Azimuthal angular spin determination: towards the LHC

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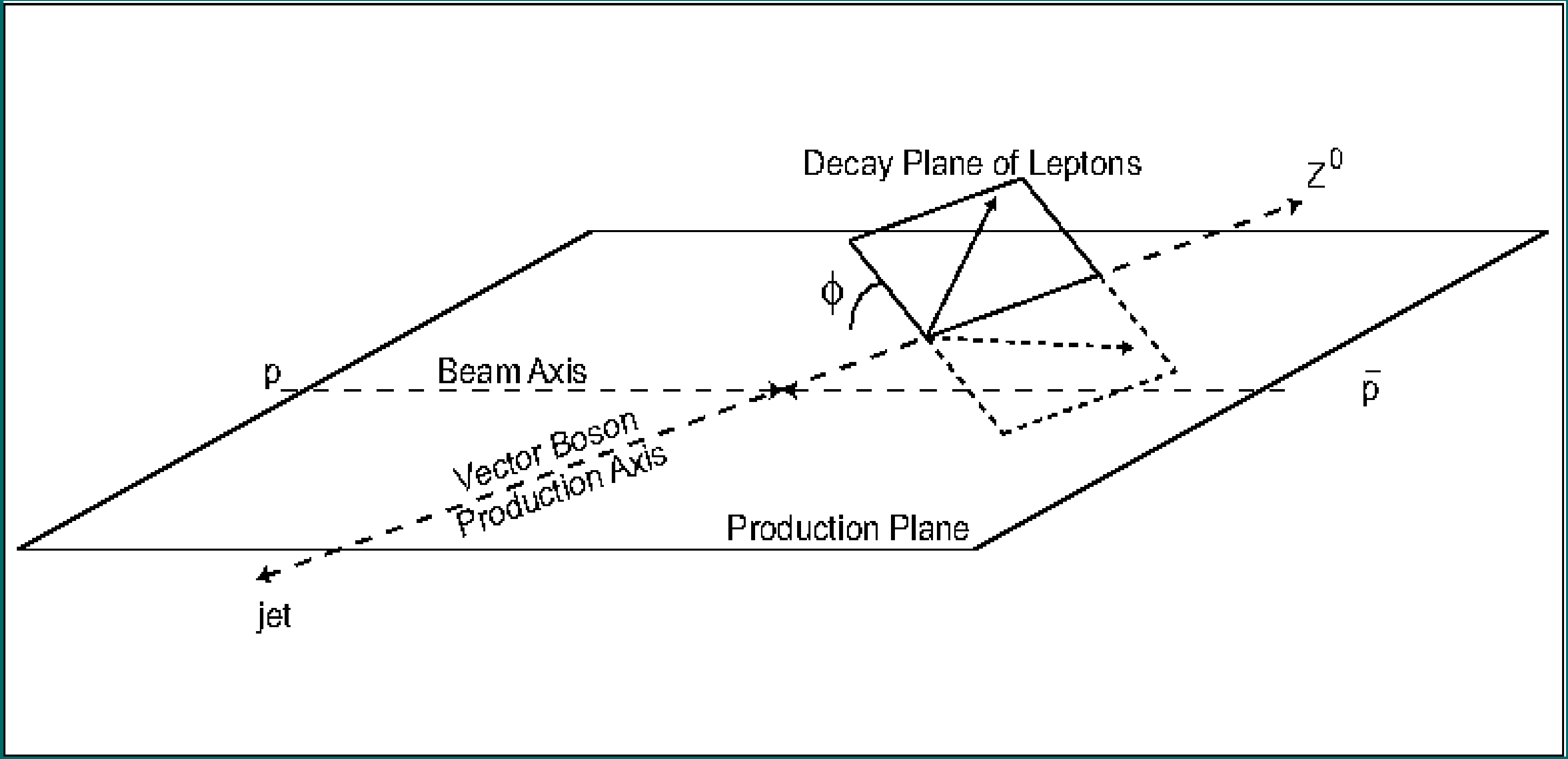
Outline

- Brief Review
- Z + jet at Tevatron
  - Rotationally invariant cuts
- Z + jet at LHC
  - Dealing with identical beams
- Z'

Our Technique



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

Our Technique

- Particle produced in multiple helicities

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

- Helicity states interfere!

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

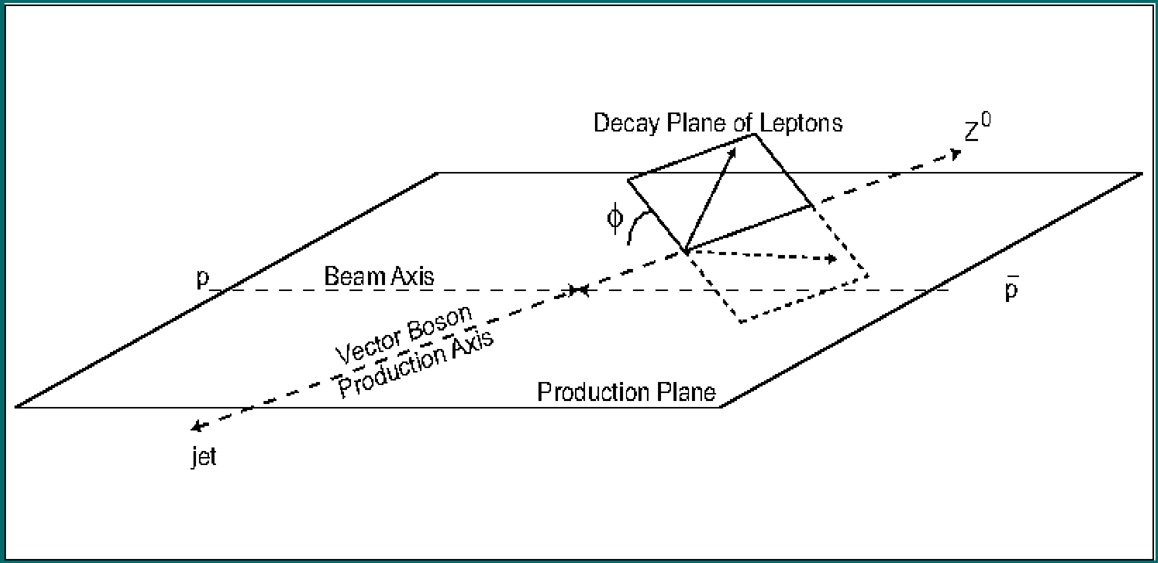
- Measuring distribution places limit on spin

