IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

東京大学 THE UNIVERSITY OF TOKYO

Deciphering New Physics Through Spin Measurement Using Quantum Interference

Hitoshi Murayama (IPMU Tokyo & Berkeley)

KITP Conference on LHC, June 2, 2008

with Matt Buckley, Willie Klemm, Vikram Rentala, Beate Heinemann, Seong Youl Choi, Kentarou Mawatari

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Motivation

New Era

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- ~1900 reached atomic scale 10^{-8}cm$\approx\alpha/m_e$

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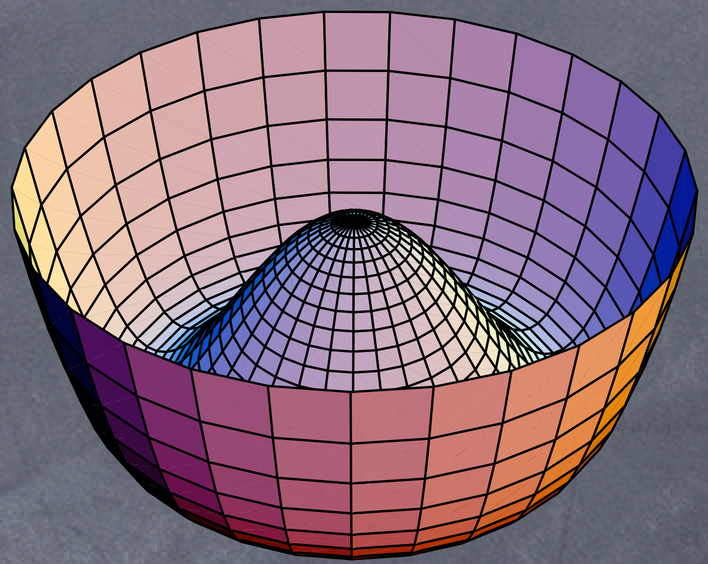
- presumably it is also a derived scale
  - from SUSY breaking? extra dimensions? string theory?
- If so, we expect rich spectrum of new

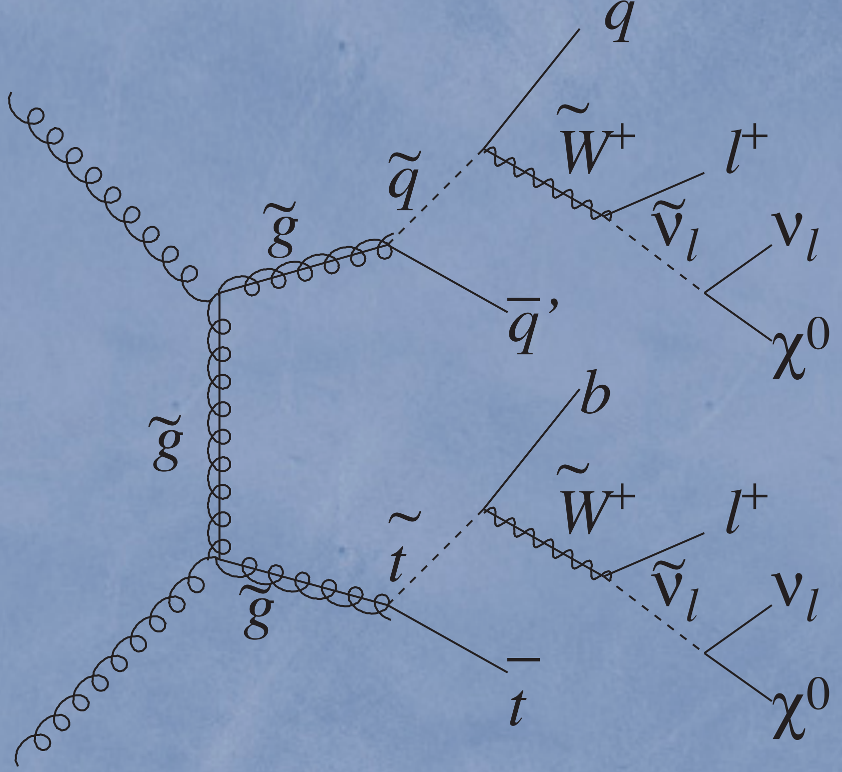
Post-Higgs Problem



- Once we discover Higgs, we see "what" is condensed
- But we still don't know "why"
- Two problems:
  - Why anything is condensed at all
  - Why is the scale of condensation $\sim$TeV<<M_{Pl}=10^{15}TeV
- Explanation most likely to be at ~TeV scale because this is the relevant energy scale

New physics looks alike

missing E_T, multiple jets, b-jets, (like-sign) leptons



SUSY

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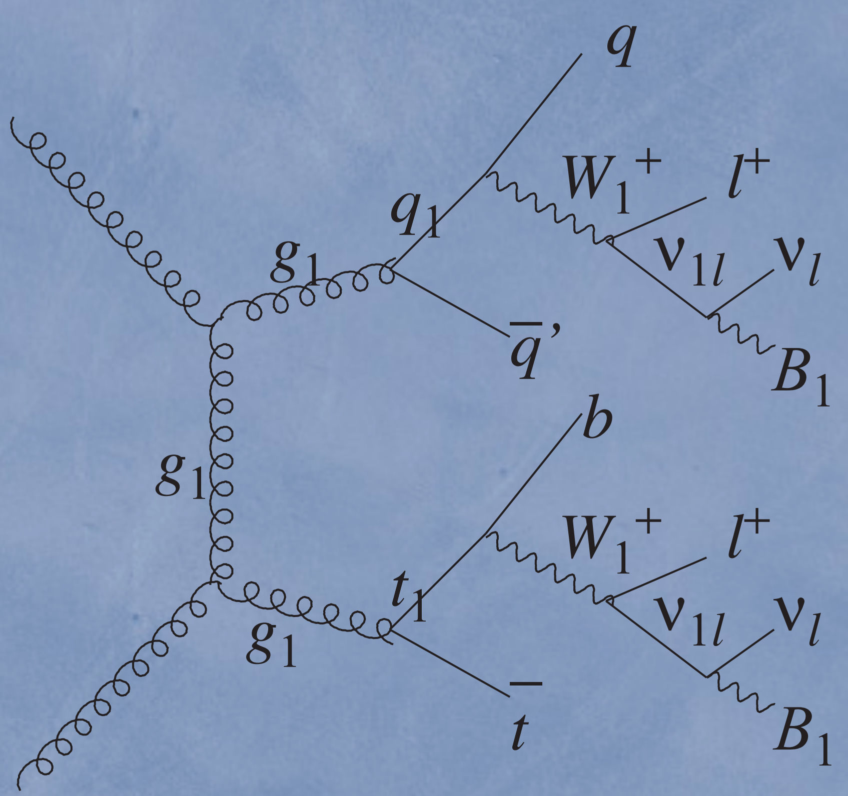
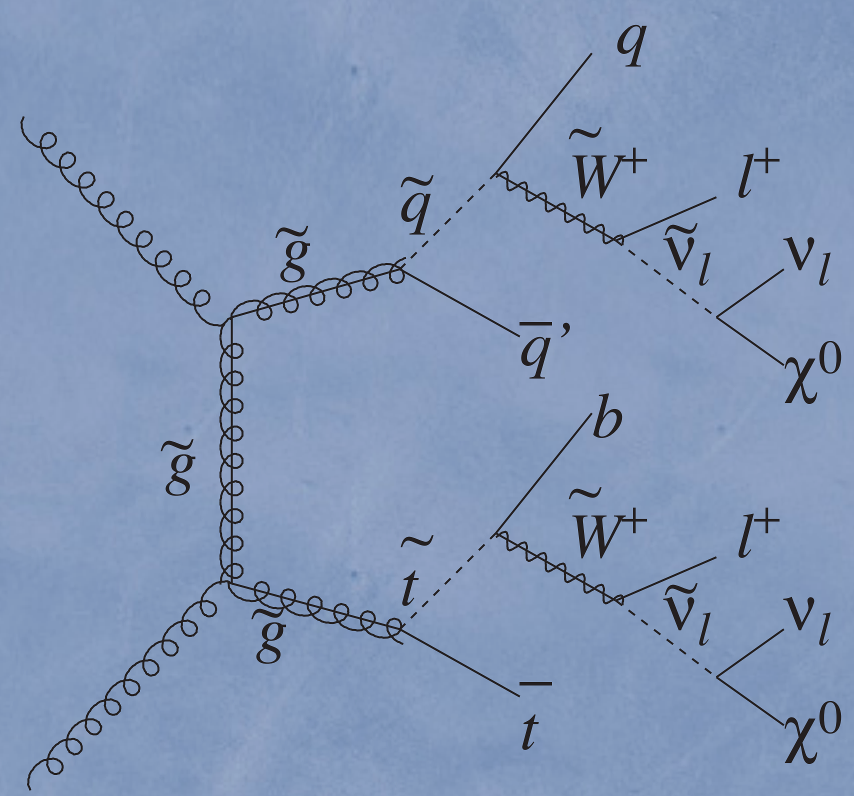


UED



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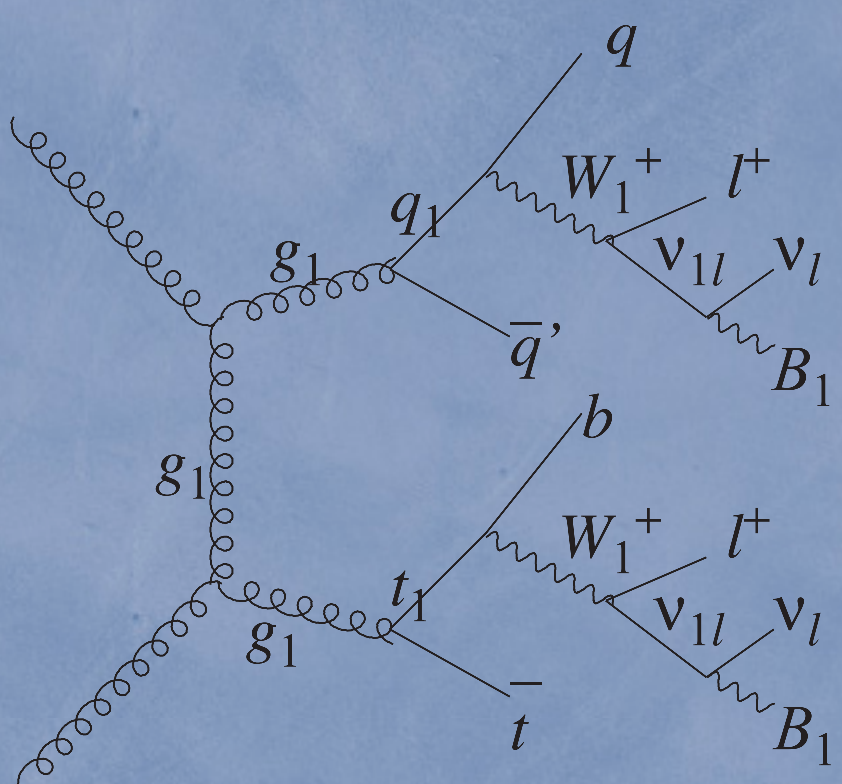

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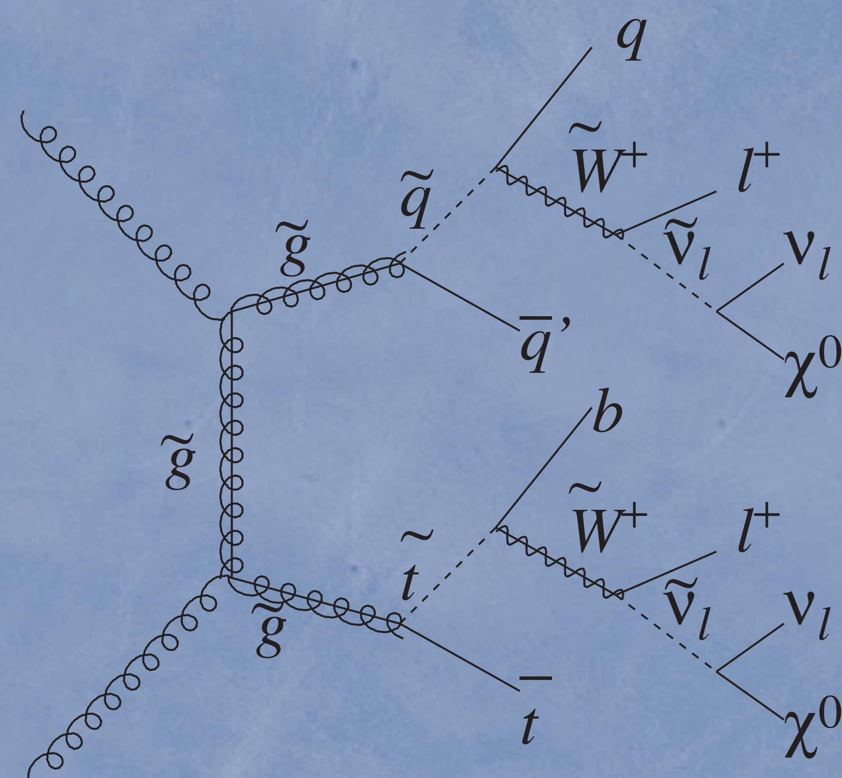
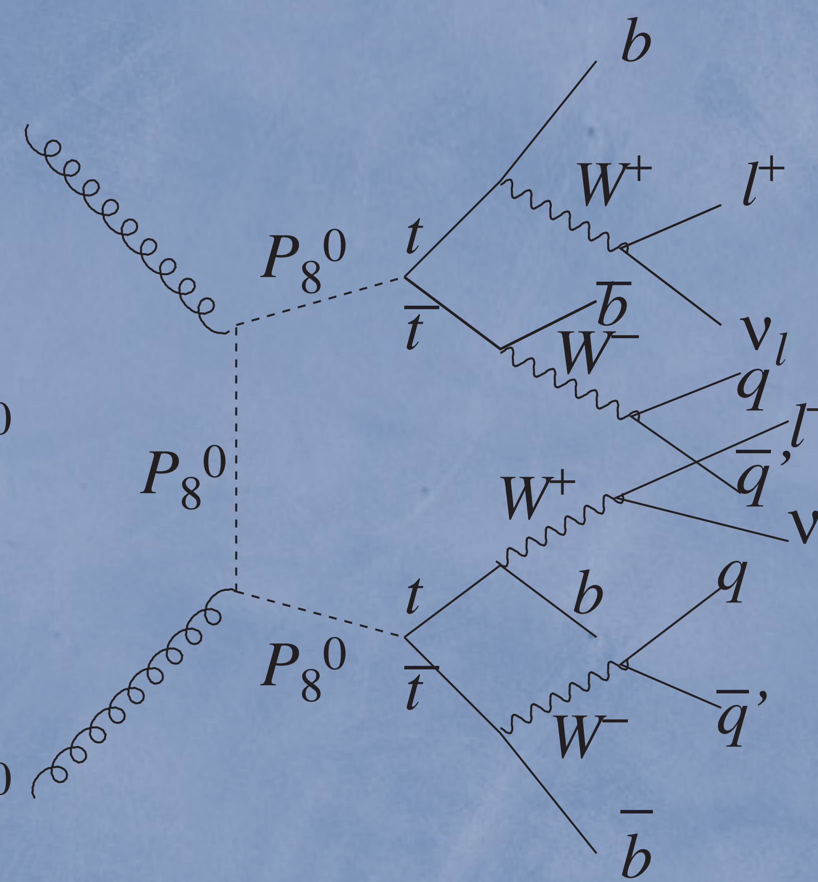


