Azimuthal angular spin determination with early LHC data

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May 7, 2009

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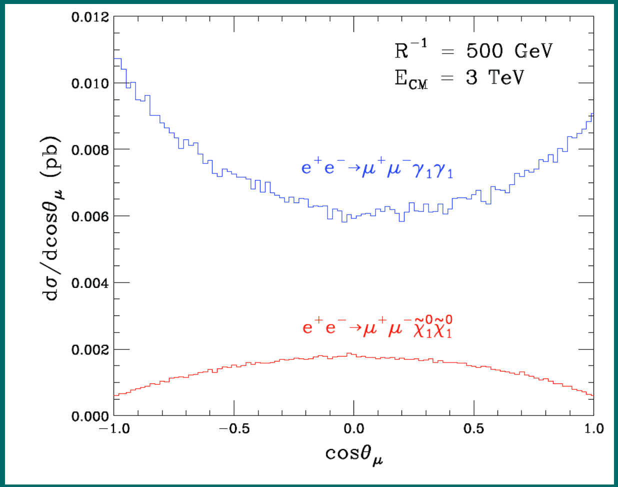
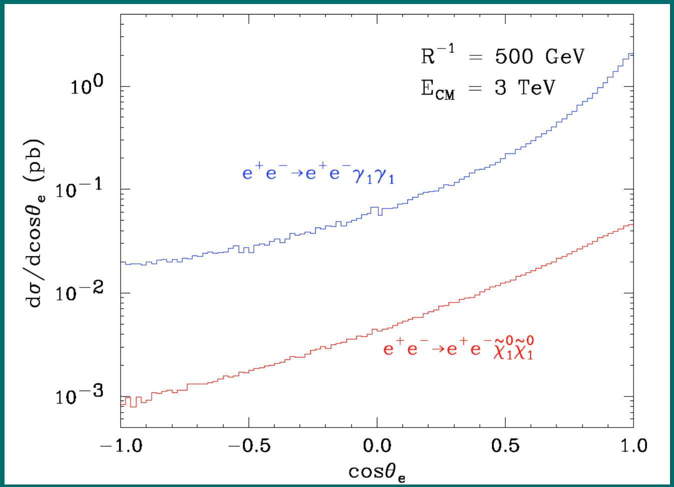
Spin Measurement Techniques

- Linear collider
  - Threshold scans: $\sigma_{scalar} \sim \beta^3, \quad \sigma_{spinor/vector} \sim \beta$
  - Production angle (s-channel pair production):