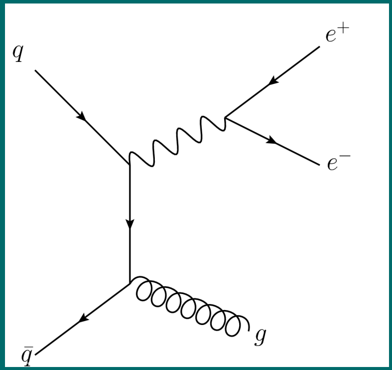
$$s \geq \frac{n_{meas}}{2}$$

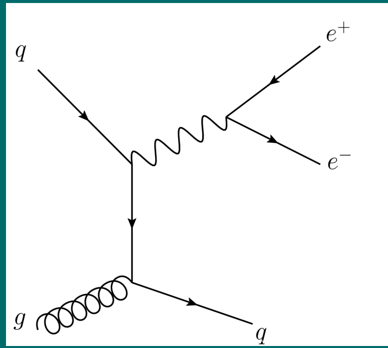
$$\begin{aligned} &scalar: A_0 \\ &spinor: A_0 + A_1 \cos(\phi) \\ &vector: A_0 + A_1 \cos(\phi) + A_2 \cos(2\phi) \end{aligned}$$

Example: Z+jet at Tevatron

- Fully reconstructible
- Z produced in multiple helicity states





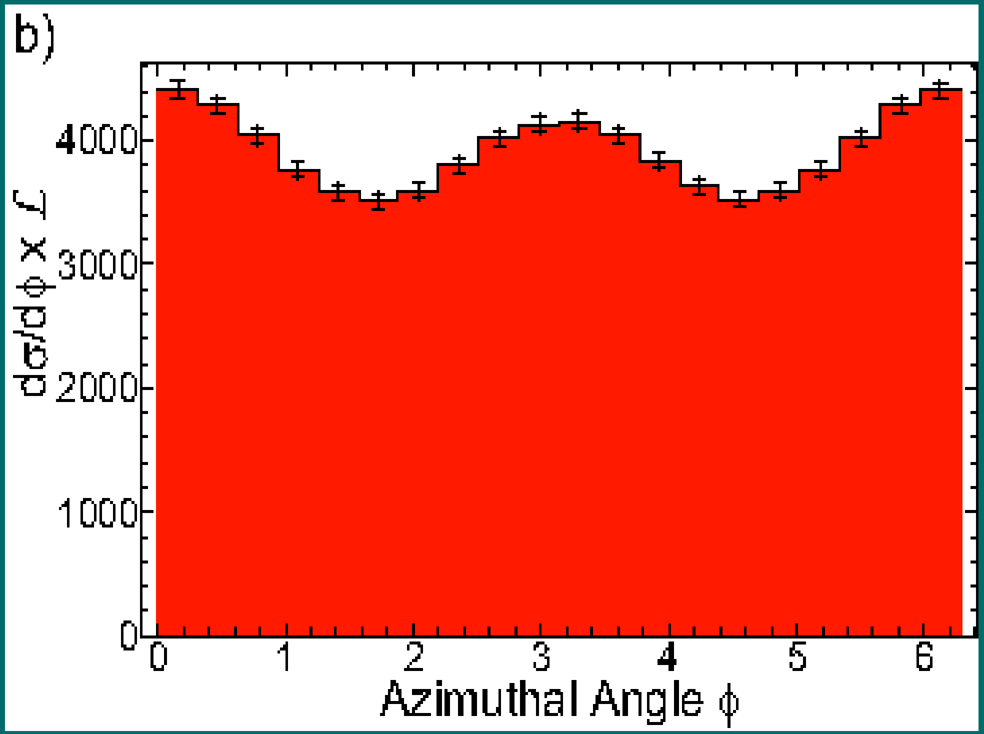


M. Buckley, B. Heinemann, WK, H. Murayama [arXiv:0804.0476]

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

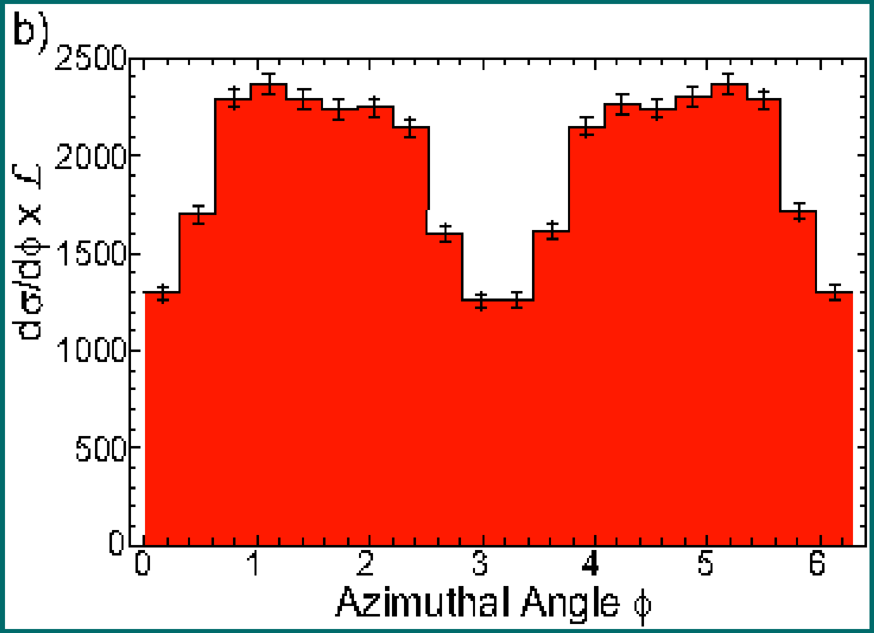
- Selection cuts necessary to improve sample, deal with detector limitations.
- CDF: 6203 events from 1.7 fb^{-1} luminosity at 1.96 TeV beam energy (after cuts)