SUSY



technicolor

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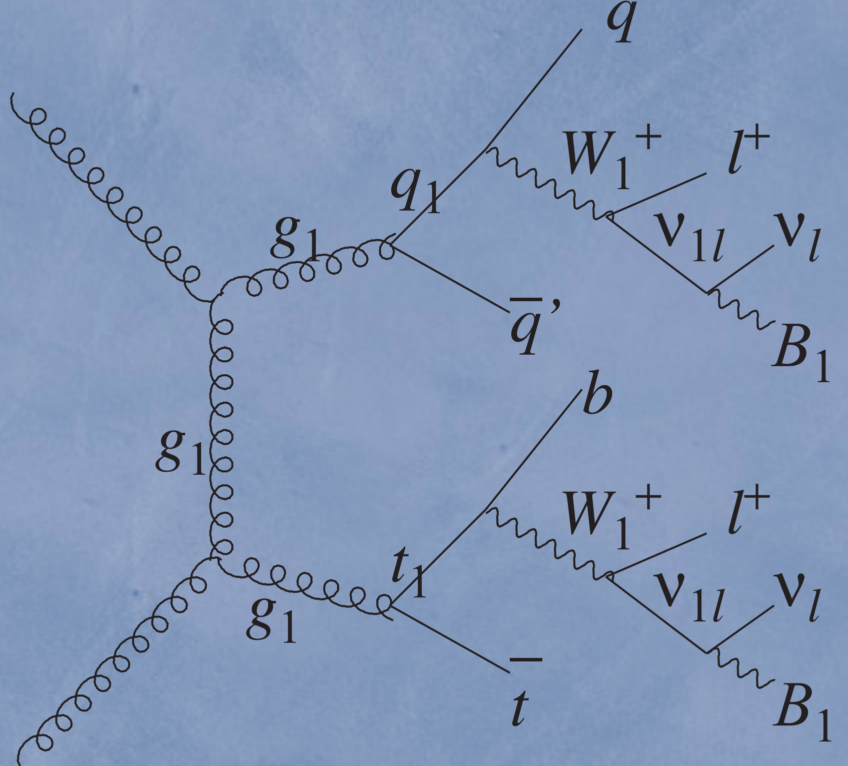
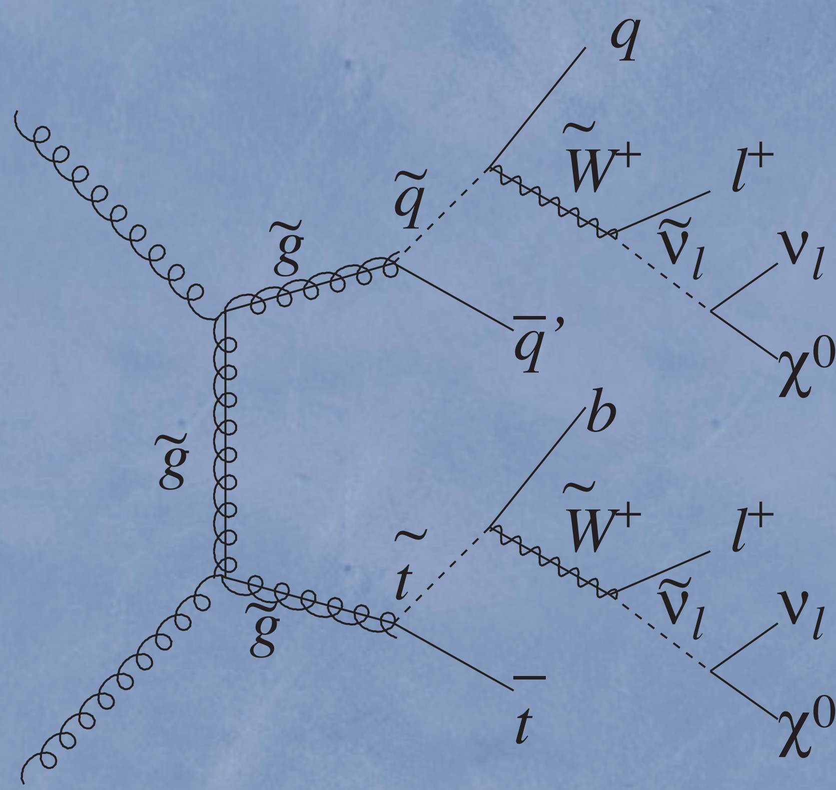
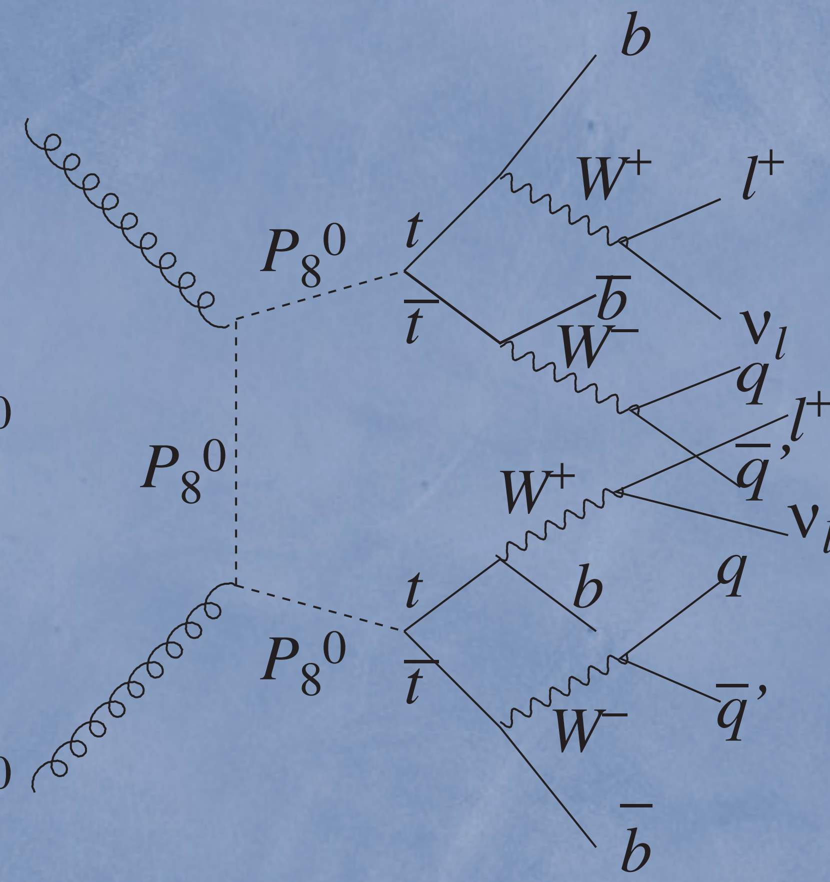


UED
spin 1



SUSY
spin 1/2



technicolor
spin 0

bosonic TC
composite Higgs
TC-TC
hypercolor
supercolor
techni-GIM
extended TC
pseudo NGB
NOT YET THOUGHT OF
effective SUSY
SUSY
NMSSM
MSSM +νR
ununified SM
axigluon
sterile ν
heavy Majorana
6th gen
5th gen
4th gen
lepto quark
vector-like family
fractionally charged
milli-charged
mono-pole
S, T, U
X Y
shadow matter
mirror symmetry
NOT YET THOUGHT OF
triplet Higgs
doubly charged Higgs
Type I
Type II
general 2HDSM
spontaneous CP
superweak
Weinberg's 3HD
milli-weak
Majoron
axion
saxion
axino
familon
NGB
worm-hole
quintessence
k-ssence
composite W, Z
contact int.
string
hetero-tic
matrix M
IIB
IIA
F
I
Extra dim
N=2
N=4
N=8
NOT YET THOUGHT OF

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The New York Times

July 23, 2009

The Other Half of the World Discovered

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"We have learned that all particles we observe have unique partners of different spin and statistics, called superpartners, that make our theory of elementary particles valid to small distances."

precision new physics measurements

- spectroscopy
- kinematic fits, partial wave analysis, Dalitz analysis, etc
- precision mass, BR measurements
- key: spin-parity

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Squarks J=0? **PDG 2012**

The following data are averaged over all light flavors, presumably u, d, s, c with both chiralities. For flavor-tagged data, see listings for Stop and Sbottom. Most results assume minimal supergravity, an untested hypothesis with only five parameters. Alternative interpretation as extra dimensional particles is possible. See KK particle listing.

SQUARK MASS

VALUE (GeV)	DOCUMENT ID	TECN	COMMENT
538±10	**OUR FIT**		**mSUGRA assumptions**
532±11	[1]ABBIENDI 11D	CMS	Missing ET with mSUGRA assumptions
541±14	[2]ADLER 11O	ATLAS	Missing ET with mSUGRA assumptions
• • • We do not use the following data for averages, fits, limits, etc • • •			
652±105	[3]ABBIENDI 11K	CMS	extended mSUGRA with 5 more parameters

[1]ABBIENDI 11D assumes minimal supergravity in the fits to the data of jets and missing energies and set A_0=0 and tanβ = 3. See Fig. 5 of the paper for other choices of A_0 and tanβ. The result is correlated with the gluino mass M_3. See listing for gluino.
[2]ADLER 11O uses the same set of assumptions as ABBIENDI 11D, but with tanβ = 5.
[3]ABBIENDI 11K extends minimal supergravity by allowing for different scalar masses-squared for Hu, Hd, 5* and 10 scalars at the GUT scale.

SQUARK DECAY MODES

MODE	BR(%)	DOCUMENT ID	TECN	COMMENT
j+miss	32±5	ABE 10U	ATLAS	
j l+miss	73±10	ABE 10U	ATLAS	lepton universality
j e+miss	22±8	ABE 10U	ATLAS	
j μ +miss	25±7	ABE 10U	ATLAS	
q χ^+	seen	ABE 10U	ATLAS	

Conventional Methods

Spin Measurements

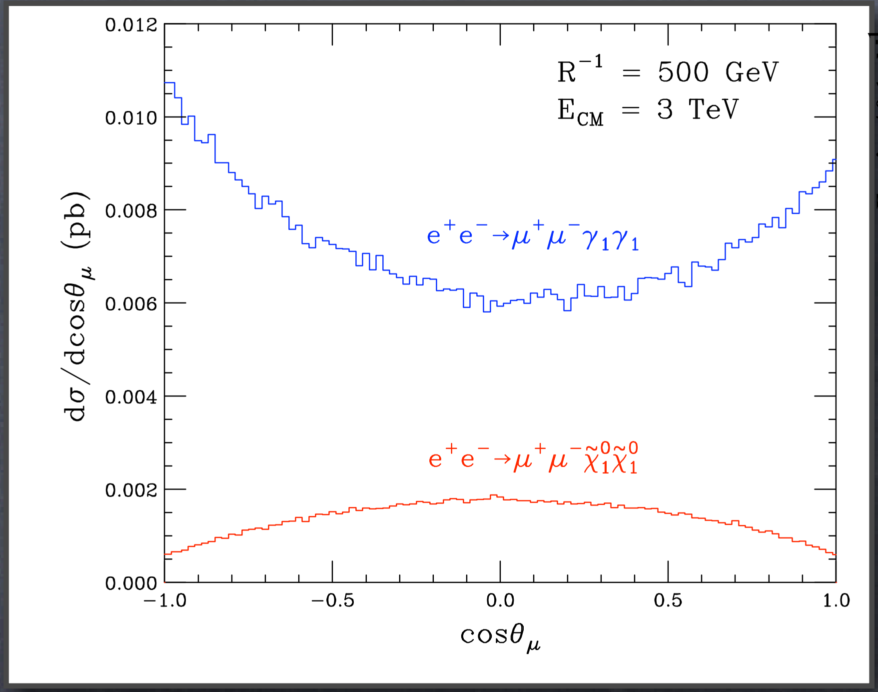
- Most techniques for next-generation colliders concentrate on distinguishing models:
  - Comparison of total cross section