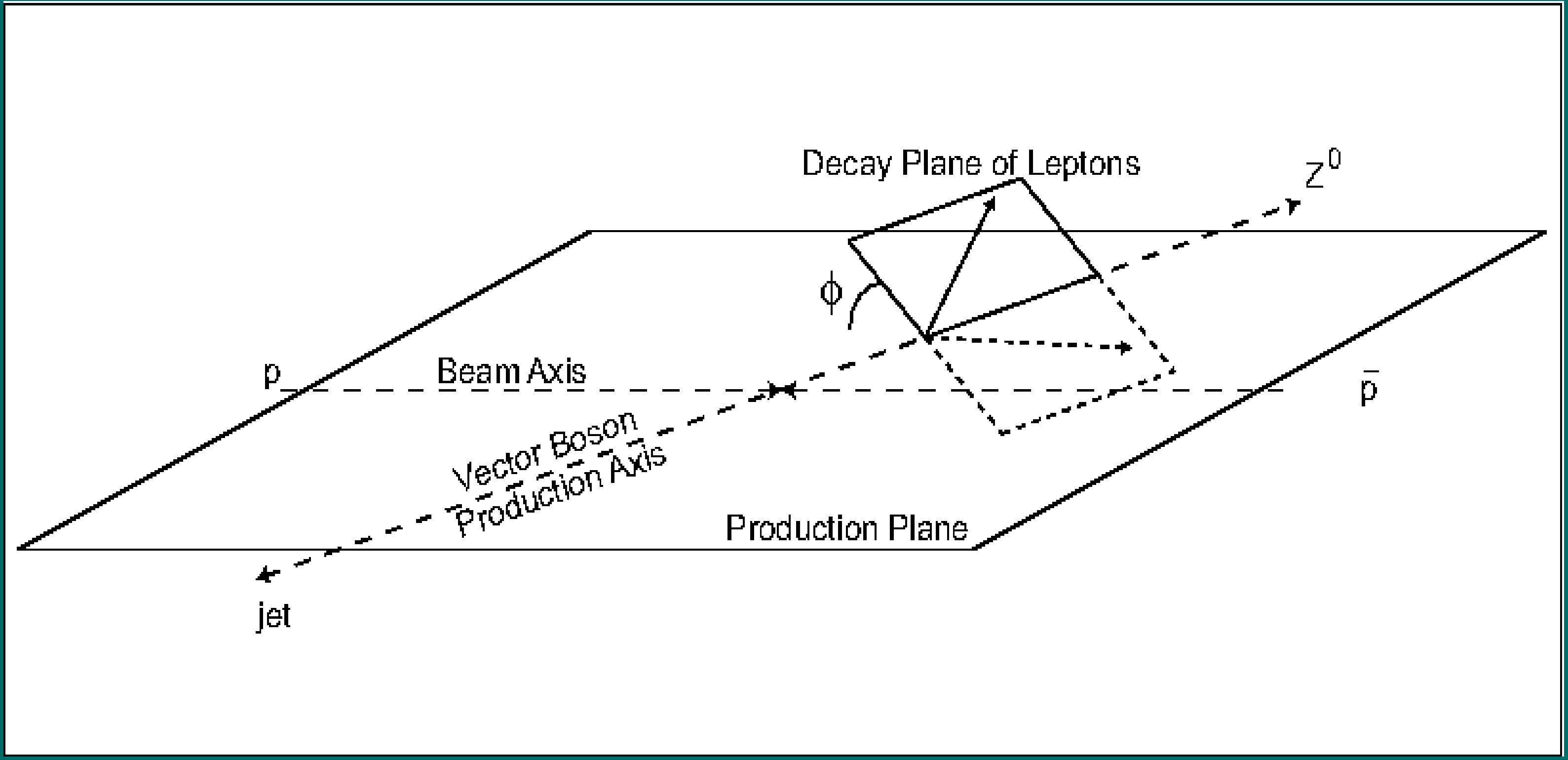
$$\sigma_{scalar} \sim \sin^2(\theta), \quad \sigma_{spinor} \sim 1 + \frac{E^2 - m^2}{E^2 + m^2} \cos^2(\theta)$$





- Linear and Hadron Collider
  - Polar decay angle – requires chiral couplings, full reconstruction

Our Technique



M. Buckley, H. Murayama, WK, V. Rentala, [0711.0364]

Our Technique

- Particle with momentum $\vec{p}$ and helicity h decays
- Rotations generated by $U(\phi) = e^{i\vec{J}\cdot\vec{\phi}} \rightarrow e^{iJ_z\phi}$
- Define *z*-axis with momentum of decaying particle

$$J_z = \frac{(\vec{s} + \vec{x} \times \vec{p}) \cdot \vec{p}}{|\vec{p}|} = \frac{\vec{s} \cdot \vec{p}}{|\vec{p}|} = h$$

- Matrix element of decay carries angle as a phase

$$M_{decay}(h, \phi) = e^{ih\phi} M_{decay}(h, \phi = 0)$$

Our Technique

- Particle produced in multiple helicities

$$\sigma \propto |\sum_{h} M_{production}(h) e^{ih\phi} M_{decay}(h, \phi=0)|^2$$

- Helicity states interfere!

$$\frac{dN}{d\phi} = \frac{d\sigma}{d\phi} \times L = A_0 + A_1 \cos(\phi) + \ldots + A_n \cos(n\phi); n = \Delta h$$