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

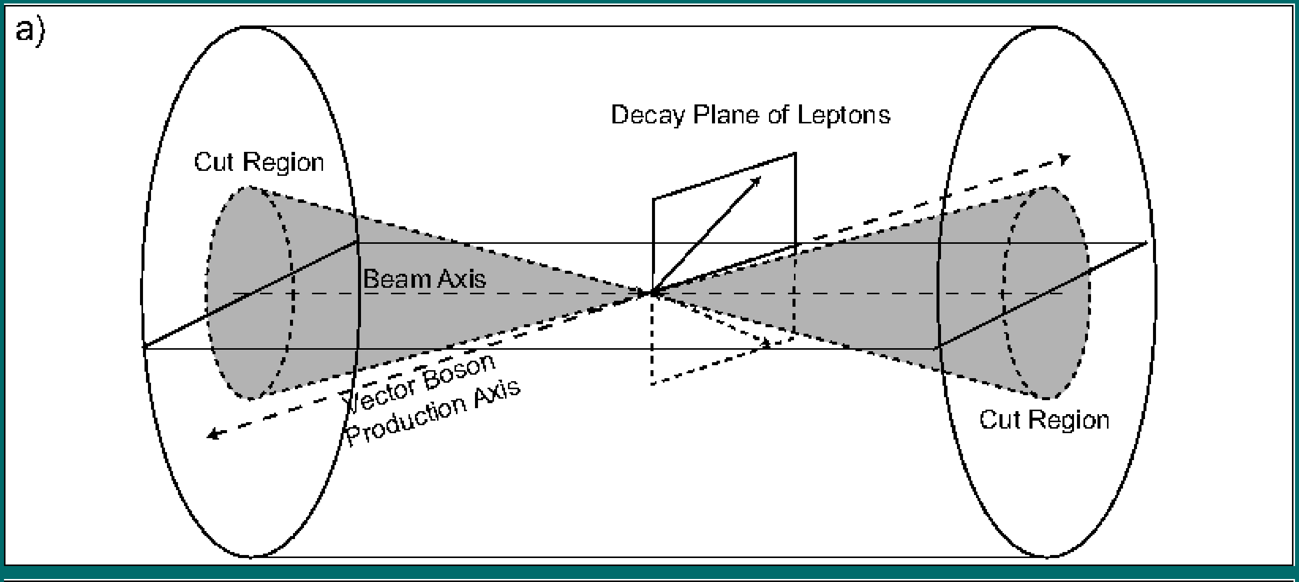
Detector Cuts

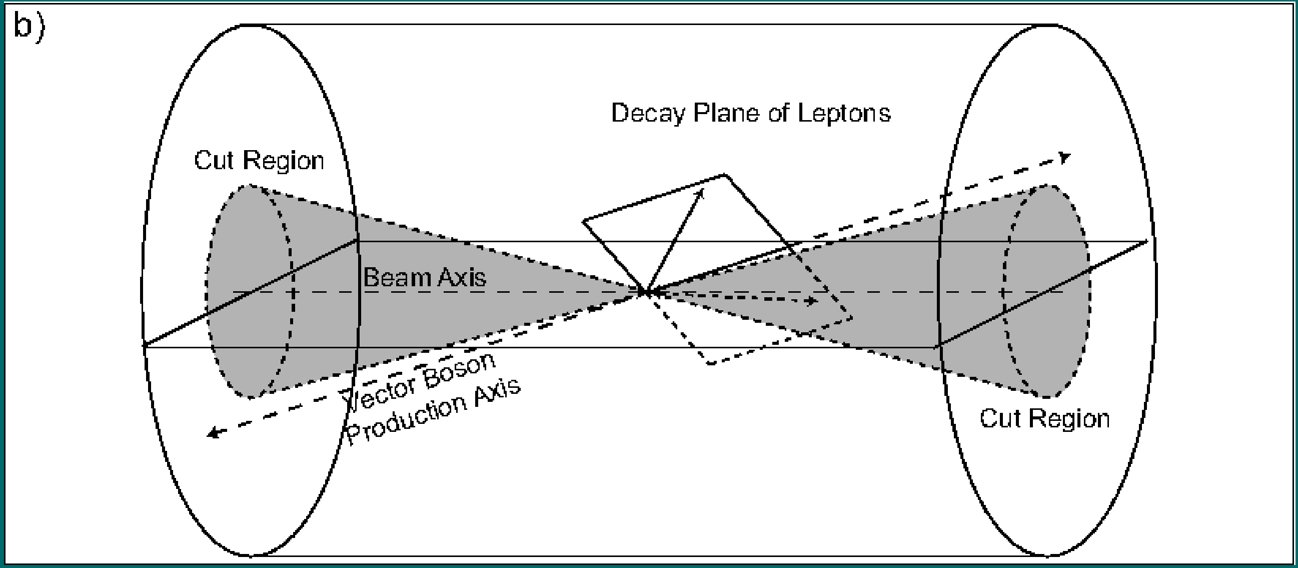
- Spurious higher order modes from the cuts