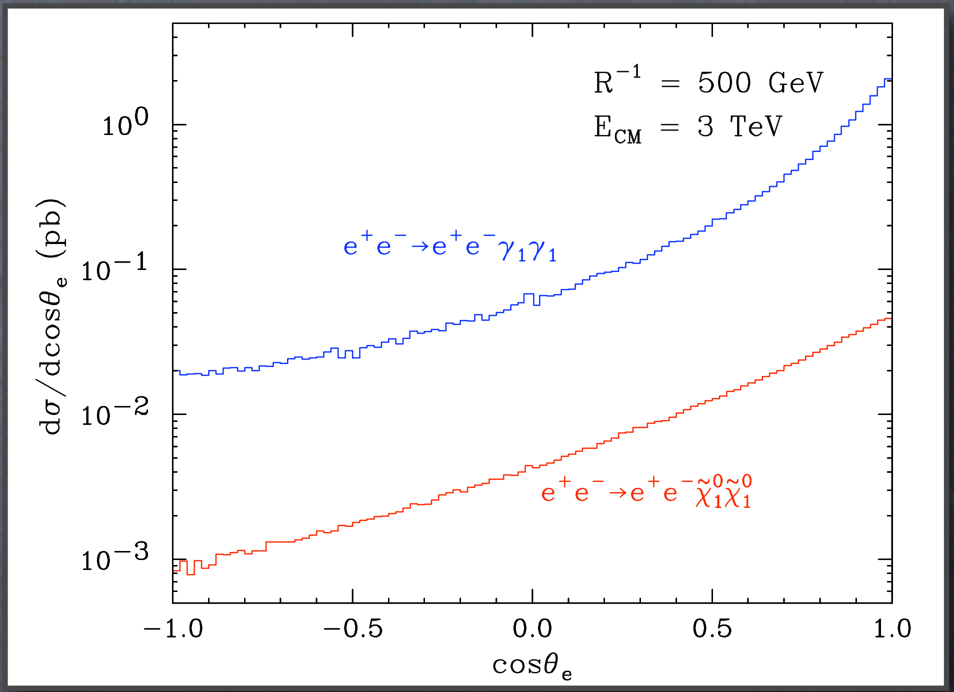
$$\sigma_{SUSY} < \sigma_{UED}$$

  - Look for higher KK modes in UED
- At a linear collider can use threshold scans:
  - Scalar $\sigma \propto \beta^3$, spinor/vector $\sigma \propto \beta$
  - Cannot distinguish higher spin modes

Spin Measurements

- At ILC: reconstruct production angle





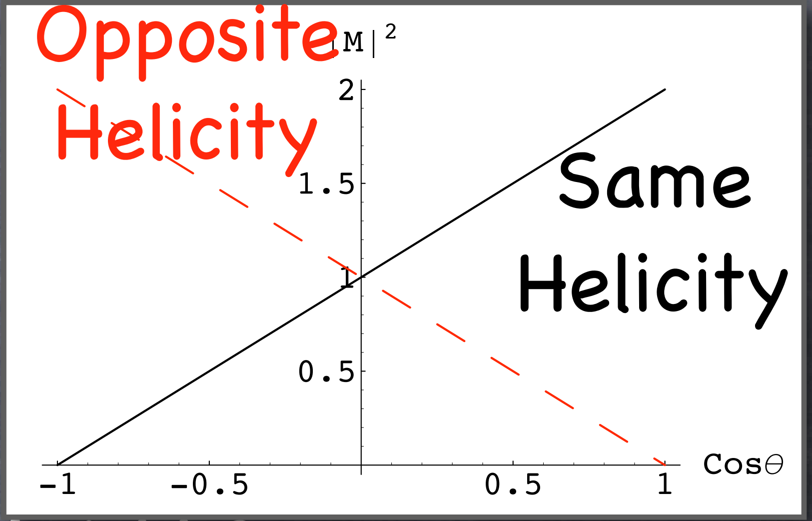
- t-channel introduces model dependence: forward peak

Spin Measurements

- Spin dependence of decay angles:

Decay of polarized spinor to spinor/scalar ⟶

Assumes chiral couplings



- Using long decay chain at LHC can distinguish spinors from phase space:

Near Far

$$\tilde{q}_L \to \tilde{\chi}_2^0 q_L \to \tilde{\ell}_R^{\pm}\ell^{\mp} q_L \to \ell^{\pm}\ell^{\mp} q_L \tilde{\chi}_1^0$$

- Polluted with near/far ambiguity, anti-squark production, and assumes chiral coupling

Typically worse

- For most LHC analyses, it is based on the comparison between the "data" and big Monte Carlo to see which one is "closer" to the data
- Not really spin measurements, more of a consistency check of the models
- How can we get information on spin of each new particle?

General Principle

Model-independent information on spin

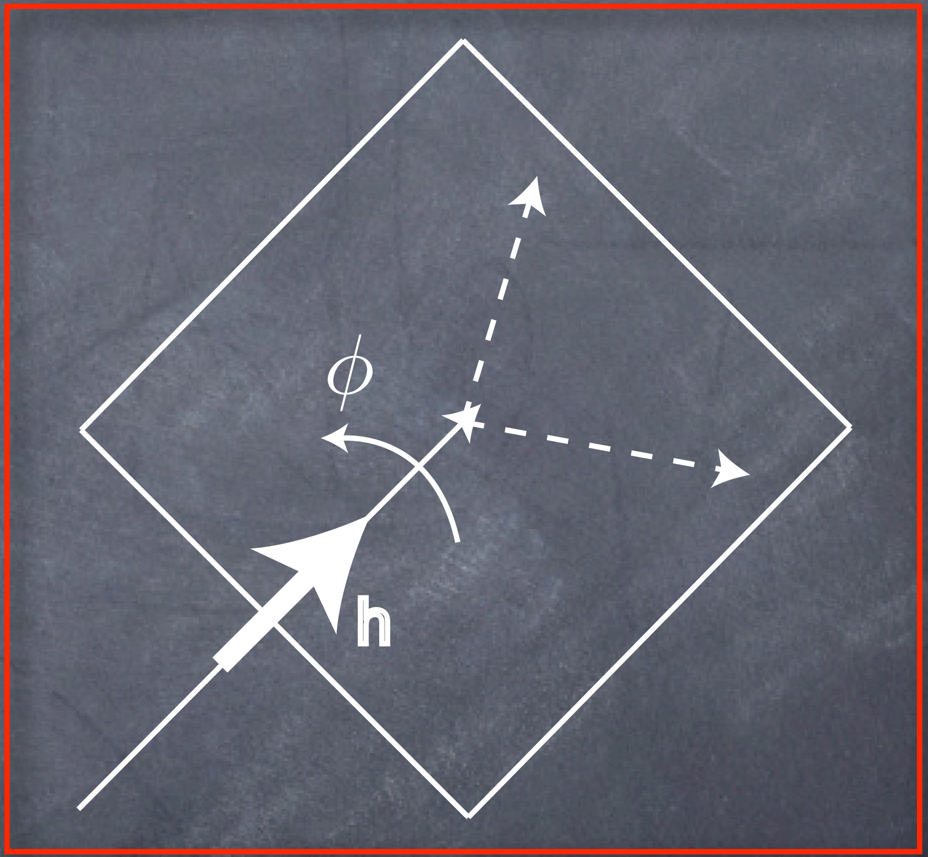
- How can we obtain information on spins without any model assumptions?
- Back to basics: quantum mechanics
- angular momentum generates rotation $U(\vec{\theta}) = e^{i\vec{J}\cdot\vec{\theta}/\hbar}$
- there is no orbital angular momentum along the momentum, and spin can be isolated

Helicity and phase

- Decay of particle with spin h along the momentum axis
- Rotations about z-axis of decay plane given by

$$\mathcal{M} \propto e^{iJ_z\phi}$$

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



- rotational invariance: a single helicity state has flat distribution in ϕ: $\left|e^{ih\phi}\right|^2 = 1$

Quantum Interference among helicities

(with M. Buckley, W. Klemm, and V. Rentala)

- If particles produced in multiple helicities:

$$\boxed{\begin{gathered}\sigma \propto \left|\sum \mathcal{M}_{prod.}\mathcal{M}_{decay}\right|^2 \\ \mathcal{M}_{decay} = e^{ih\phi}\mathcal{M}_{decay}(h, \phi = 0)\end{gathered}}$$

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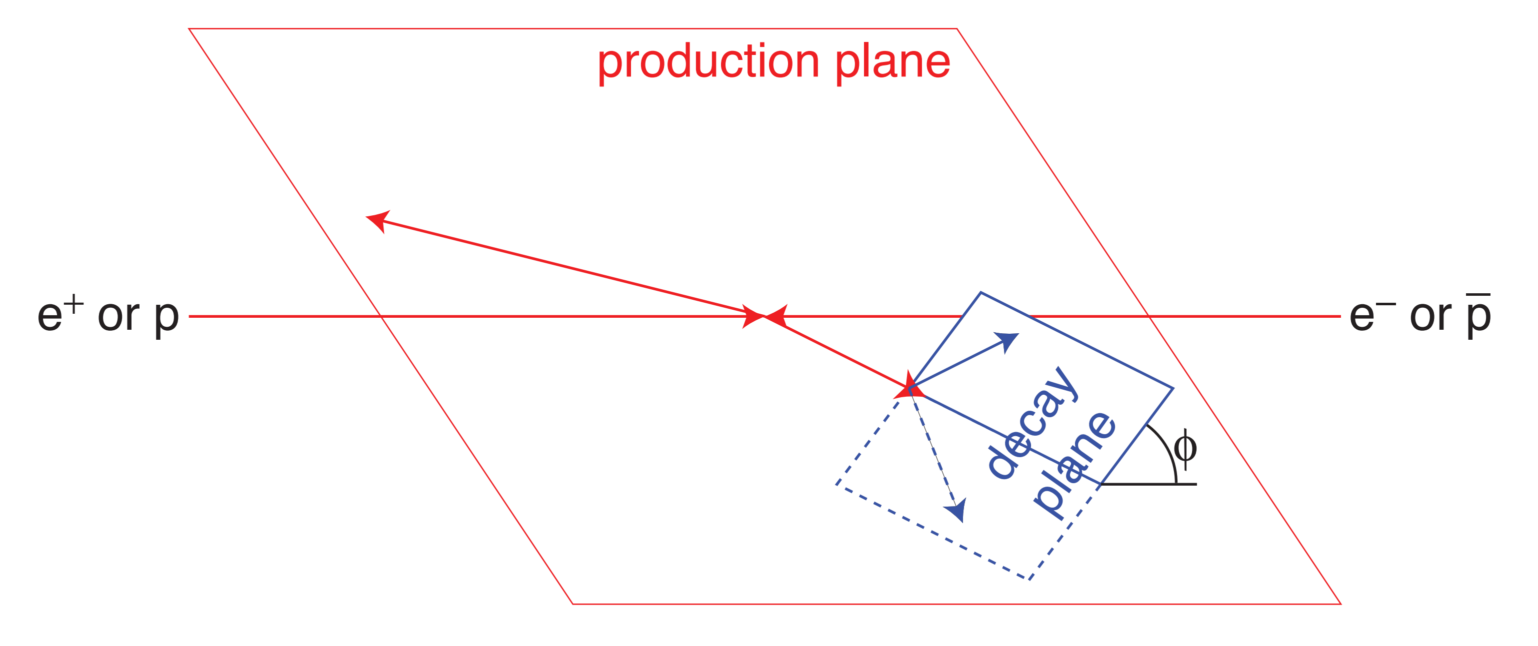
- Different helicities interfere once they decay!
- ϕ dependence of cross section tells us what helicities contributed to the interference.
- Can measure only helicity differences (akin to neutrino oscillation)

Definition of the azimuthal angle

- Beam and produced particles span the production plane
- Parent particle and its decay products span the decay plane
- azimuth is the relative angle between two planes



Spin and Quantum Interference

- Vector Boson Decay:

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

- Spinor Decay:

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

$$\left|\sum \mathcal{M}\right|^2 = A_0 + A_1\cos\phi + A_2\cos 2\phi \qquad \left|\sum \mathcal{M}\right|^2 = A_0 + A_1\cos\phi$$

- In general:

$$\sigma = A_0 + A_1\cos(\phi) + \cdots + A_n\cos(n\phi),\ \ n = 2\times\text{spin}$$

Simple example

$$e_L^- e_R^+ \rightarrow \tilde{w}^- \tilde{w}^+ \rightarrow (\mu^- \tilde{\nu}_\mu^*)(e^+ \tilde{\nu}_e)$$

$$\mathcal{M}(-+) \propto (1+\cos\theta) \cos\frac{\hat{\theta}_1}{2} e^{-i\hat{\phi}_1/2} \cos\frac{\hat{\theta}_1}{2} e^{-i\hat{\phi}_2/2}$$

$$\mathcal{M}(+-) \propto (1-\cos\theta) \sin\frac{\hat{\theta}_1}{2} e^{+i\hat{\phi}_1/2} \sin\frac{\hat{\theta}_1}{2} e^{+i\hat{\phi}_2/2}$$

$$\mathcal{M}(--) \propto -\sin\theta \frac{M}{E} \cos\frac{\hat{\theta}_1}{2} e^{-i\hat{\phi}_1/2} \sin\frac{\hat{\theta}_1}{2} e^{+i\hat{\phi}_2/2}$$

$$\mathcal{M}(++) \propto -\sin\theta \frac{M}{E} \sin\frac{\hat{\theta}_1}{2} e^{+i\hat{\phi}_1/2} \cos\frac{\hat{\theta}_1}{2} e^{-i\hat{\phi}_2/2}$$

(HM: LCWS 2000 @ Fermilab)

Real-life Examples

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e.g., J.D. Jackson and K. Gottfried, Nuovo Cimento, 33, 309 (1964)