- Measuring distribution places limit on spin

$$s \geq \frac{n_{meas}}{2}$$

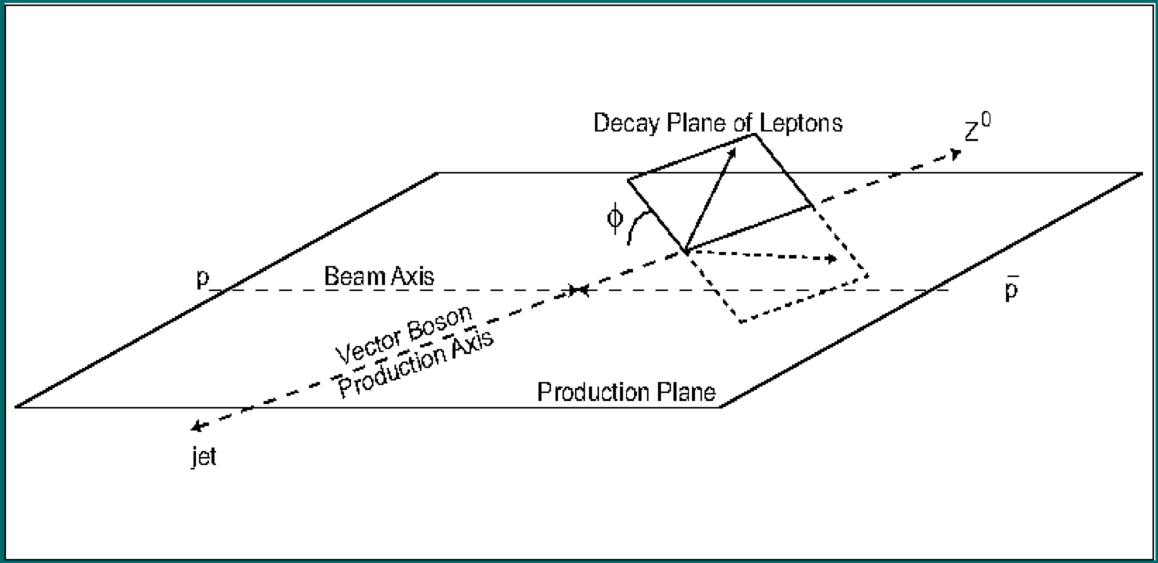
$scalar: A_0$

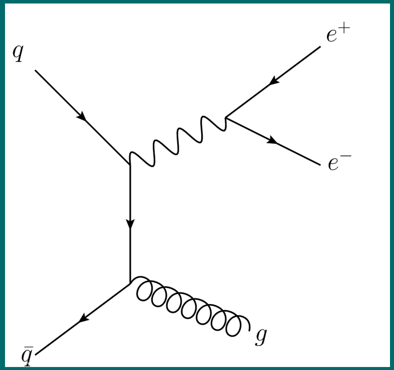
$spinor: A_0 + A_1 \cos(\phi)$

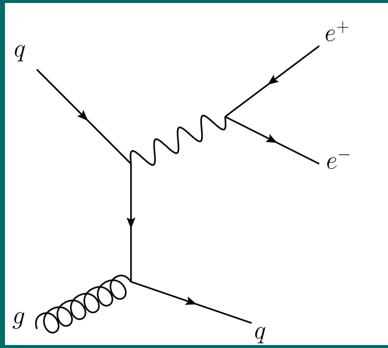
$vector: A_0 + A_1 \cos(\phi) + A_2 \cos(2\phi)$