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



Rotationally Invariant cuts

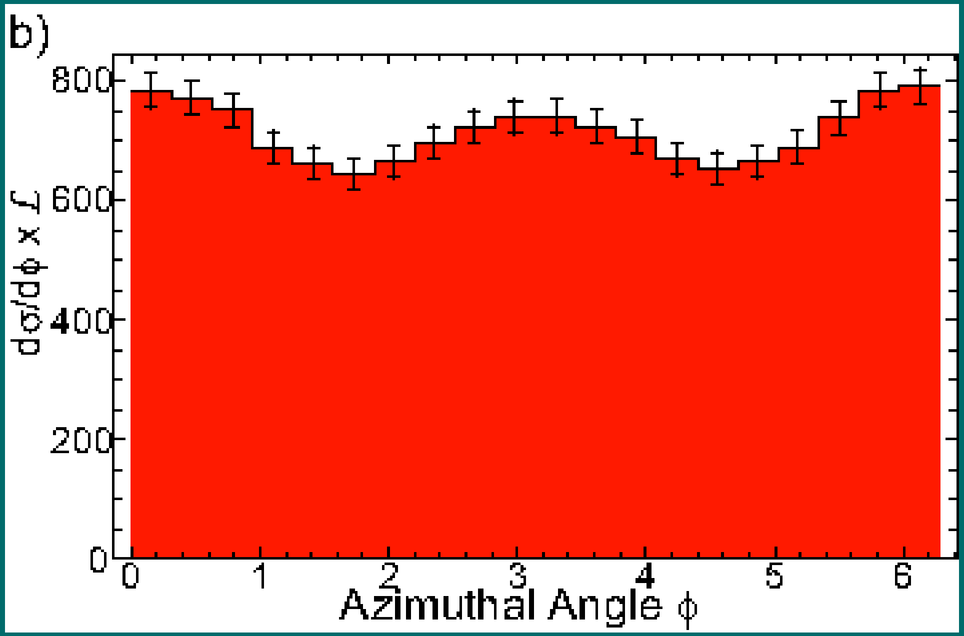




Revised results

- 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
- Cuts:

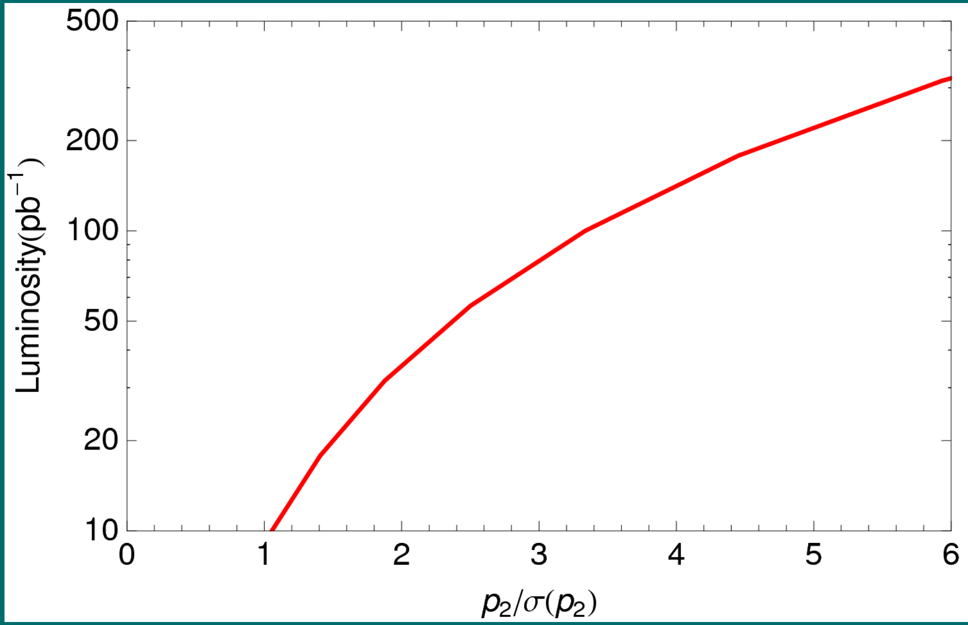
$$jet:\,p_T>40\,GeV\,,\,|\eta|<3.2$$
$$lepton:one\ p_T>10\,GeV\,,one\ p_T>20\,GeV$$
$$lepton:|\eta|<2.5$$
$$jet-lepton:\Delta R>0.7$$
$$lepton\ pair:66<m_{ll}<116\,GeV$$