LEP-II

- $e^+e^- \rightarrow W^+ W^-$
- study semileptonic
  - $W^- \rightarrow l^-$ nu
  - $W^+ \rightarrow j\ j$
- $\sqrt{s}$ = 200 GeV
- A_1/A_0=-26%
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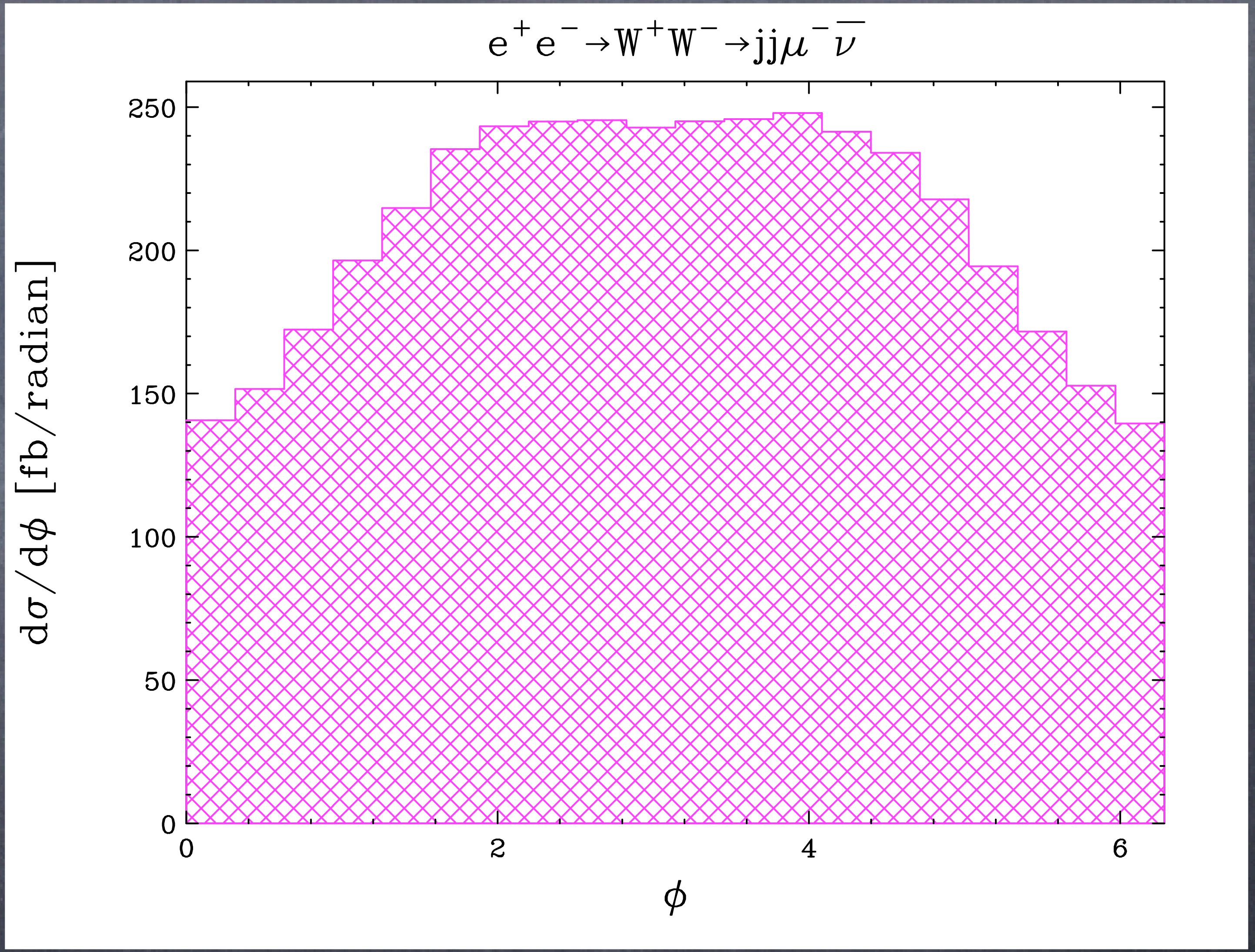

Tevatron

- p pbar → Z + gluon
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- A_1/A_0=6.0%
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used $p_T(g)$>7 GeV

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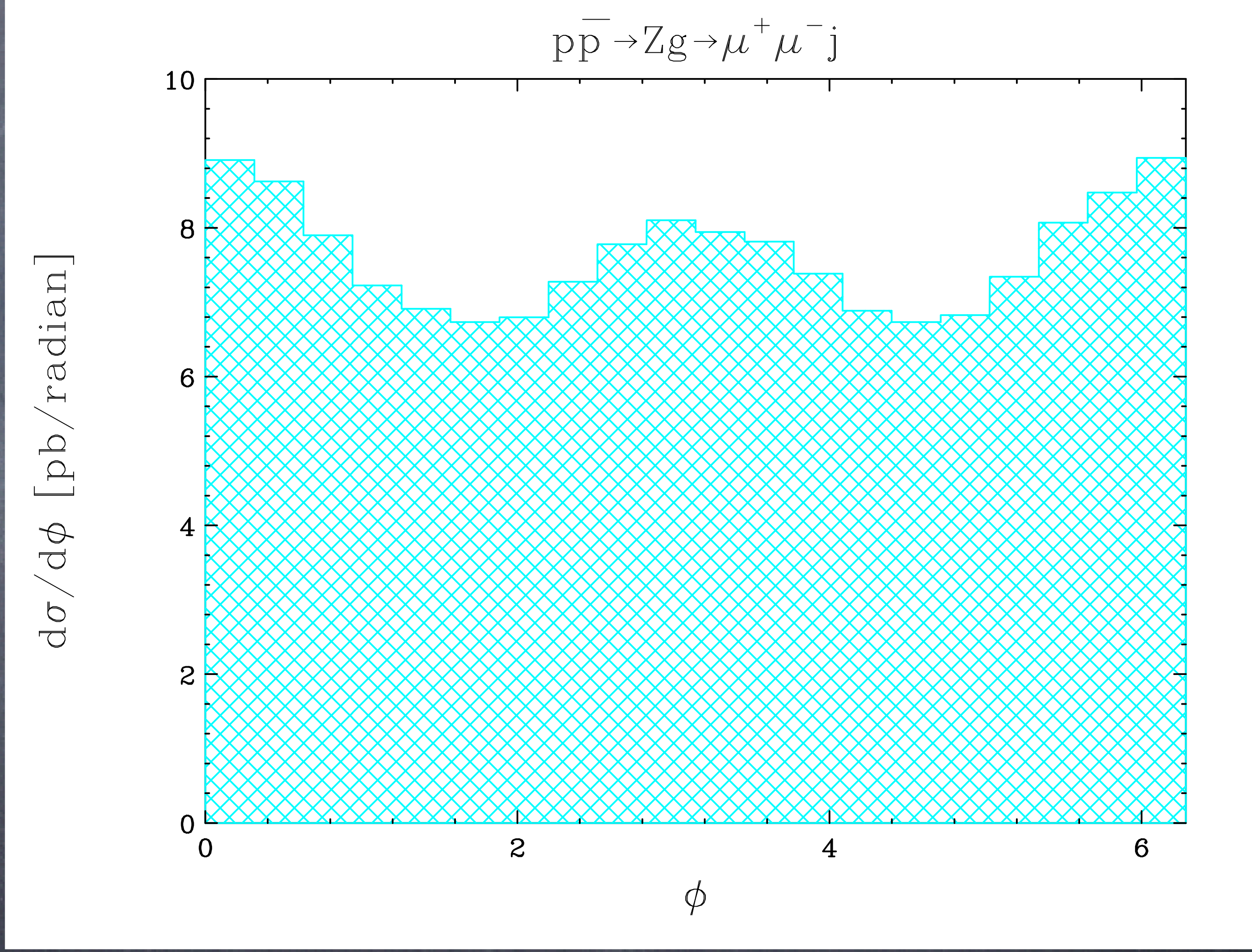
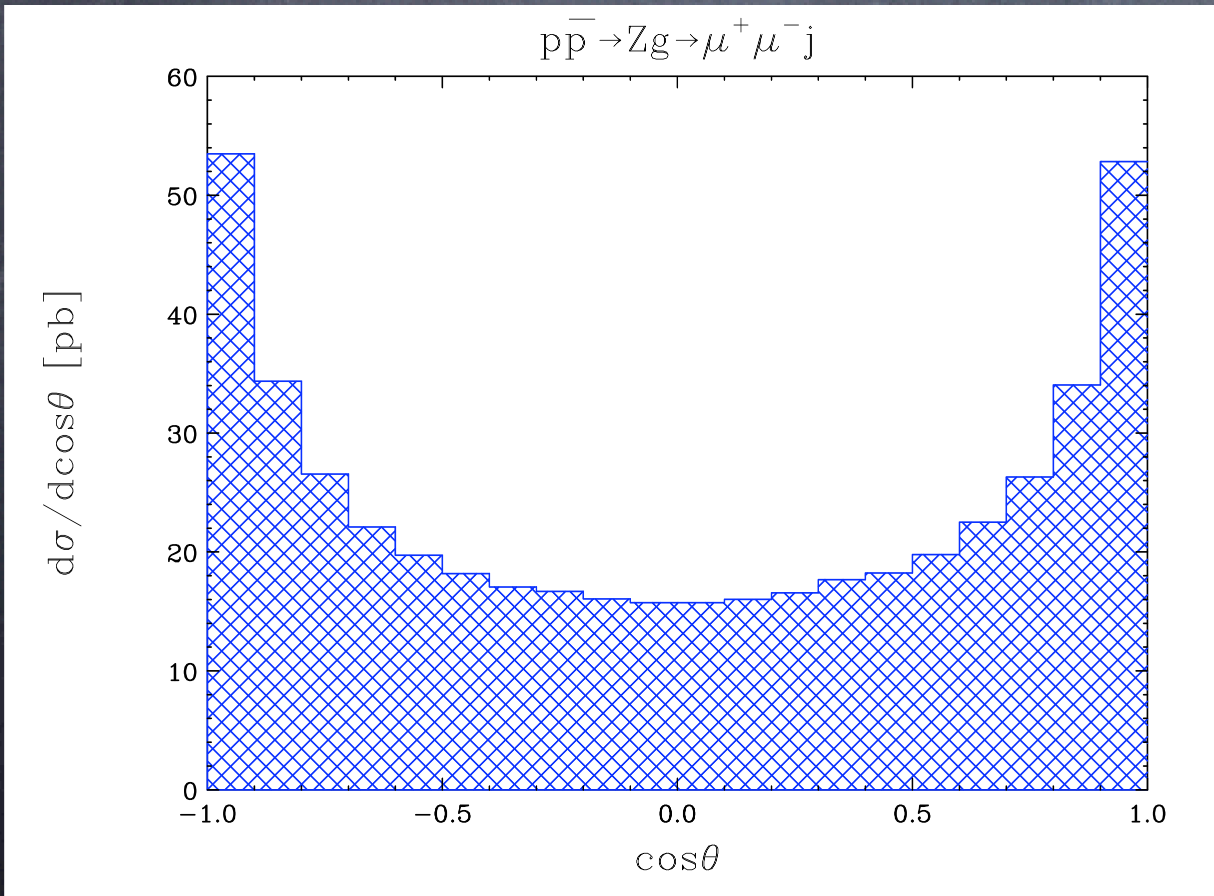
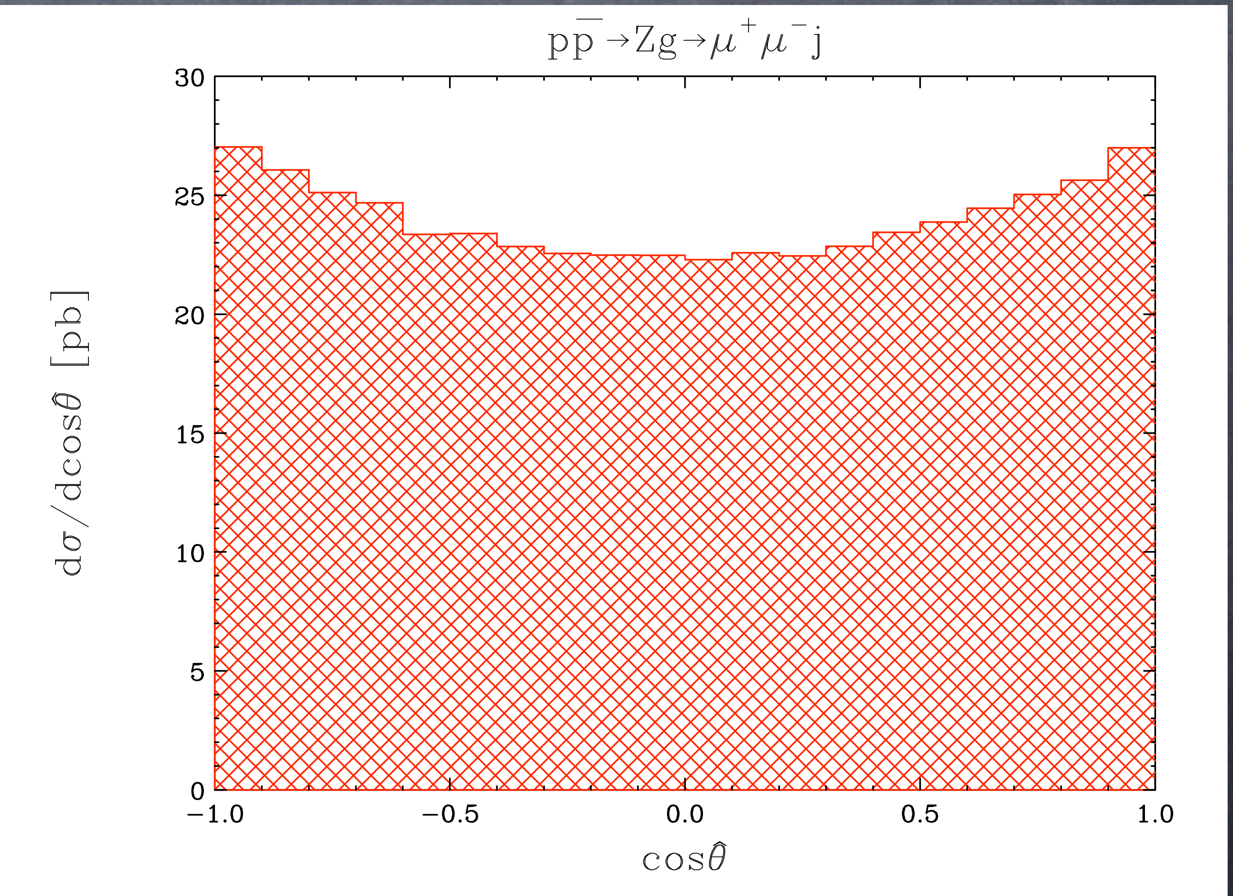


Other distributions

- cos θ distribution of the production shows t- and u-channel process, no spin information
- cos $\hat{\theta}$ distribution of the decay does not show a big spin effect because the process is primarily near threshold





Practicalities

acceptance cuts

- actual experimental data always suffer from acceptance cuts because of the geometry of the detector
- In addition, background also forces us to place additional cuts
- They tend to destroy the needed rotational invariance

Applications

(with M. Buckley, W. Klemm, and B.Heinemann)