Example: Z+jet at Tevatron

- Fully reconstructible
- Z produced in multiple helicity states





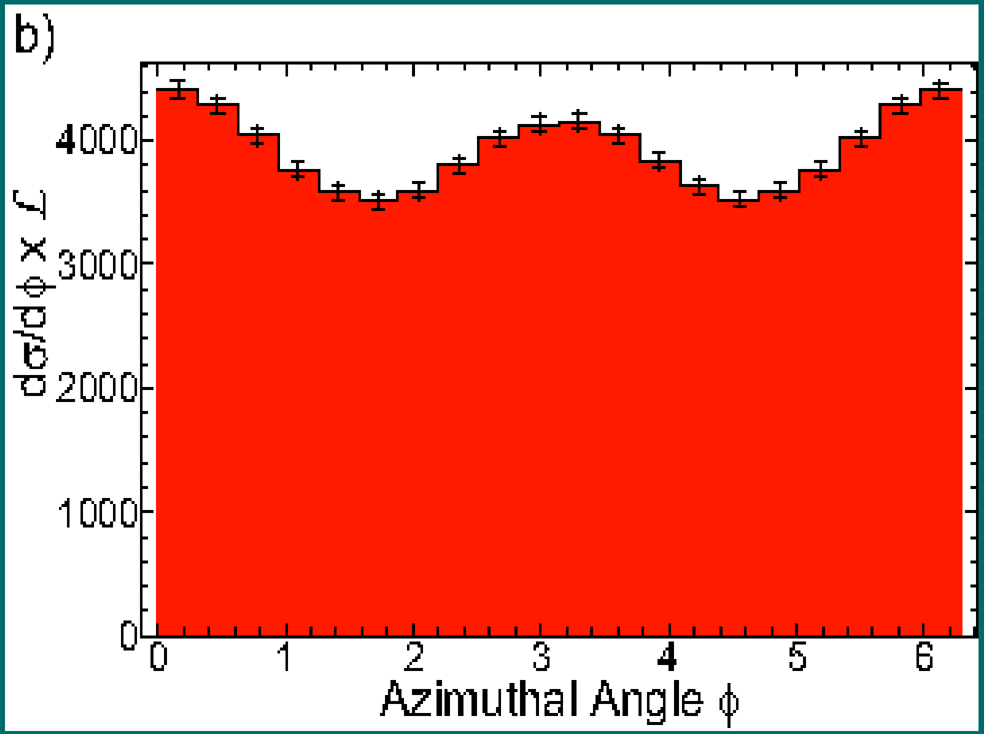


M. Buckley, B. Heinemann, WK, H. Murayama [0804.0476]

Initial results

- The *Z* is a vector boson!

$$A_1 / A_0 = 0.036$$
$$A_2 / A_0 = 0.100$$
$$A_3 / A_0 = 0.000$$
$$A_4 / A_0 = 0.000$$



Cuts on jet: $p_T > 30\,GeV$, $|\eta| < 2.1$

Detector Cuts

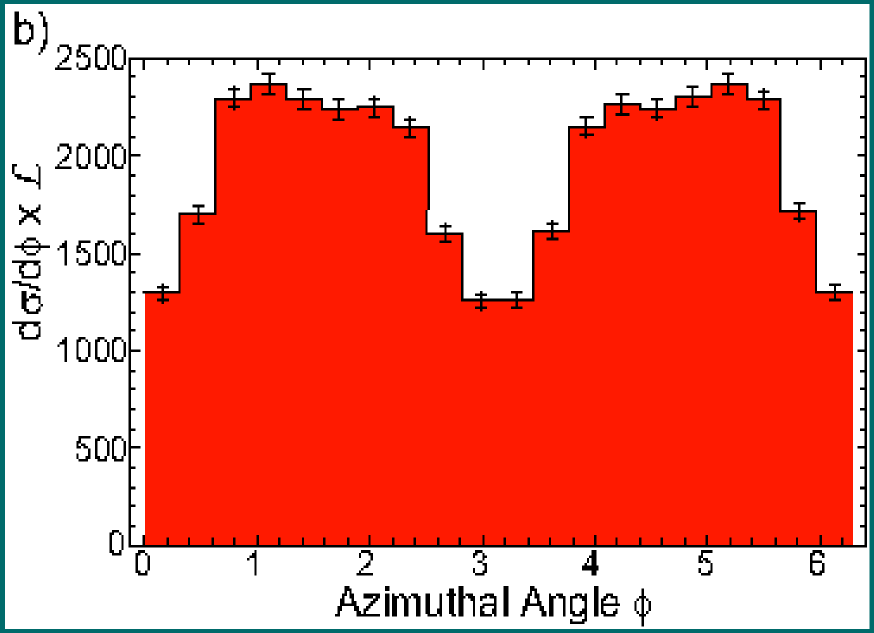
- Selection cuts necessary to improve sample, deal with detector limitations.
- CDF: 6203 events from 1.7 fb^{-1} luminosity at 1.96 TeV beam energy (after cuts)

Jet transverse momentum	$p_{T,j} > 30$ GeV
Jet η	$\lvert\eta\rvert < 2.1$
Invariant mass of lepton pair	$66 < m_{\ell\ell} < 116$ GeV
Central electron η	$\lvert\eta\rvert < 1$
Second electron η	$\lvert\eta\rvert < 1$ or $1.2 < \lvert\eta\rvert < 2.8$
Electron E_T	$E_T > 25$ GeV
Electron isolation cuts	$\Delta R_{ej} > 0.7$