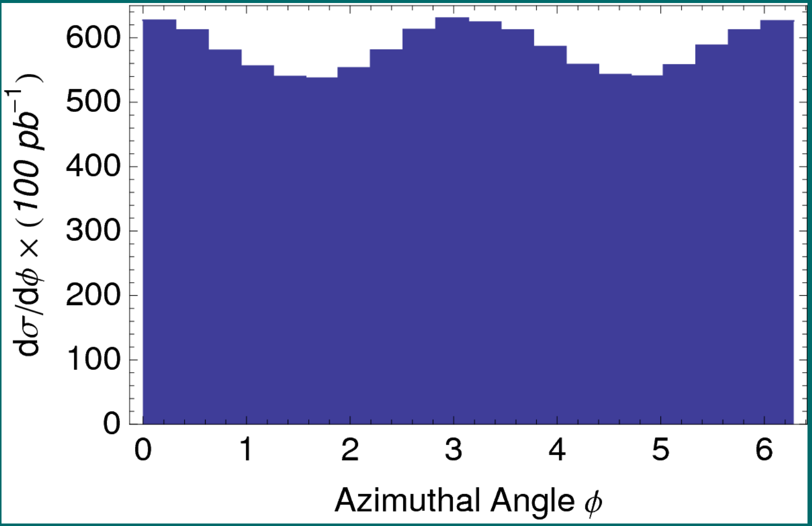
with H. Murayama

Z+jet at the LHC: Results

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

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





Challenges at the LHC

- Identical beams
- Missing Energy

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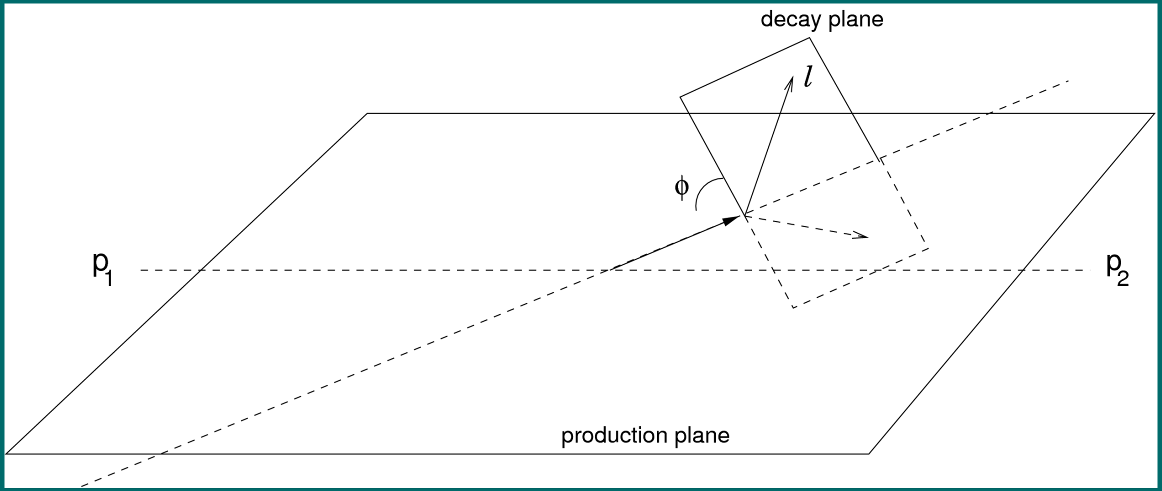
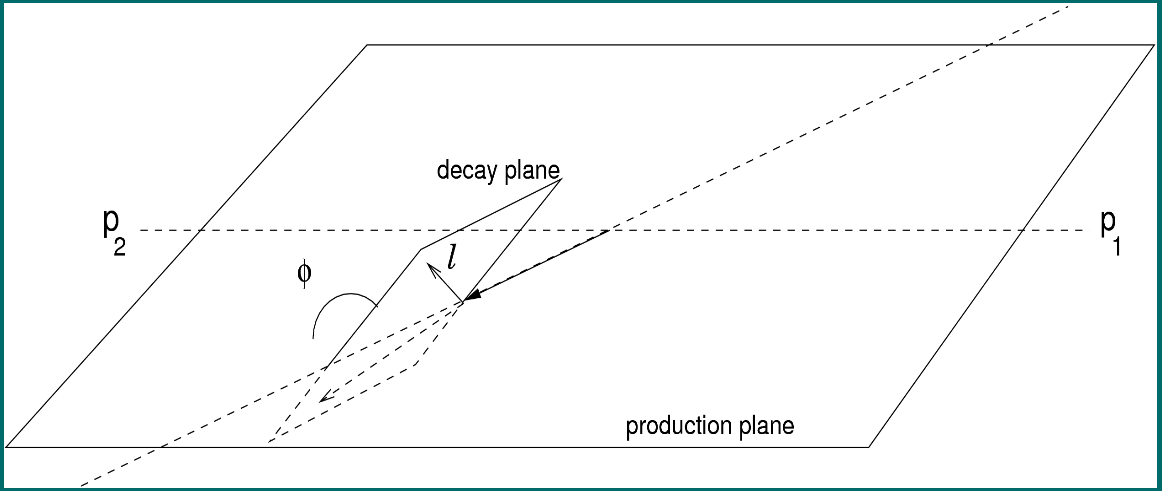
$$\cos(\phi)=\frac{\hat{z}\times\vec{p}_Z}{|\hat{z}\times\vec{p}_Z|}\cdot\frac{\vec{p}_Z\times\vec{p}_l}{|\vec{p}_Z\times\vec{p}_l|}$$



$$\phi\rightarrow\pi-\phi$$



$$\frac{dN}{d\,\phi}(p_1\,p_{2,}\,\phi)=\frac{dN}{d\,\phi}(p_2\,p_{1,}\,\pi-\phi)$$