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- $\sigma = 7 \text{ pb}$ with
  $p_{T\text{jet}} > 30 \text{ GeV}, \ |\eta_\text{jet}| < 2.1$
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- $1.7(8.0) \text{ fb}^{-1}$ total luminosity

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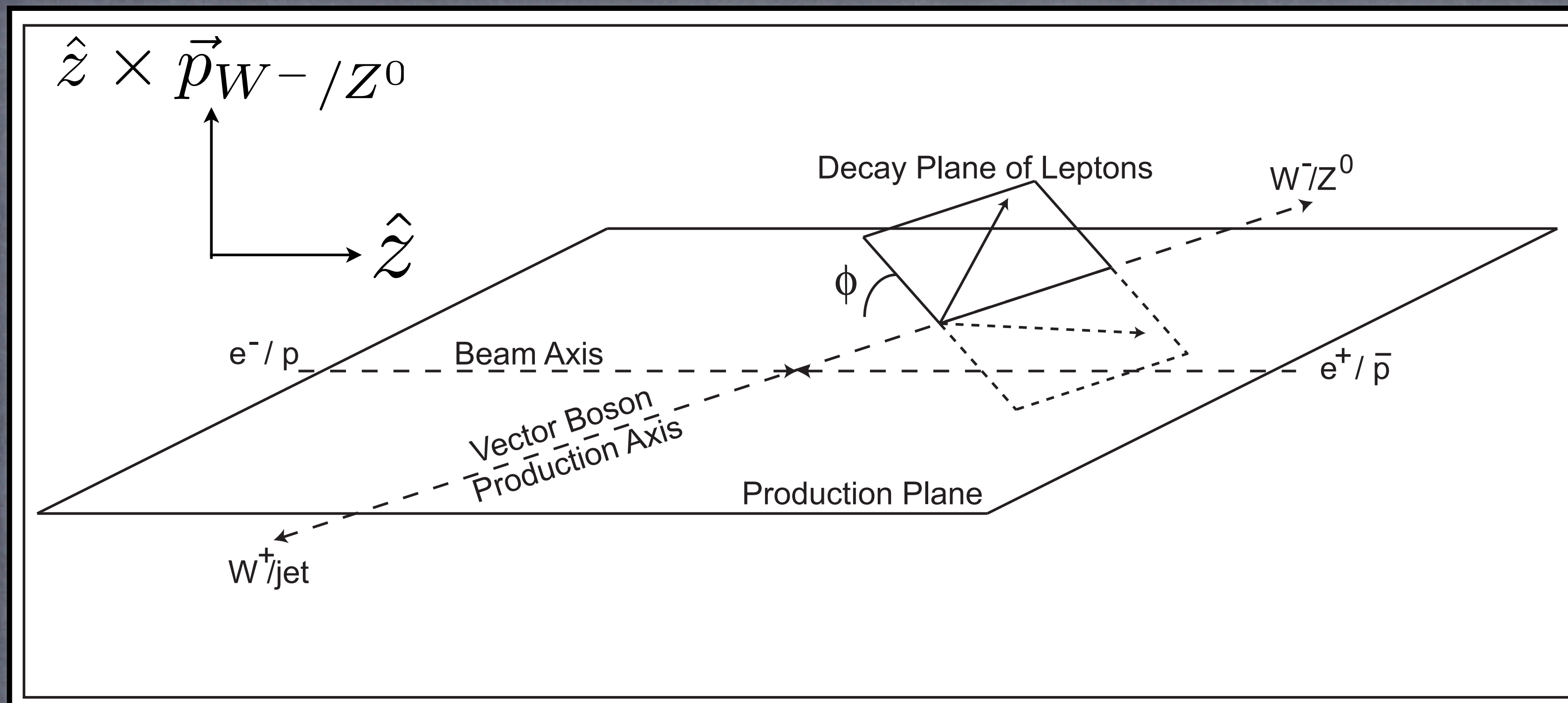
In both cases, expect non-zero

$$A_0, A_1, A_2$$

Kinematics



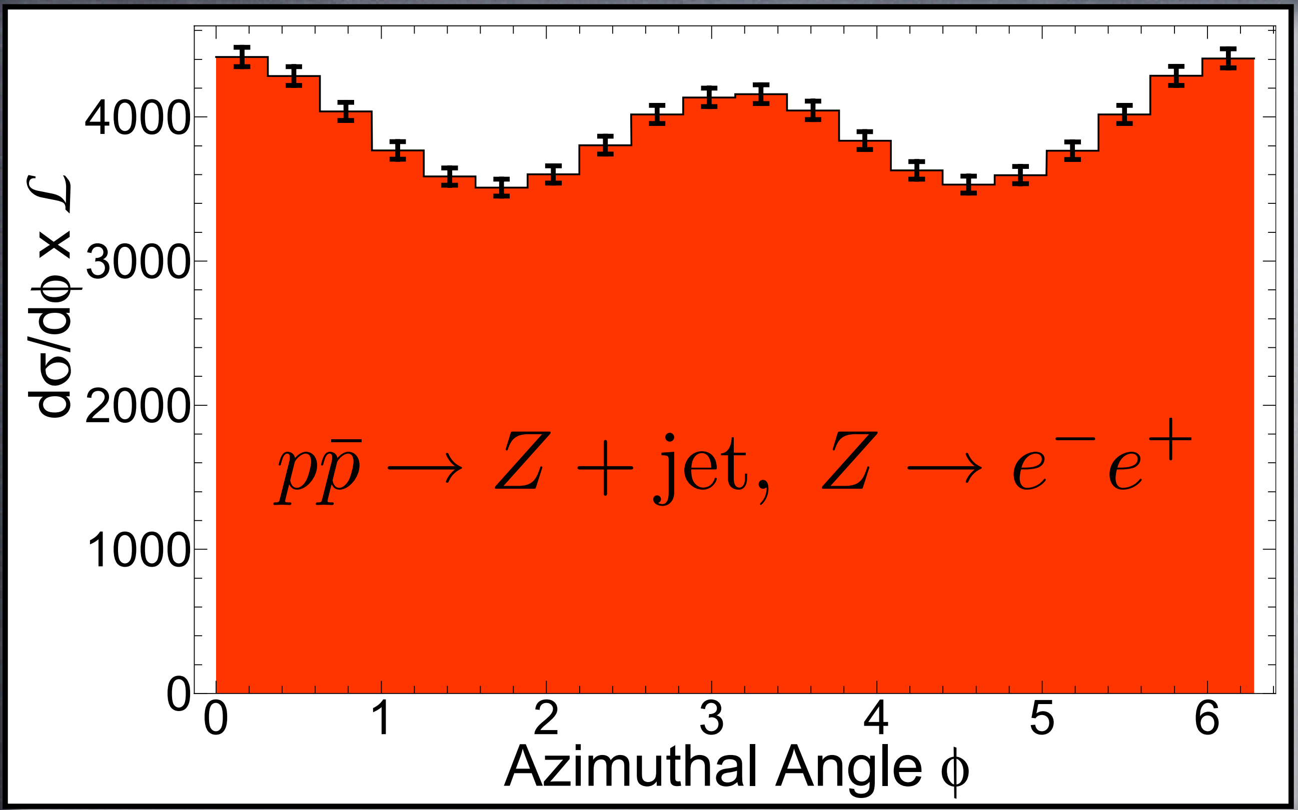
$$\cos\phi = \frac{\hat{z} \times \vec{p}_{W^\pm/Z^0}}{|\hat{z} \times \vec{p}_{W^\pm/Z^0}|} \times \frac{\vec{p}_{W^\pm/Z^0} \times \vec{p}_{\ell^\pm/e^-}}{|\vec{p}_{W^\pm/Z^0} \times \vec{p}_{\ell^\pm/e^-}|}$$

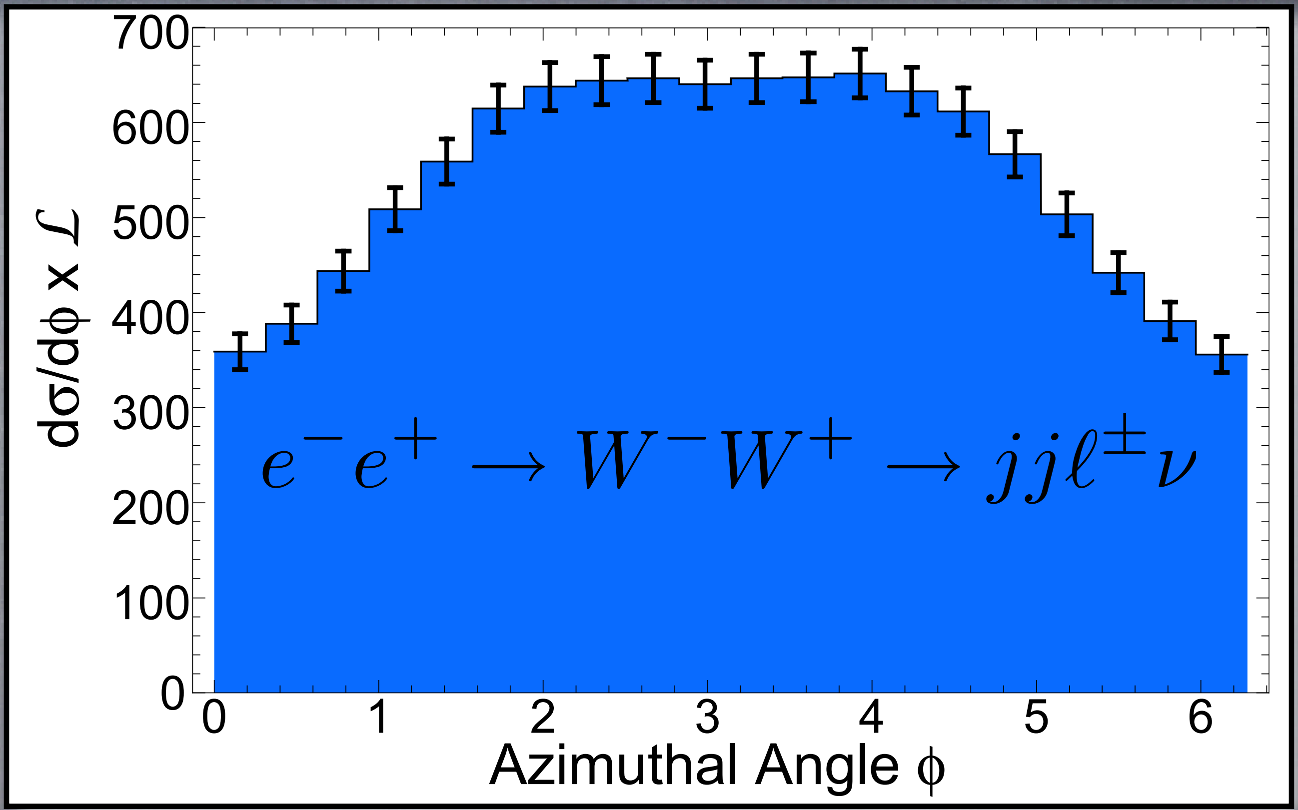
Define positive ϕ to be in the direction of

$\hat{z} \times \vec{p}_{W^\pm/Z^0}$

Results

- Calculated cross sections using HELAS and the adaptive Monte-Carlo program BASES.
- With only cuts on jet $p_T,\ \eta$ for Tevatron data, and no cuts on LEP-II:



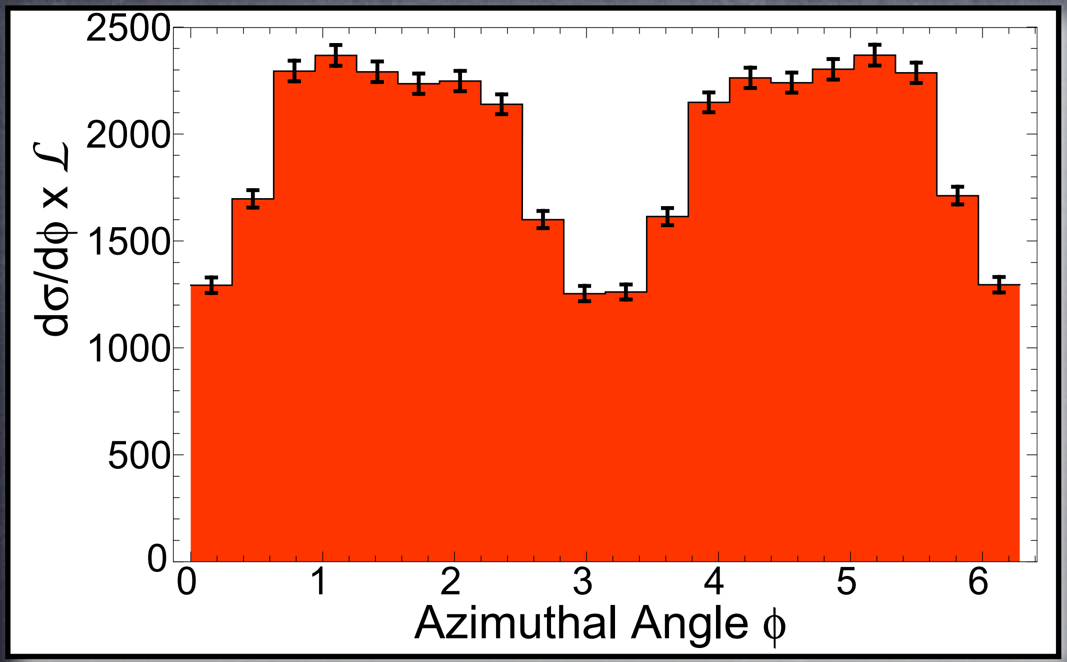


Effects of Cuts

- However, detectors cannot see forward regions, and need isolation cuts on jets/leptons.