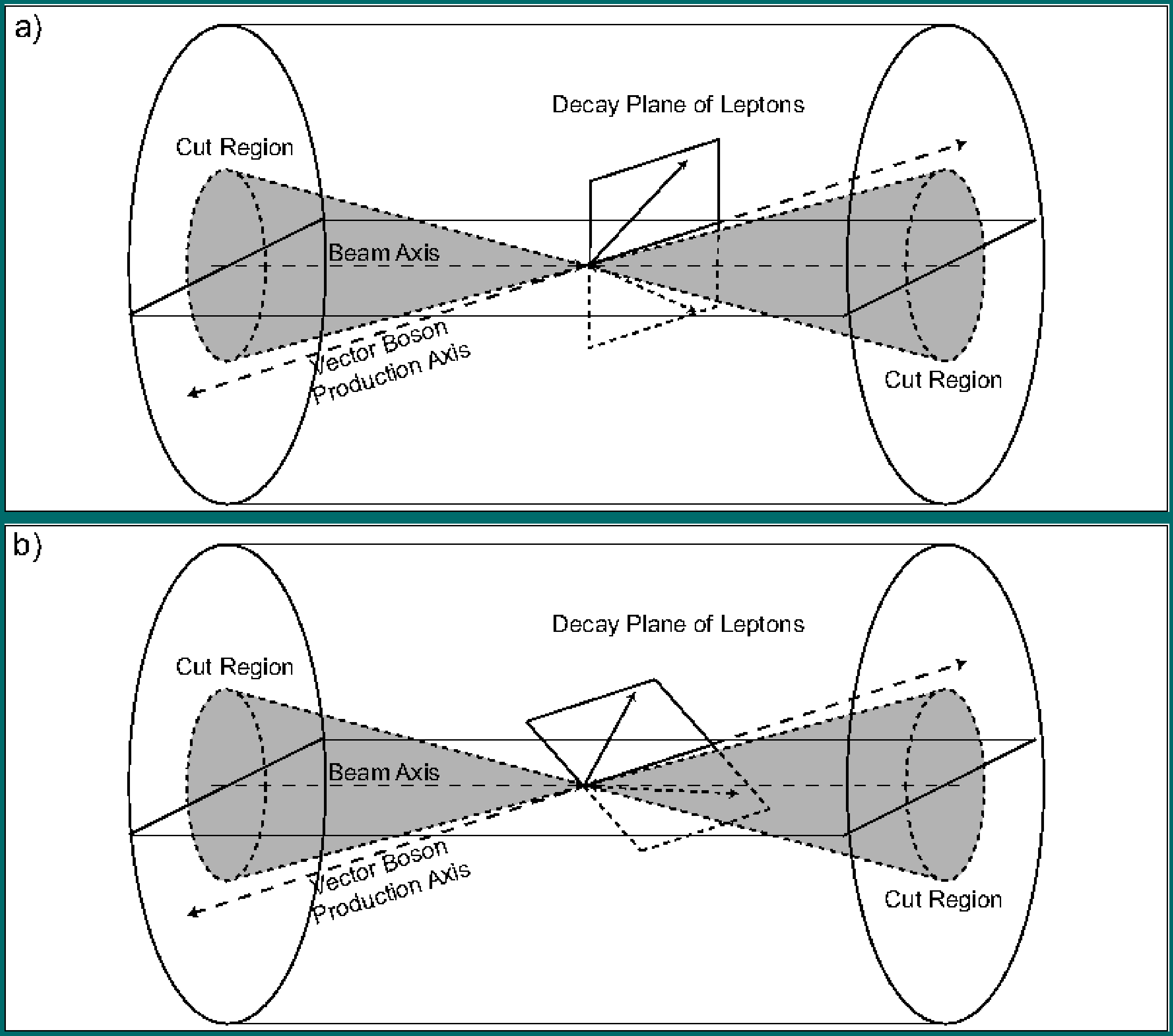
Detector Cuts

- Spurious higher order modes from the cuts

$$A_1/A_0 = 0.029$$
$$A_2/A_0 = -0.277$$
$$A_3/A_0 = -0.021$$
$$A_4/A_0 = -0.123$$



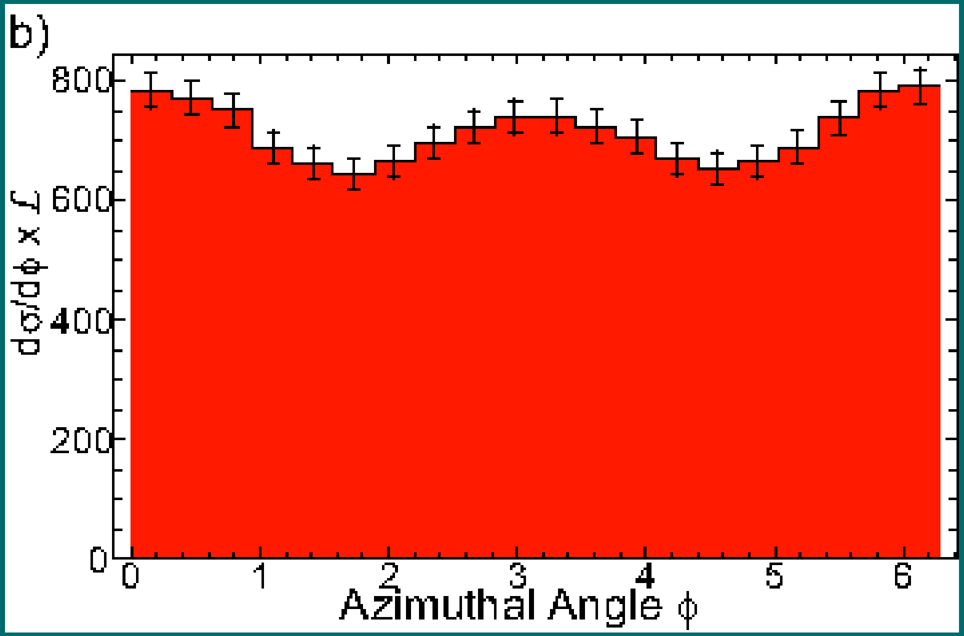
Rotationally Invariant cuts



Revised results

- New cuts restore expected behavior
- Inefficient -> loosened cuts

$$A_1/A_0 = 0.039 \pm 0.022$$
$$A_2/A_0 = 0.083 \pm 0.021$$
$$A_3/A_0 = 0.000 \pm 0.022$$
$$A_4/A_0 = 0.000 \pm 0.023$$



