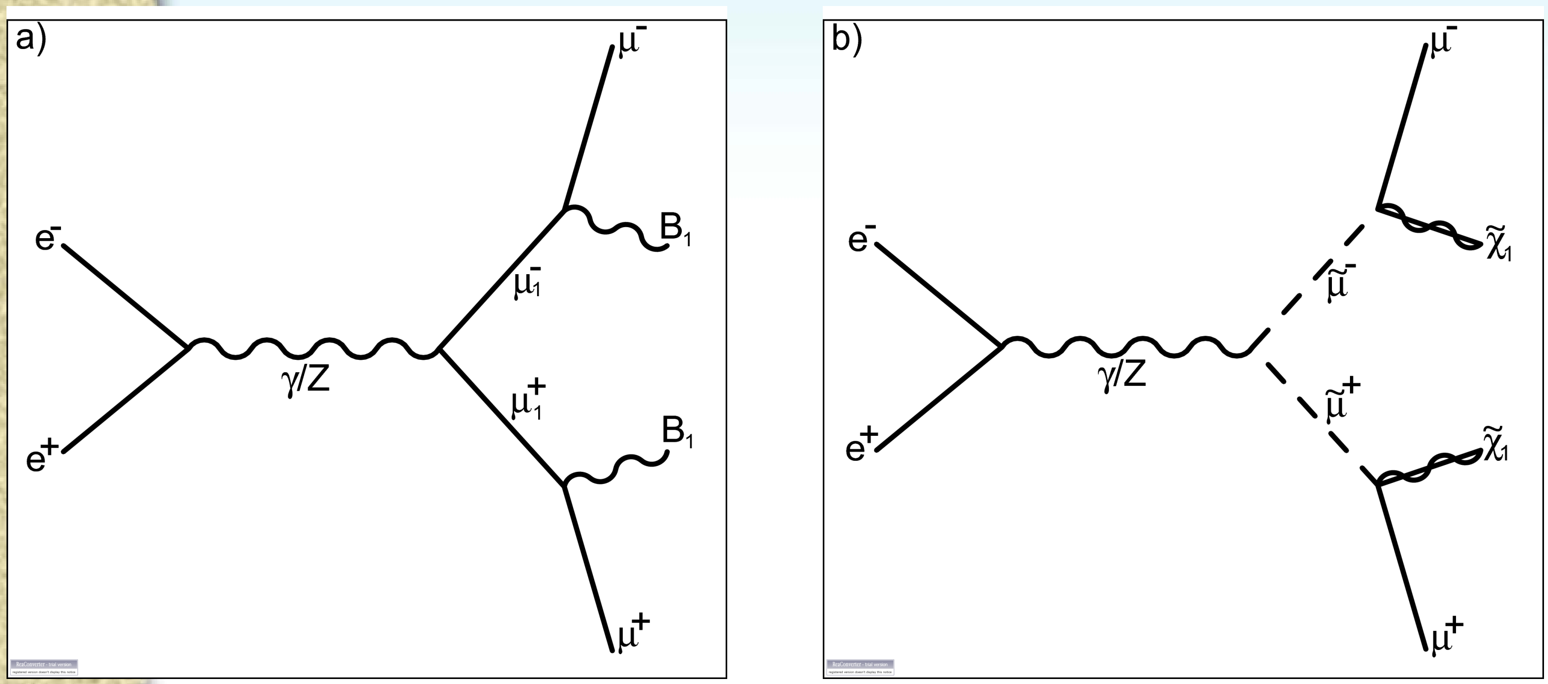
- **Spin measurement** at LHC is a challenge, but for **RS gravitons looks quite feasible**
- ~3% signal in $|A_4/A_0|$ for values of $m_1 < 1$ TeV and large values of the coupling $c \sim 0.1$.
- Can distinguish scalars from spin-2 objects easily even with low luminosities! (Look at $|A_2/A_0|$)
- Error 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


QUESTIONS, COMMENTS, SUGGESTIONS?

Spin Measurement at ILC

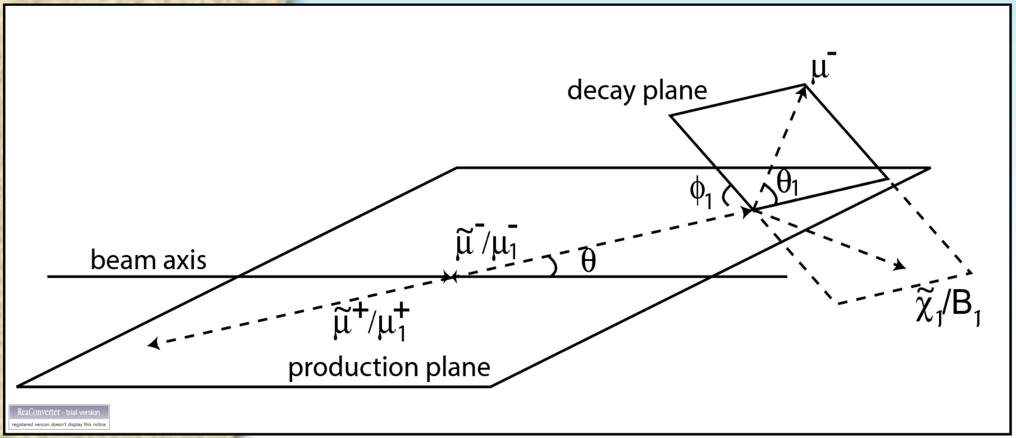
M.R. Buckley, H. Murayama , W. Klemm, V. Rentala arXiv:0711.0364 [hep-ph]

- Typical pair production processes followed by 2 body decay
- 2 body → 2 body → 4 body final state



- Characteristic signal is $\ell^+ \ell^-$ and missing energy (LKP/LSP) – fairly generic to most extensions of the SM
- Need to be able to reconstruct the momenta of the parent particle

2-fold ambiguity



- **θ is the production angle**
- **θ_i,φ_i are the decay angles in the lab frame**
- **φ_i are the same in the rest frame of the parent particle**

- Knowns: Outgoing lepton momenta, incoming energy-momentum, masses of all particles
- Unknowns: Missing Particles 4-momentum for a total of 8 unknowns
- Equations:
  - Overall energy momentum conservation: 4 equations
  - 4 mass shell constraints for the parent/missing particles = 4 equations

8 equations and 8 unknowns!

But mass-shell constraints are quadratic! Kinematic reconstruction leads to a true and a false solution.