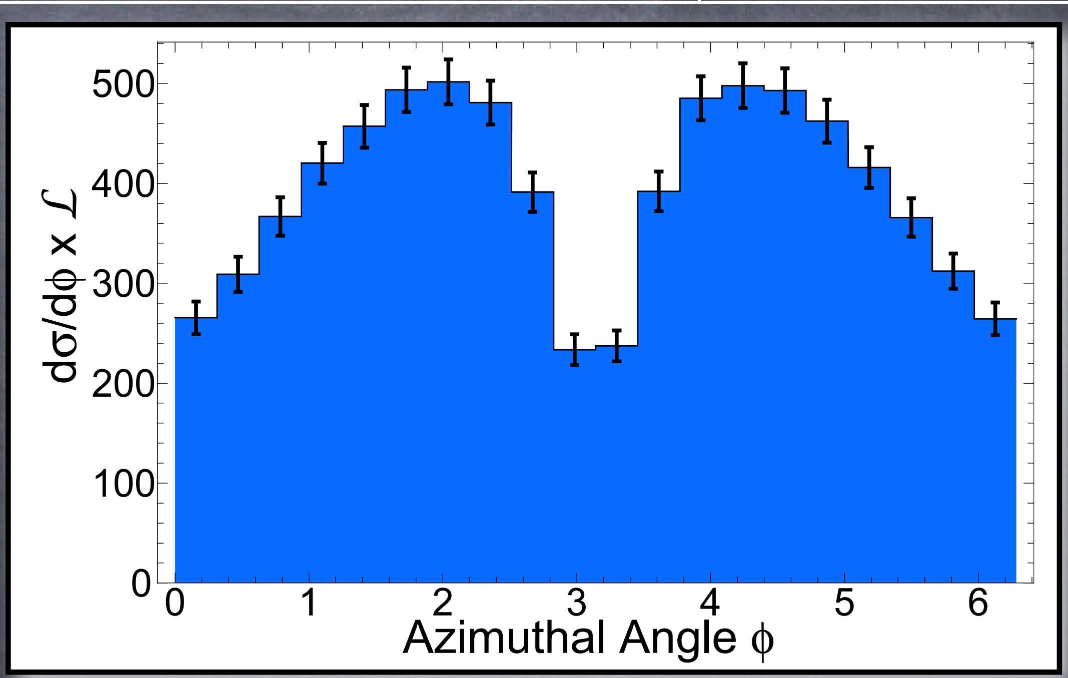
CDF cuts:

Jet transverse momentum	$p_{T,j} > 30$ GeV
Jet η	$\|\eta\| < 2.1$
Invariant mass of lepton pair	$66 < m_{\ell\ell} < 116$
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	$\Delta R_{e-j} > 0.7$



OPAL cuts:

Lepton momentum	$p_\ell > 25$ GeV
Polar angle θ of final state particles	$\|\cos\theta\| < 0.95$
Neutrino energy fraction	$R_\nu > 0.07$
Visible energy fraction	$R_{\text{vis}} > 0.3$
Neutrino transverse momentum	$p_{T,\nu} > 16$ GeV
Lepton isolation	$\Delta R > 0.75, 0.5, 0.2$



Rotational Invariance

- Cuts introduce new directional dependences.
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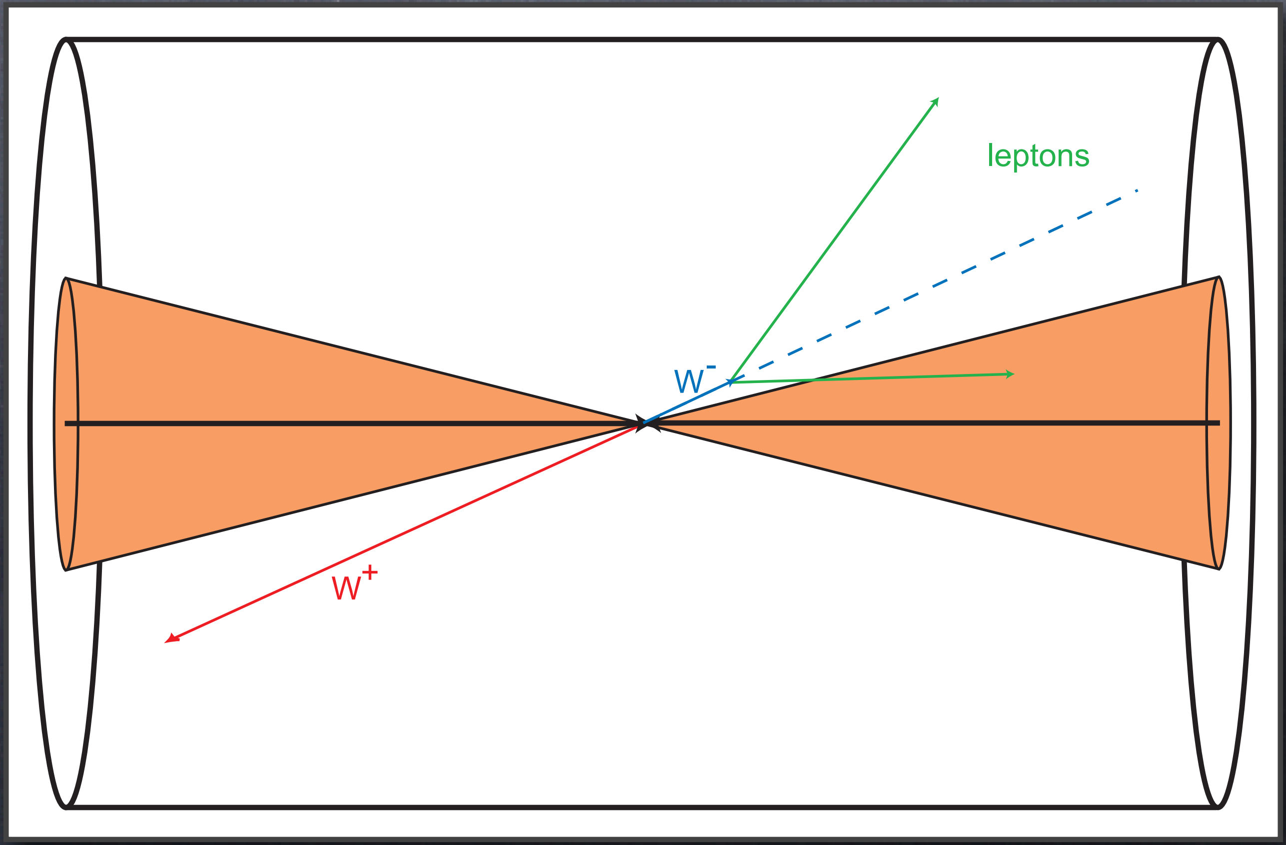

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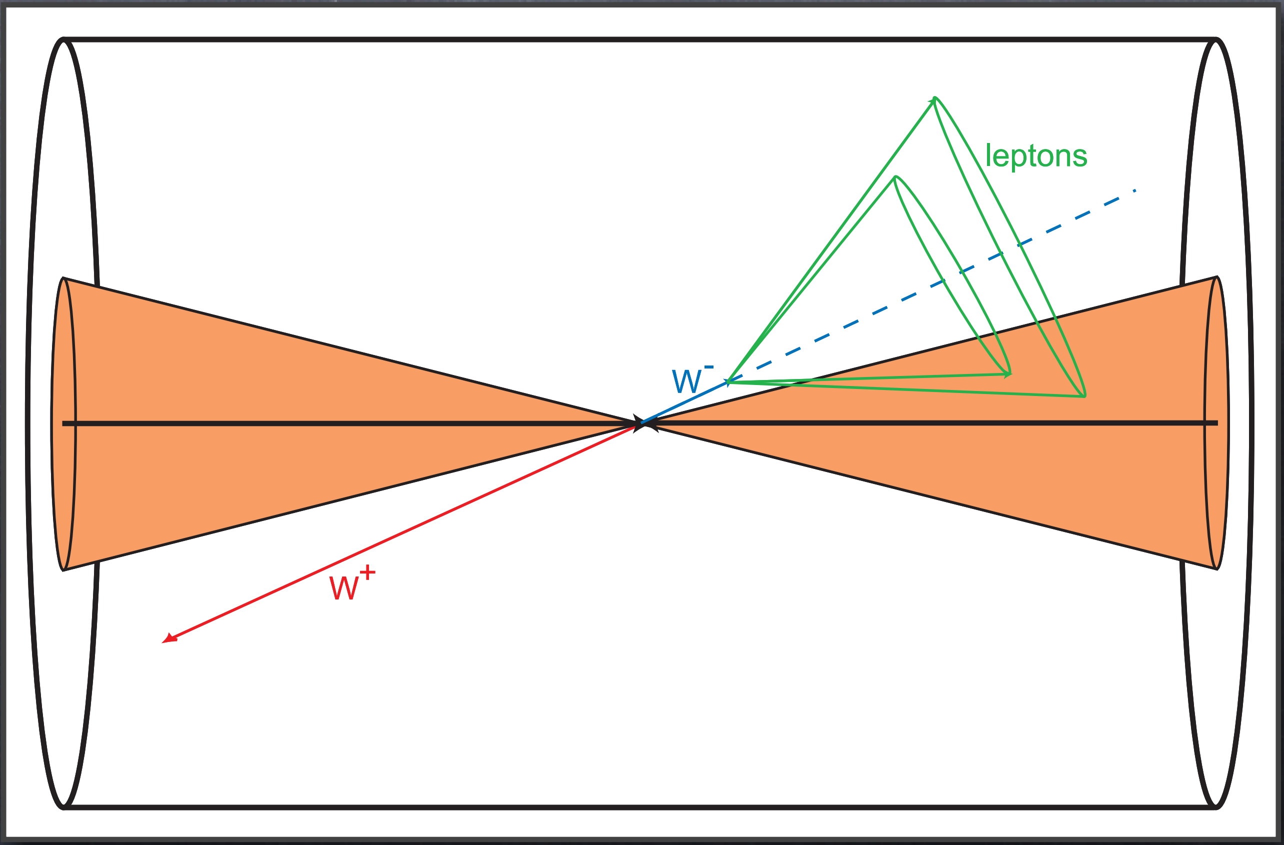
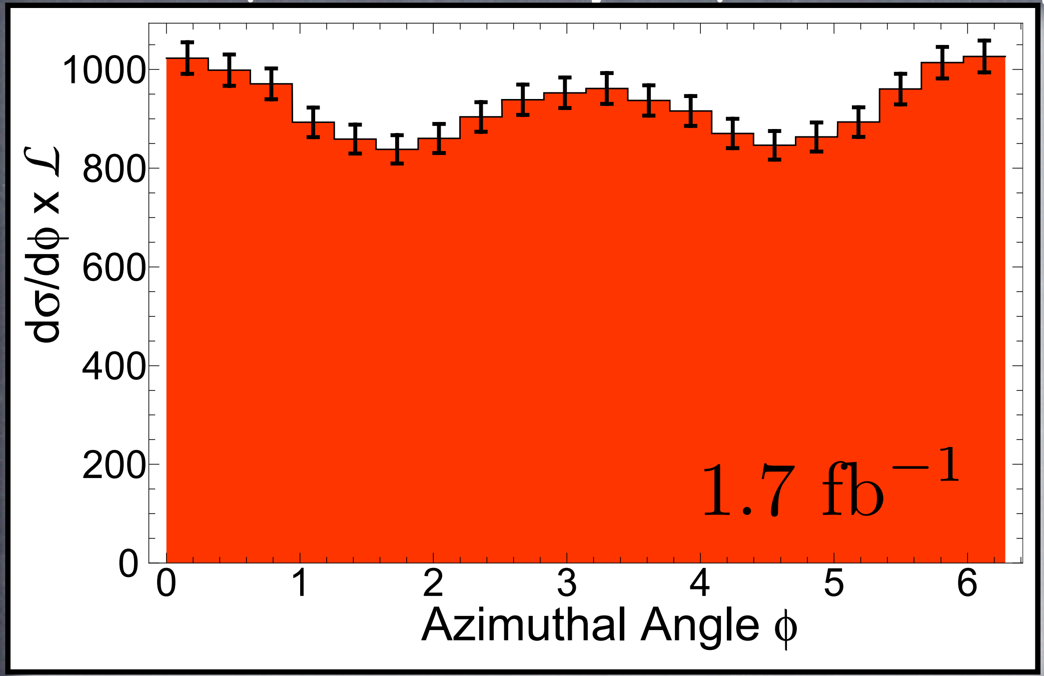
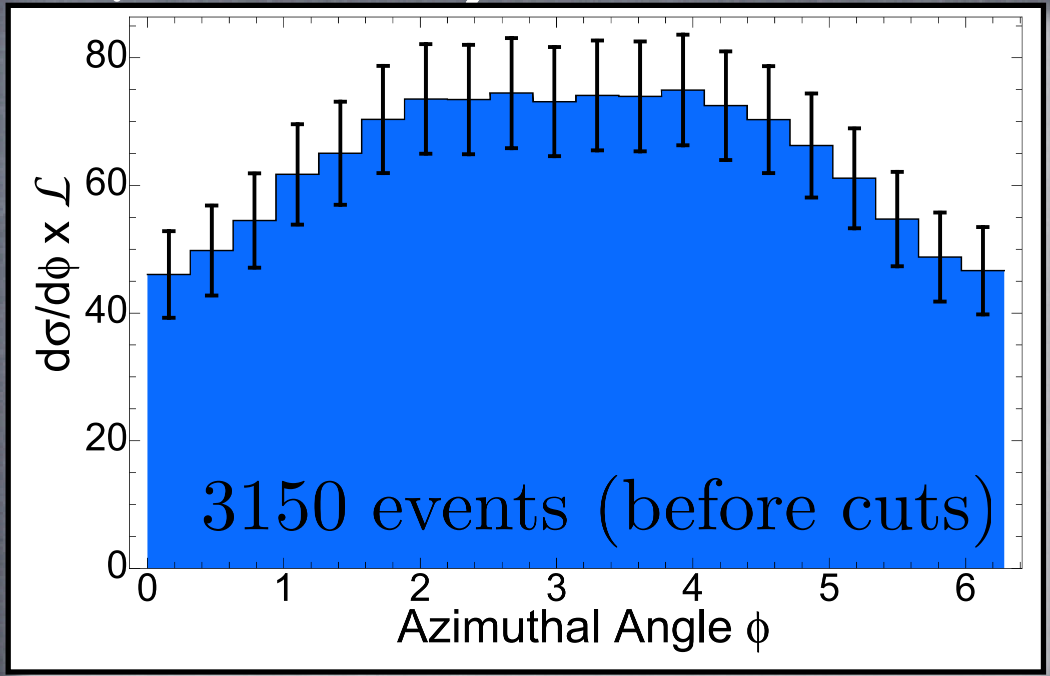