- More data collection – smaller error bars

Z+jet at the LHC

- What physics can be done with the early LHC data?

$$(E_{beam}=5\,TeV\,,\sim 100\,pb^{-1}\,integrated\ luminosity)$$

- Even at low luminosity, very high production rate
- Challenge: ISR
- Cuts:

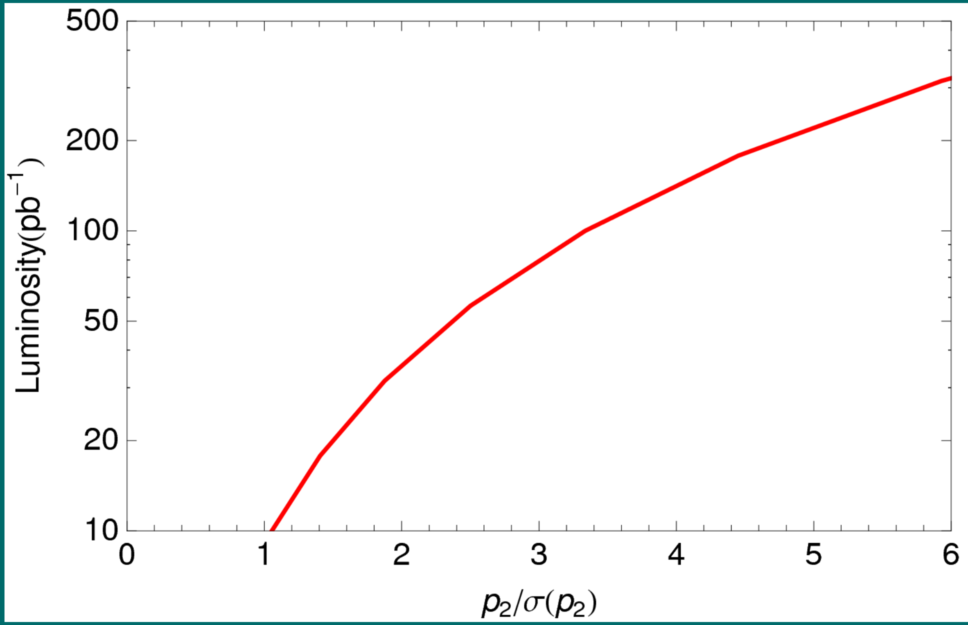
$$jet: p_T > 40\,GeV\,,\ |\eta| < 3.2$$
$$lepton: one\ p_T > 10\,GeV\,,\ one\ p_T > 20\,GeV$$
$$lepton: |\eta| < 2.5$$
$$jet-lepton: \Delta R > 0.7$$
$$lepton\ pair: 66 < m_{ll} < 116\,GeV$$