Challenges at the LHC

$$\frac{dN}{d\phi}(p_1 p_{2,}\ \phi)=\frac{dN}{d\phi}(p_2 p_{1,}\ \pi-\phi)$$

$$\frac{dN}{d\phi}(p_1 p_2)=a_0+a_1\cos(\phi)+a_2\cos(2\phi)$$

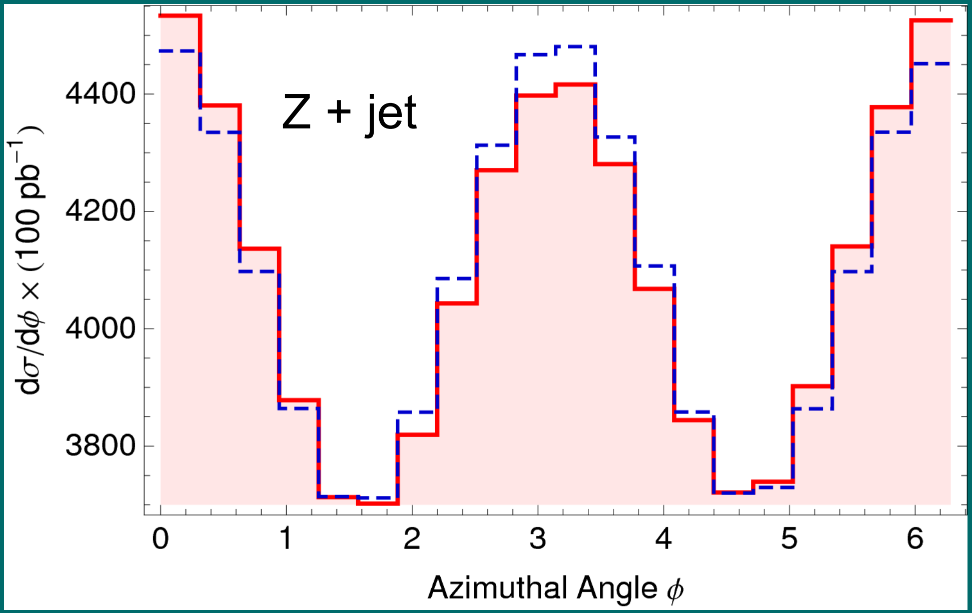
$$\frac{dN}{d\phi}(p_2 p_1)=a_0+a_1\cos(\pi-\phi)+a_2\cos(2(\pi-\phi))$$

$$=a_0-a_1\cos(\phi)+a_2\cos(2\phi)$$

$$\frac{dN}{d\phi}(p_1 p_2+p_2 p_1)=2\mathrm{a}_0+0\cos(\phi)+2a_2\cos(2\phi)$$

- Odd modes disappear

Odd modes: If we knew everything



Red: idealized filter

$$\phi(q\bar{q},\ qg,\ g\bar{q}) \rightarrow \phi$$
$$\phi(\bar{q}q,\ gq,\ \bar{q}g) \rightarrow \pi - \phi$$

Blue: no filter

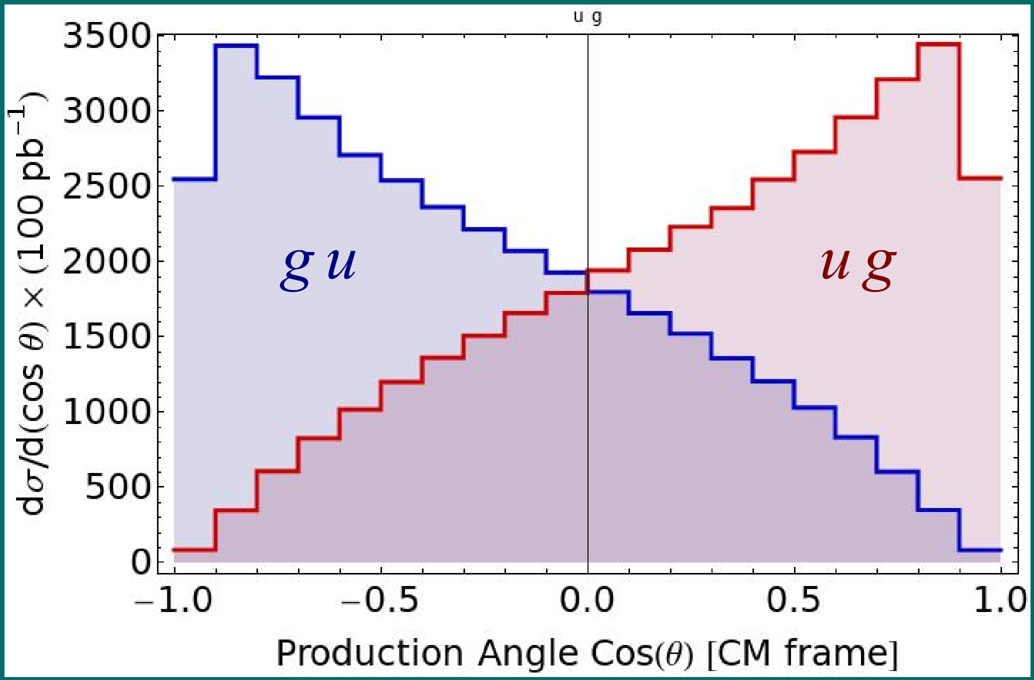
$$A_1/A_0 = 0.000$$
$$A_2/A_0 = 0.096$$
$$A_3/A_0 = 0.000$$
$$A_4/A_0 = 0.000$$