Rotationally Invariant Cuts

- Applying these rotationally invariant cuts (with looser acceptances at Tevatron: $E_T>20$GeV, $E_T>10$GeV, $|\eta|<2.6$; BG<5%)

$\Delta R=0.75$





A_1/A_0	0.040 ± 0.023
A_2/A_0	0.082 ± 0.023
A_3/A_0	0.000 ± 0.023
A_4/A_0	0.000 ± 0.024

A_1/A_0	-0.219 ± 0.063
A_2/A_0	-0.063 ± 0.063
A_3/A_0	0.000 ± 0.078
A_4/A_0	0.000 ± 0.078

LEP-II Efficiencies

- OPAL uses energy deposition cuts to isolate leptons
  - We used ΔR cuts with lower efficiencies.
  - Higher efficiency $\rightarrow$ better statistics
  - Using $\Delta R = 0$, $\epsilon \sim 90\%$ (non-rotational cuts)
    $\epsilon \sim 15\%$ (rotational cuts)
- Combine ALEPH, L3, DELPHI, OPAL:

  ΔR=0.2

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A_1/A_0	-0.211 ± 0.050
A_2/A_0	-0.081 ± 0.049
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A_1/A_0	-0.211 ± 0.025
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A_4/A_0	0.000 ± 0.029

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- effect particularly strong near threshold (good news for future hadron collider!)
- seeing $\cos(n\phi)$ dependence implies spin$\geq n/2$
- works well if fully reconstructible

Challenges

Partially Reconstructable

- Many solutions to Hierarchy problem contain a weakly coupled, stable massive particle.
  - Ex: $\tilde{\chi}_1^0$ in SUSY, B_1 in UED
  - The symmetry which makes these good DM candidates also means they are pair-produced
- Pair-production followed by single decay
  - Cannot fully reconstruct events due to 2 sources of missing momentum

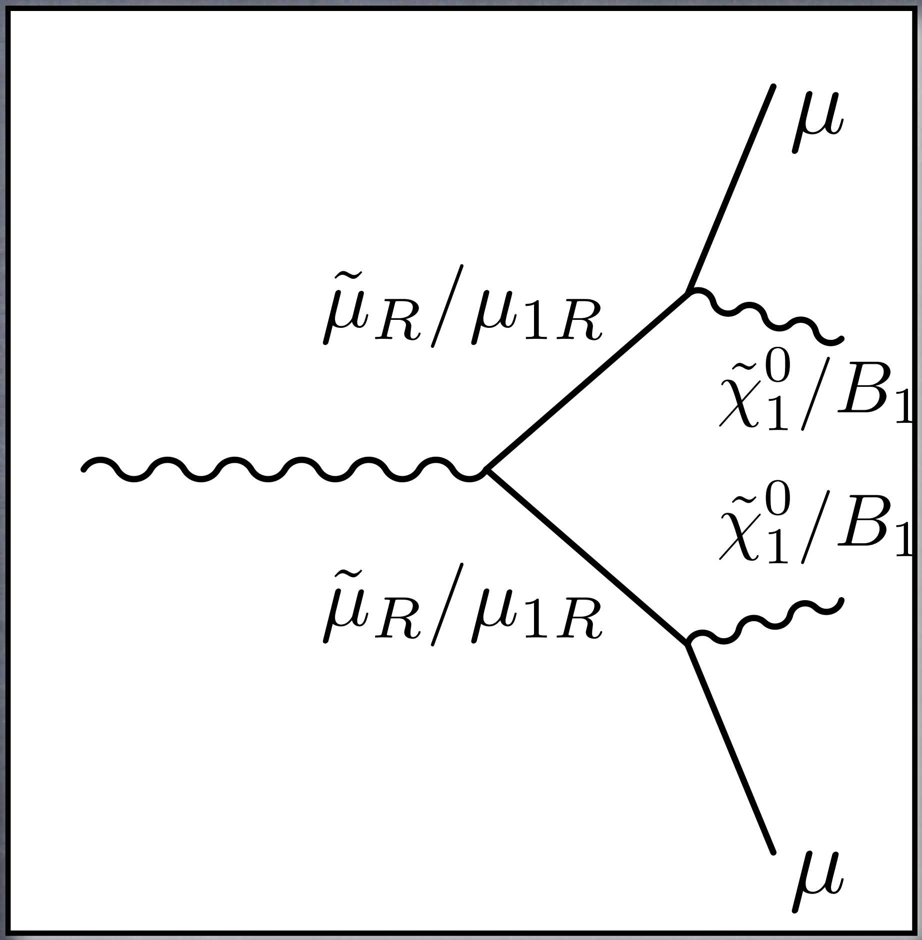
False Solutions

(with M. Buckley, S-Y. Choi, and K.Mawatari)

- If masses of μ/B partners are known:

  4+4 unknown momenta
  -4 measured $\not{p}$
  -4 mass relations

- System specified up to two-fold ambiguity



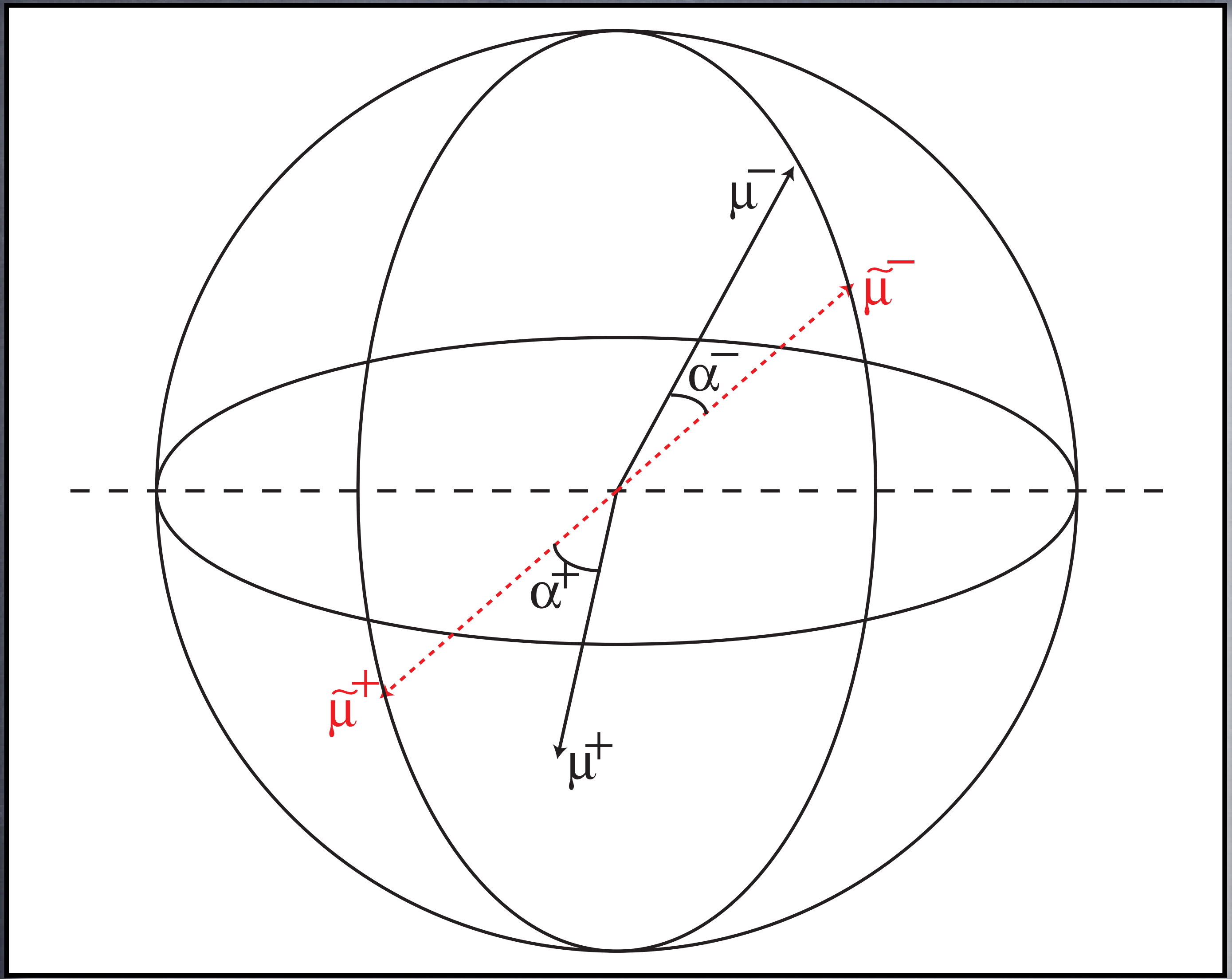
False Solutions

(with M. Buckley, W. Klemm, and V. Rentala)

- Plotting both true and false distribution gives spurious high-frequency noise in ϕ distributions
- ϕ_1, ϕ_2 are not observable, but $\Delta\phi$ is.

Scalar decay:

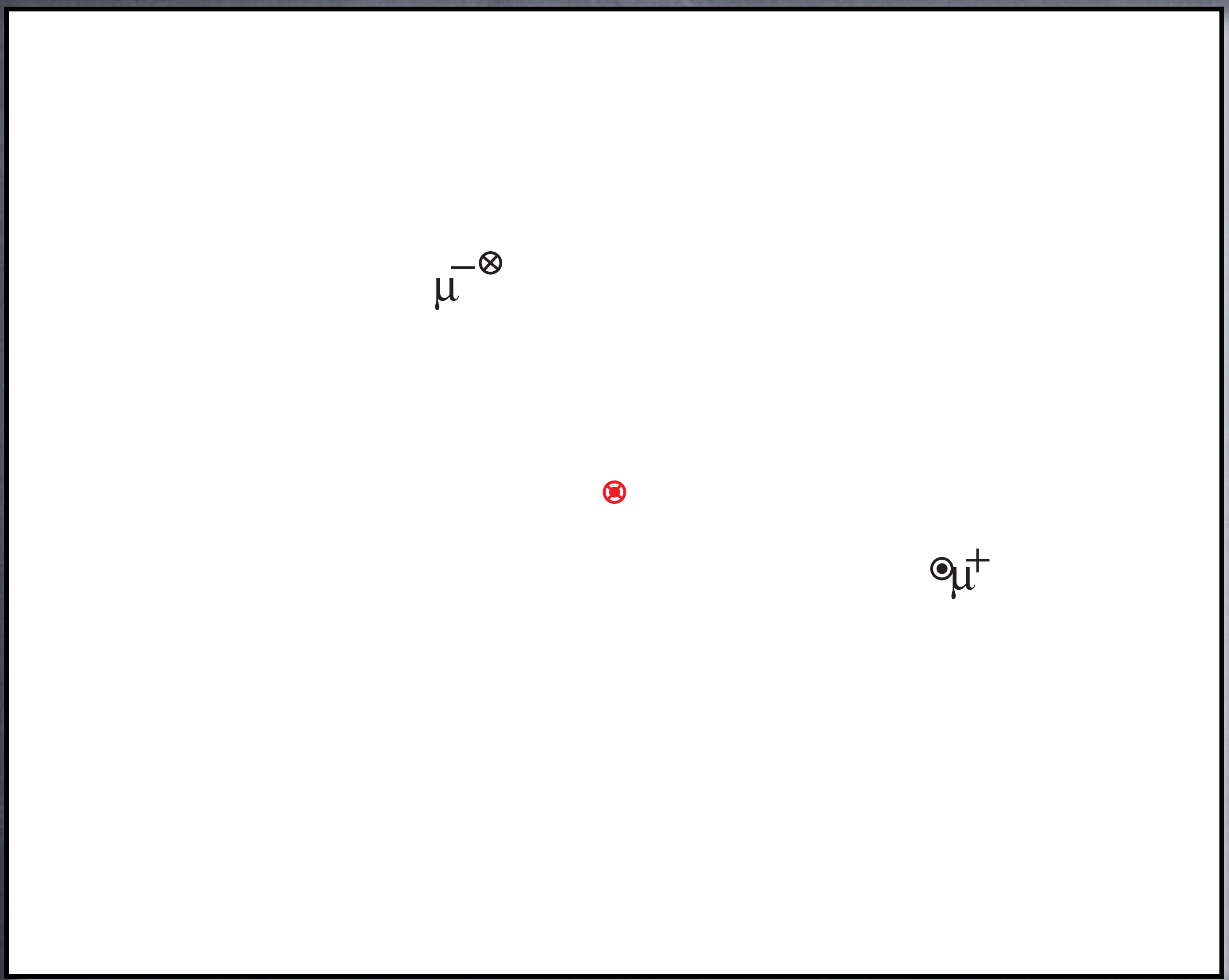
$\Delta\phi$



Opening angles $\alpha^{\pm}$ defined by

$$m^2_{\tilde{\mu}^{\pm}} - m^2_{\tilde{\chi}} = \sqrt{s} E_{\tilde{\mu}^{\pm}} (1 - \beta_{\tilde{\mu}^{\pm}} \cos\alpha^{\pm})$$