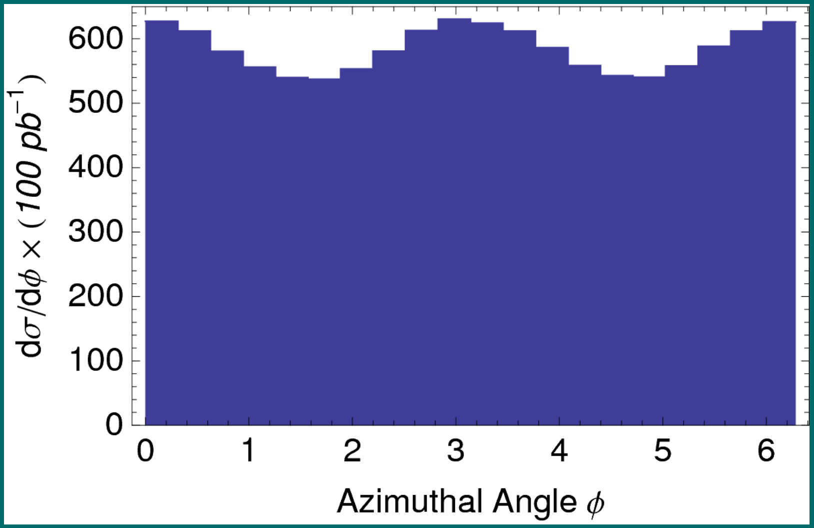
with H. Murayama

Z+jet at the LHC: Results

- Better than 3 sigma for $100\ pb^{-1}$

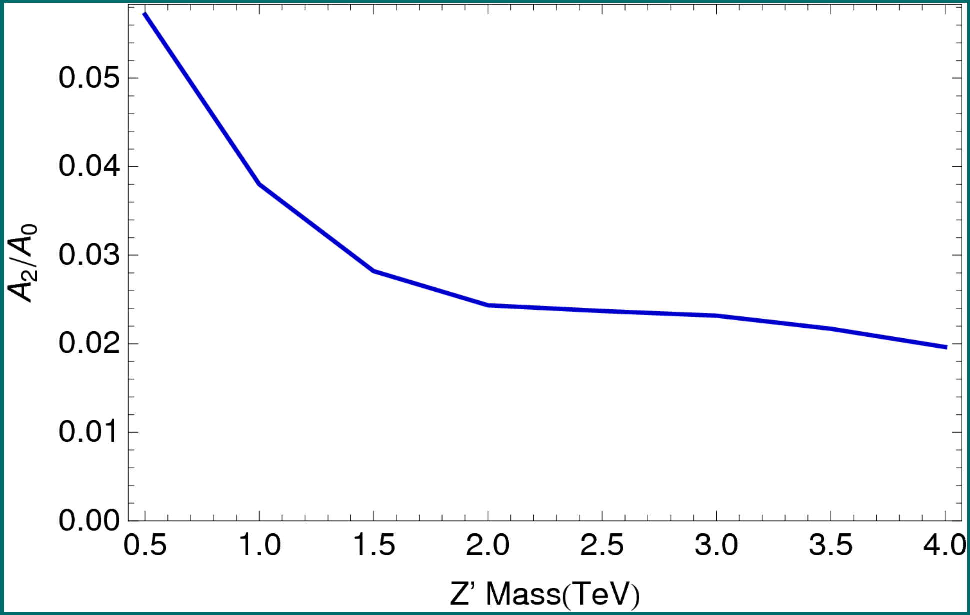
$$A_1/A_0 = 0.000 \pm 0.024$$
$$A_2/A_0 = 0.079 \pm 0.024$$
$$A_3/A_0 = 0.000 \pm 0.024$$
$$A_4/A_0 = 0.000 \pm 0.025$$