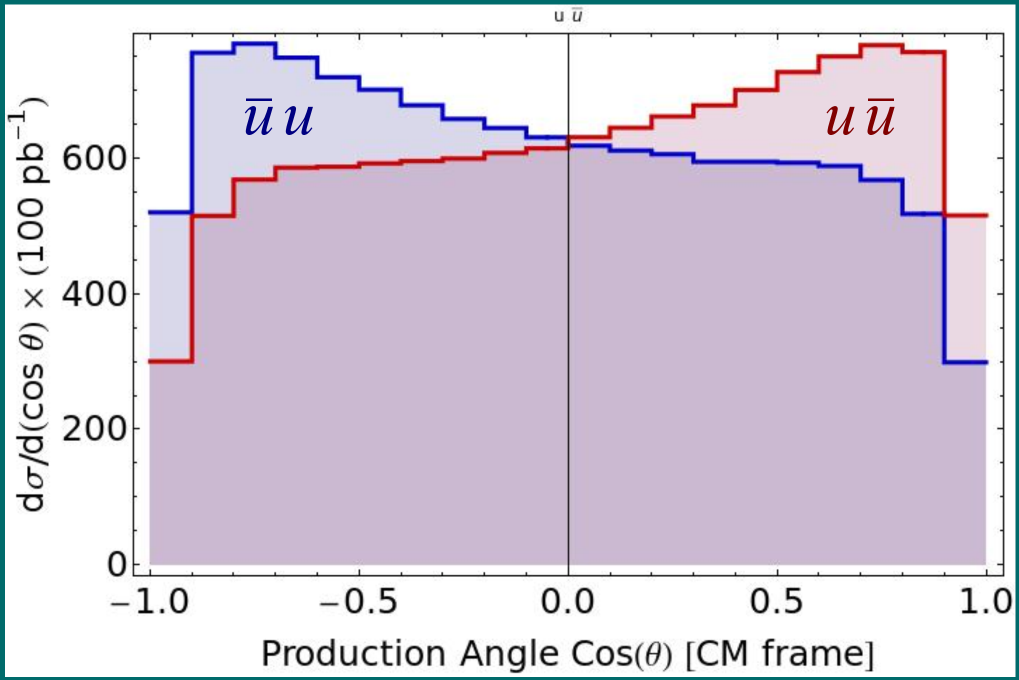
$$A_1/A_0 = 0.015$$
$$A_2/A_0 = 0.096$$
$$A_3/A_0 = 0.000$$
$$A_4/A_0 = 0.000$$

Odd modes

- Production angle differentiates initial partons

$$p_1 \, p_2 \rightarrow Z \; jet$$



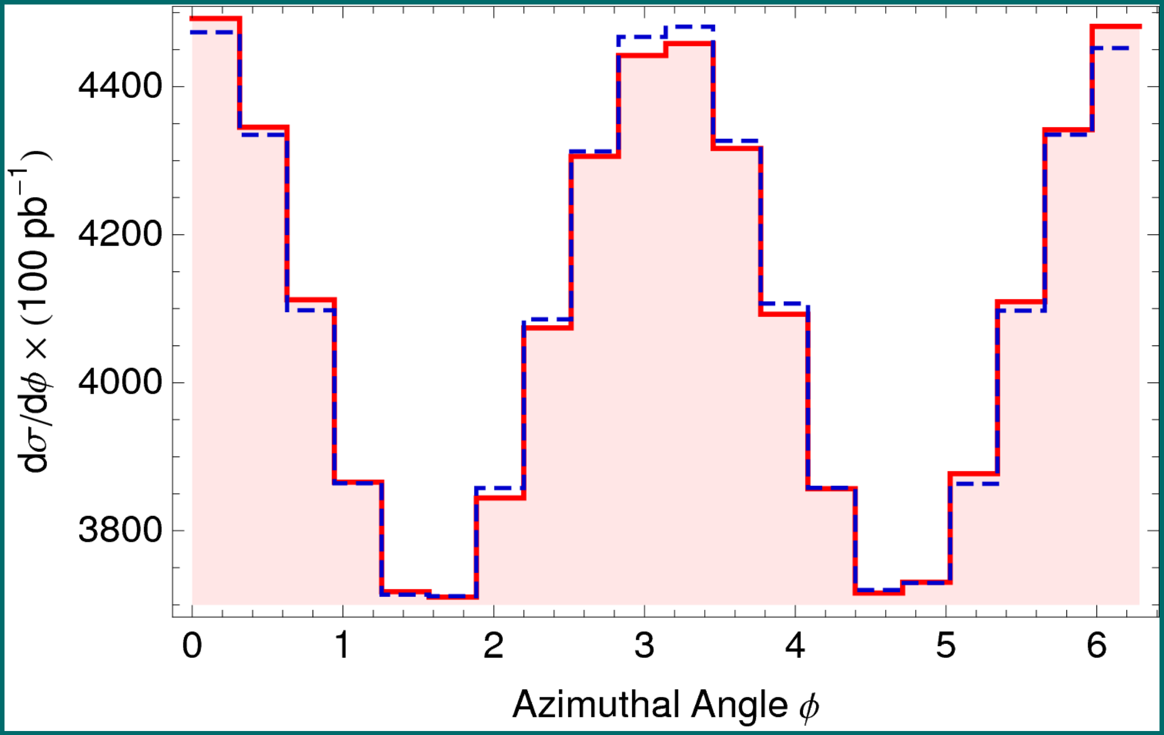


Filter:

$$\phi(\cos(\theta)>0) \rightarrow \phi$$
$$\phi(\cos(\theta)<0) \rightarrow \pi-\phi$$

Odd modes

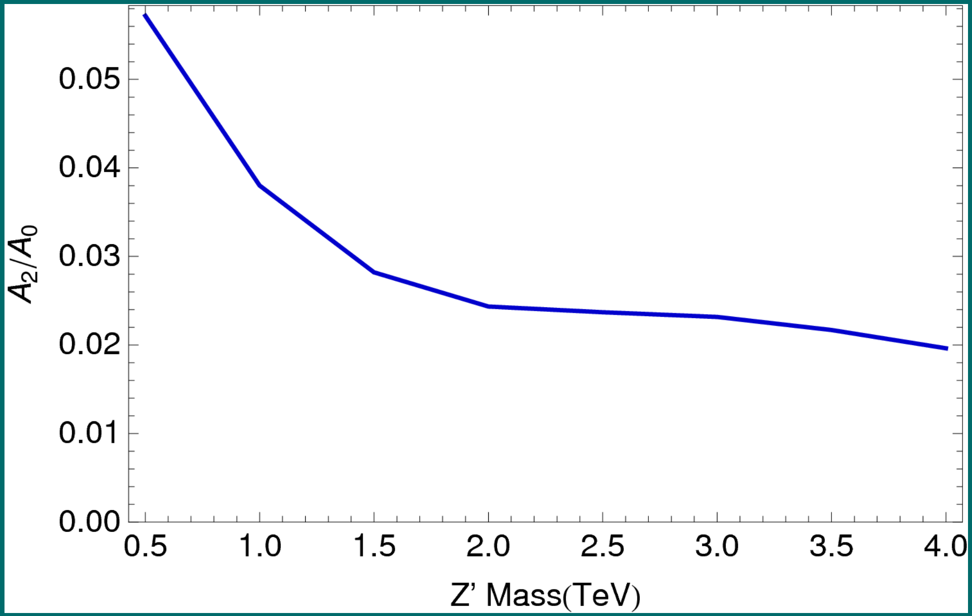
- Success (in principle)