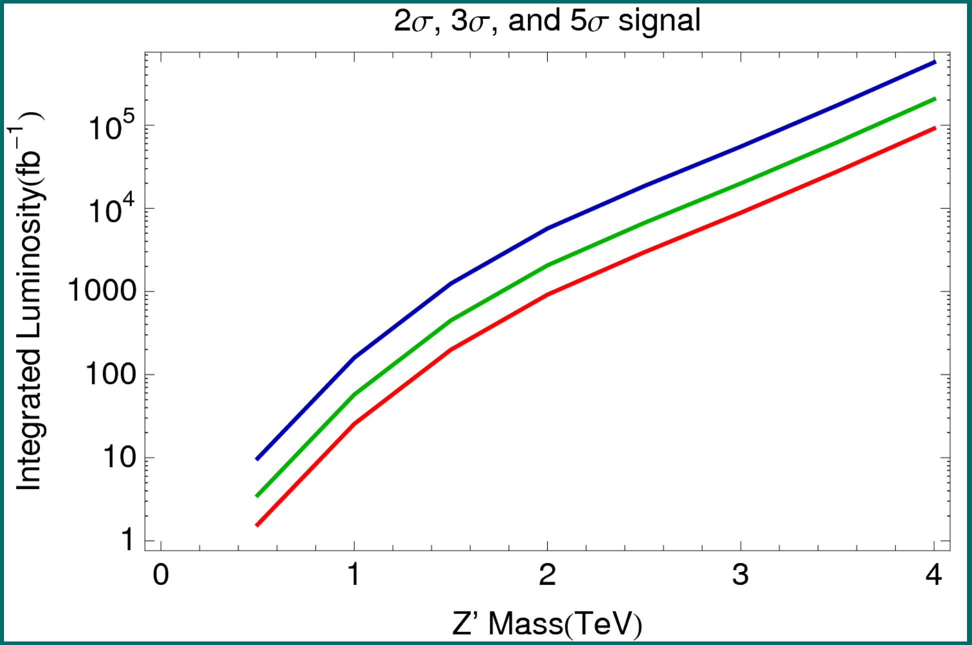




Z' + jet

- Model: Z' with SM couplings
- Simulation at 14 TeV





with H. Murayama

RS Graviton

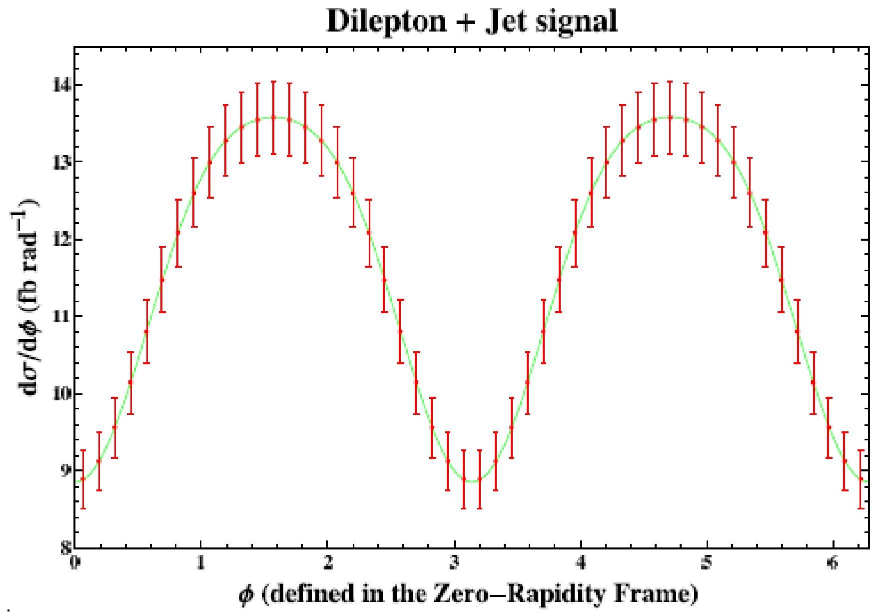


FIG. 5: Differential distribution ($\frac{d\sigma}{d\phi}$) for m_1 = 1 TeV and c = 0.05. A strong cos (2ϕ) mode can be seen but there is also a cos (4ϕ) component. The theoretical curve (produced from simulations) is shown in green. The red dots indicate the binned values, with error bars corresponding to Gaussian errors for a luminosity of 500 fb^{-1}

m_1 (TeV)	c	10 fb^{-1}	100 fb^{-1}	500 fb^{-1}
0.75	0.1	0.43	0.14	0.06
1.0	0.01	8.03	2.54	1.14
1.0	0.02	3.97	1.26	0.56
1.0	0.05	1.65	0.52	0.23
1.0	0.1	0.93	0.29	0.13
1.5	0.1	5.42	1.71	0.77
2.0	0.1	23.52	7.44	3.32

TABLE III: Statistical Error $\Delta S_4/S_4$ for different integrated luminosities for the process $pp \to e^+e^-j$. $\Delta S_4/S_4 < 0.5(0.71)$ corresponds to a 2σ confirmation of the graviton spin, and $\Delta S_4/S_4 < 0.2(0.28)$ corresponds to a 5σ confirmation. The values in brackets denote the 2σ and 5σ confidence levels if one includes $\mu^+\mu^-j$ production channels as well.

H. Murayama and V. Rentala [0904.4561]

Conclusions

- Model-independent spin measurement
- Selection cuts must be made 'rotationally invariant' to preserve form of distribution
- Technique can be tested using existing data and early LHC data
- Useful exercise for eventual Z' and graviton spin determination

END