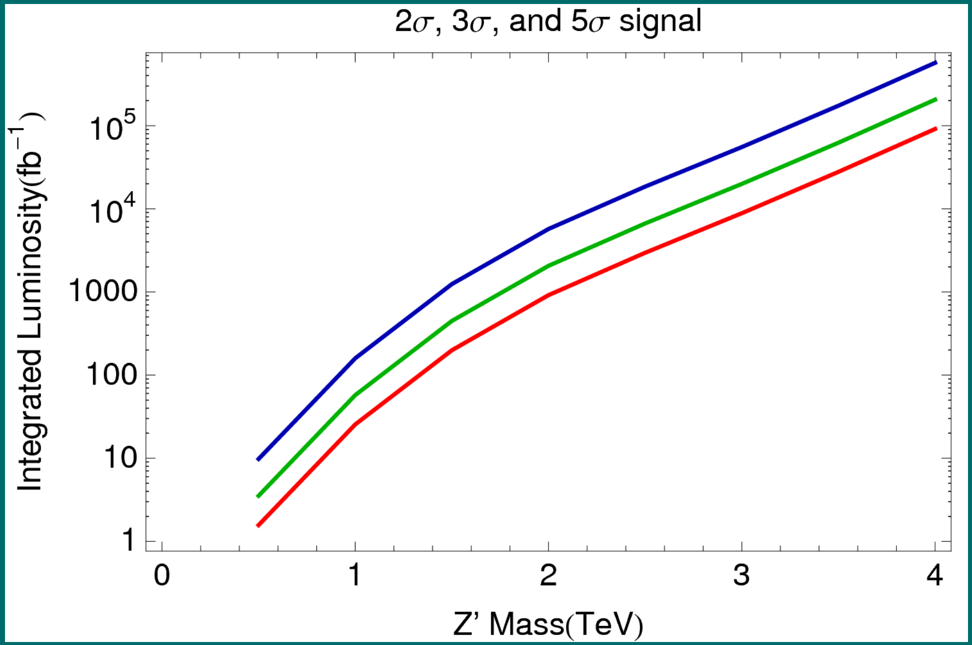


$A_1/A_0 = 0.005$
$A_2/A_0 = 0.096$
$A_3/A_0 = 0.000$
$A_4/A_0 = 0.000$

Z' + jet

- Model: Z' with SM couplings
- Simulation at 14 TeV
- Same cuts as Z + jet (with sliding invariant mass window)





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Conclusions

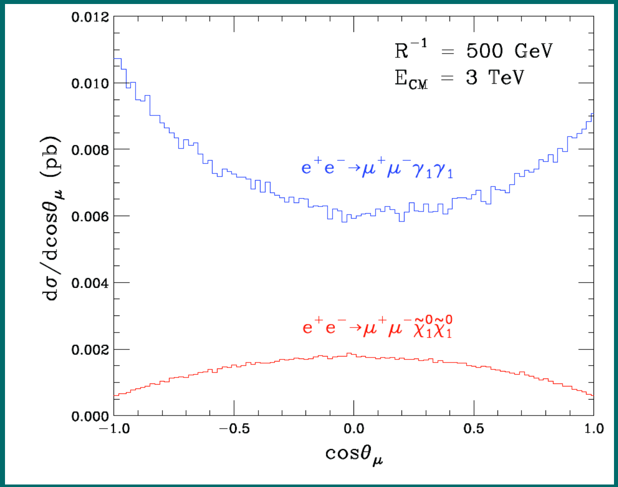
- Model-independent spin measurement
- Selection cuts must be made 'rotationally invariant' to preserve form of distribution
- Technique can be tested using existing data and early LHC data
- Z' spin determination
- Identical beams at LHC necessitate careful treatment of odd modes
- Processes with missing energy require a better solution

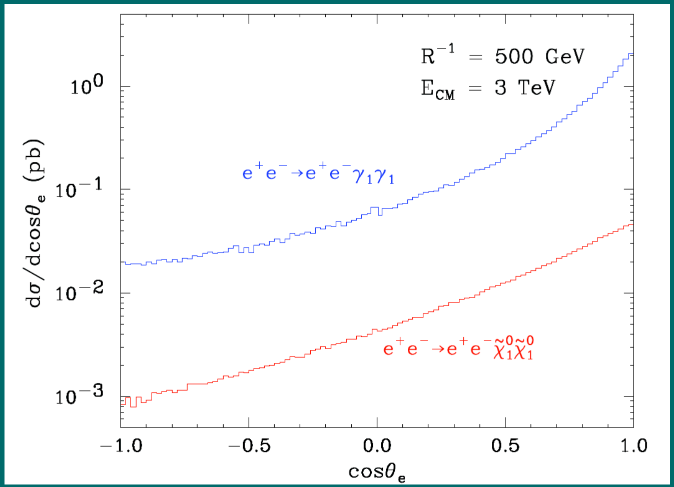
END

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

- 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

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