$\Delta\phi$



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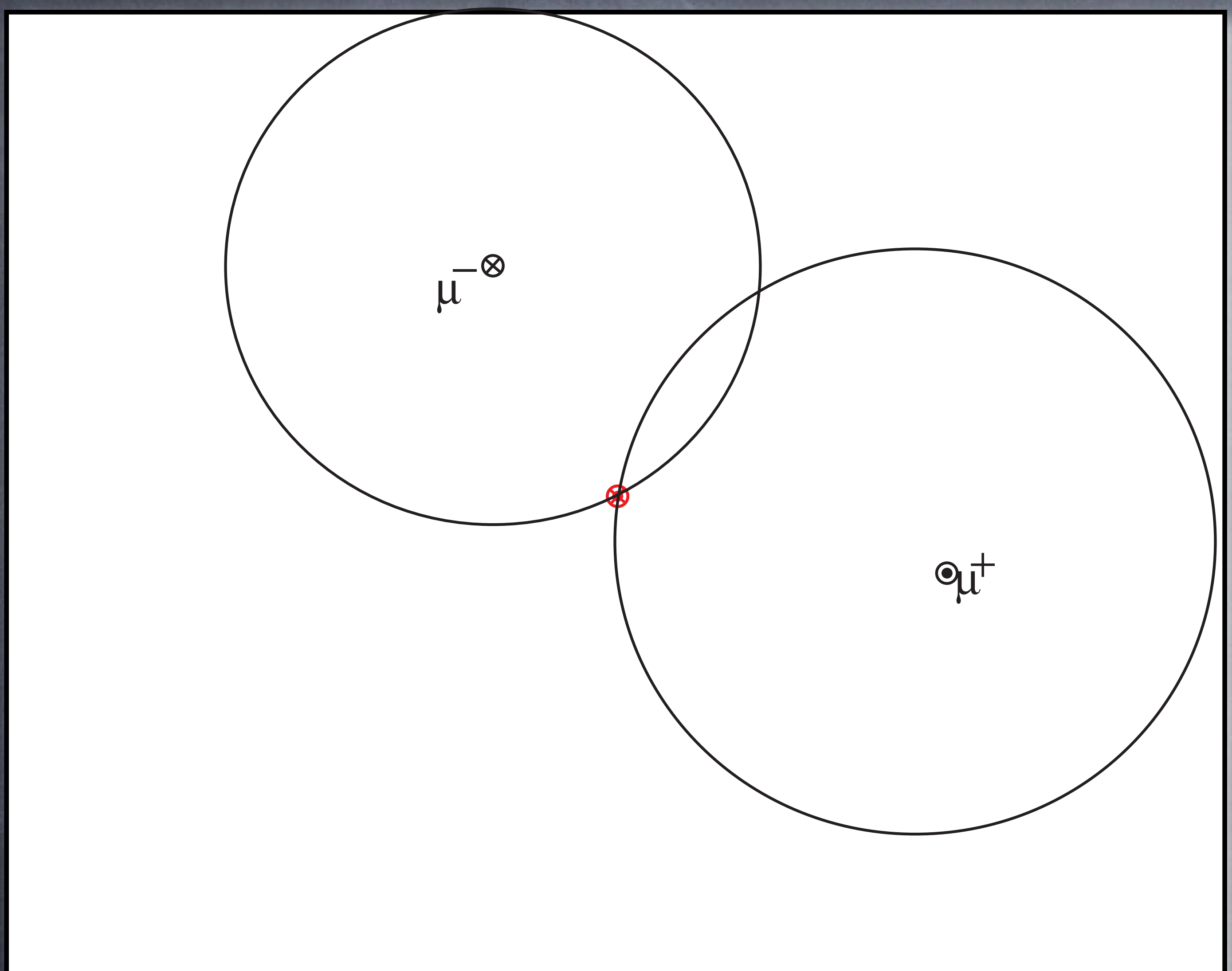

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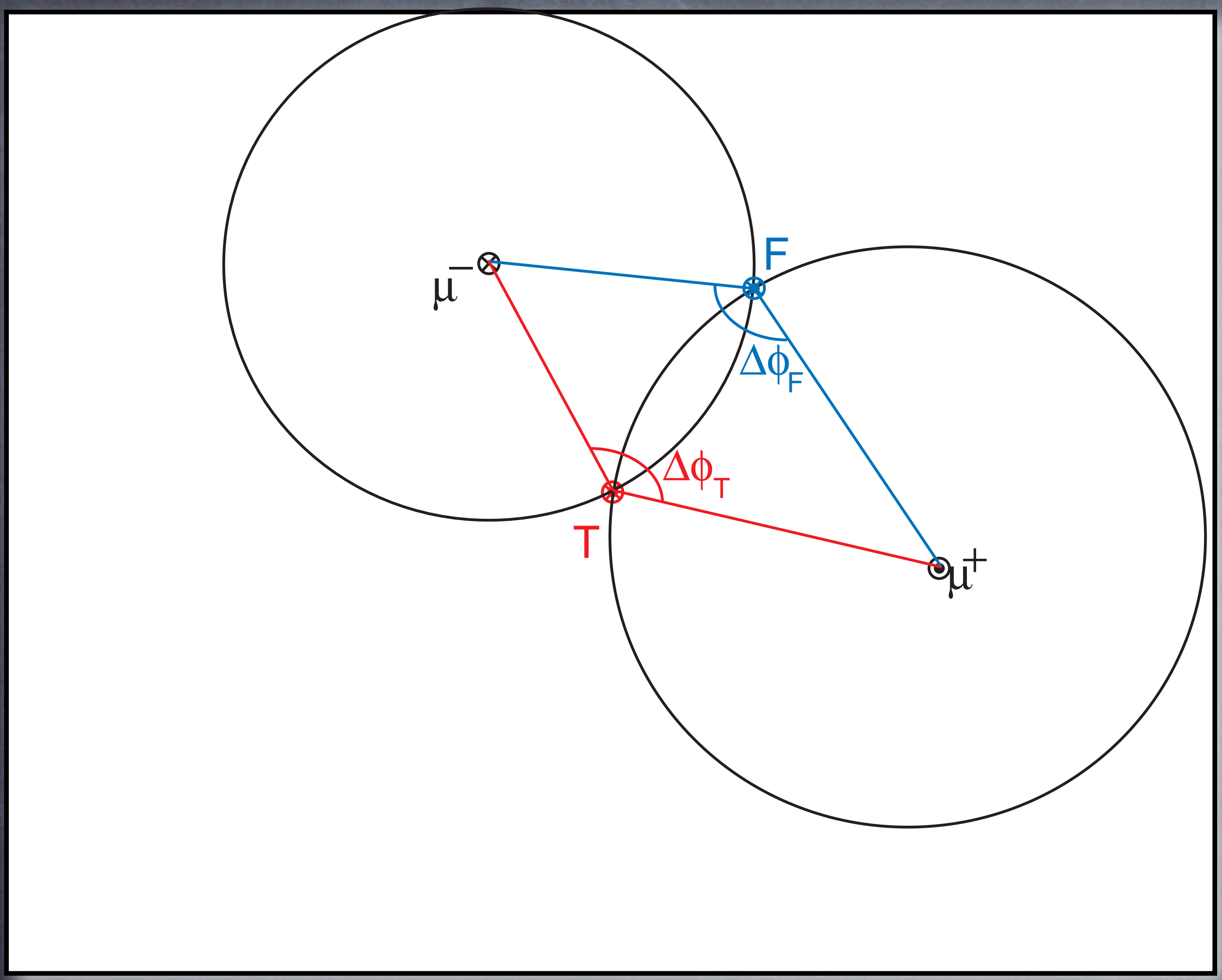

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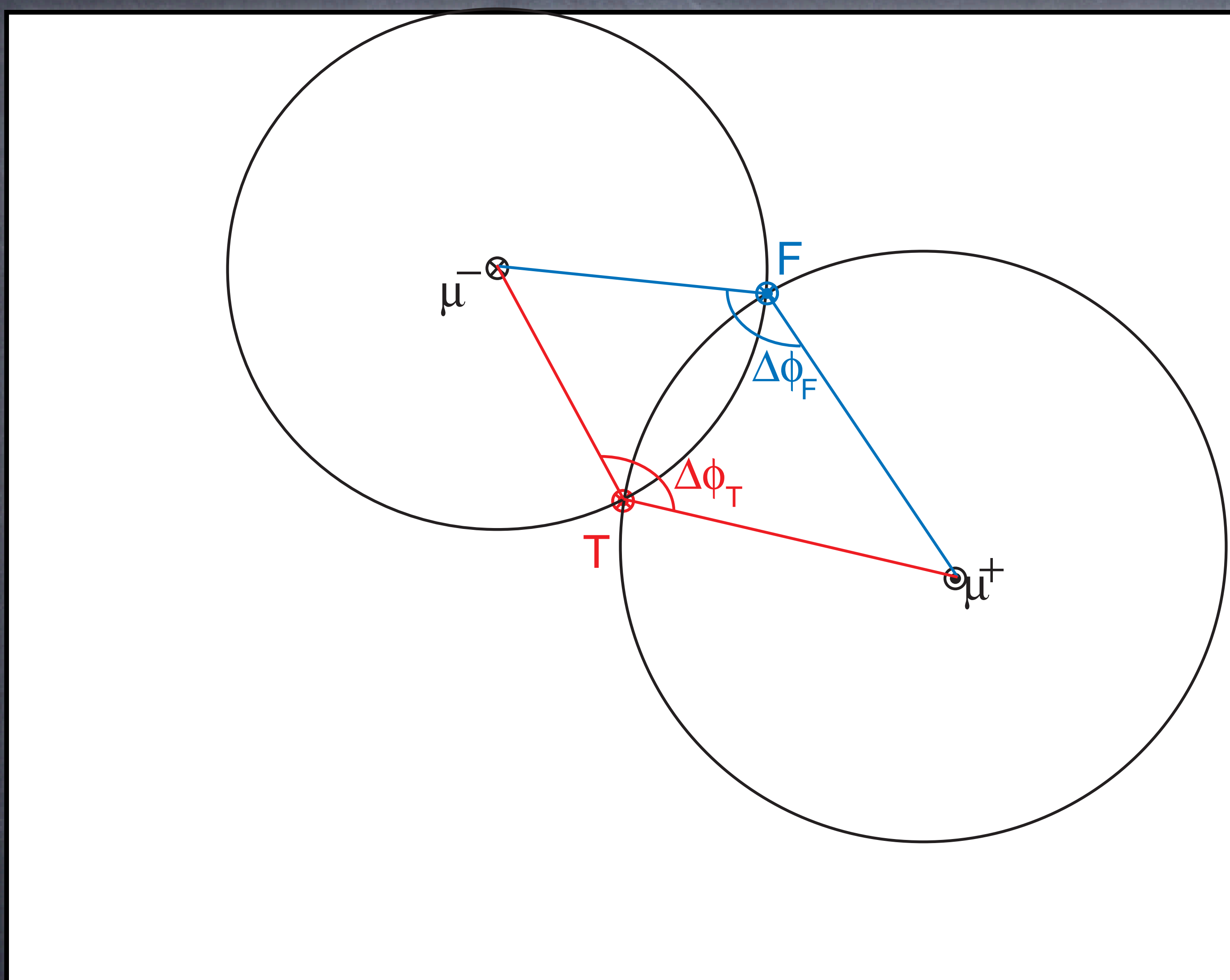

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$$m^2_{\tilde{\mu}^\pm} - m^2_{\tilde{\chi}} = \sqrt{s} E_{\tilde{\mu}^\pm} (1 - \beta_{\tilde{\mu}^\pm} \cos\alpha^\pm)$$

Straightforwardly,

$$\Delta\phi_T = \Delta\phi_F$$

Since interference argument only needs some reference plane,

we expect same expansion in $\cos n\phi$ and $\cos n\Delta\phi$

Spin at the ILC

- Consider pair production of μ -partners ($\tilde{\mu}, \mu_1$) decaying to μ 's and missing energy ($\tilde{\chi}_1^0, B_1$)
  - Couplings assumed to be those of MSSM/ Minimal Universal Extra Dimensions

- MUED:
  - Single extra dimension of radius R compactified on S^1/Z_2
  - Flavor universal boundary terms set to zero at Λ

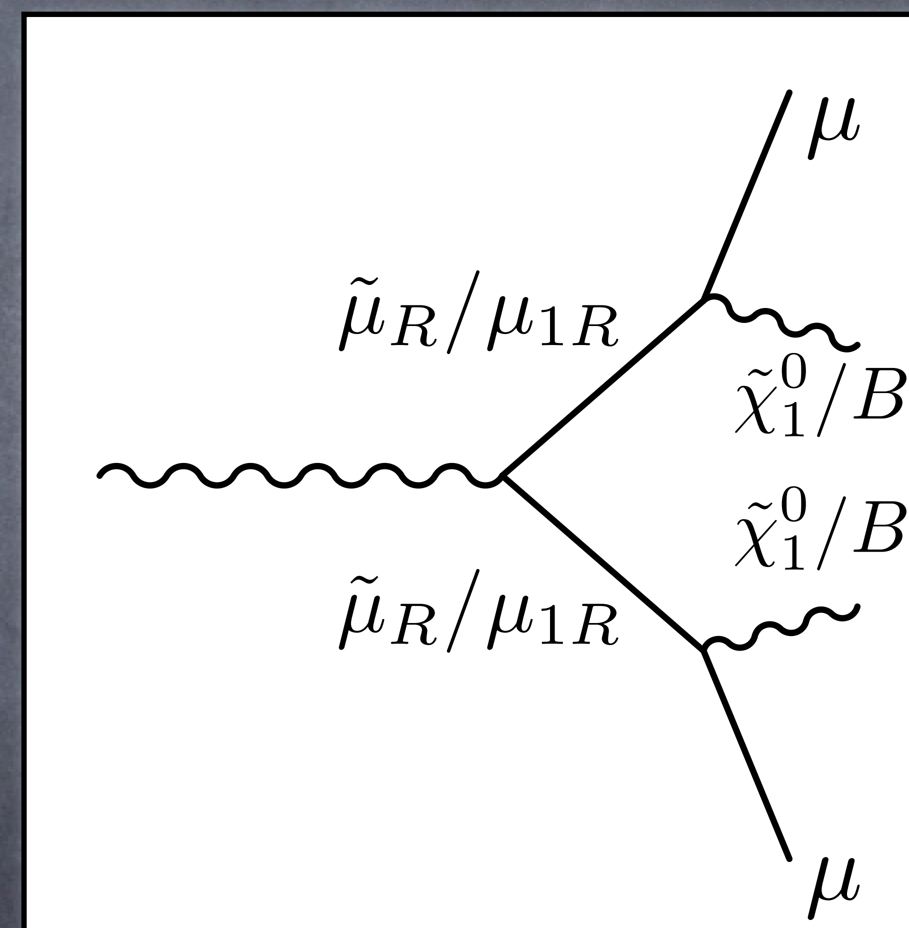
Spin at the ILC

- Choose:

$$m_{\tilde{\mu}^\pm} = m_{\mu 1} = 200 \text{ GeV}$$

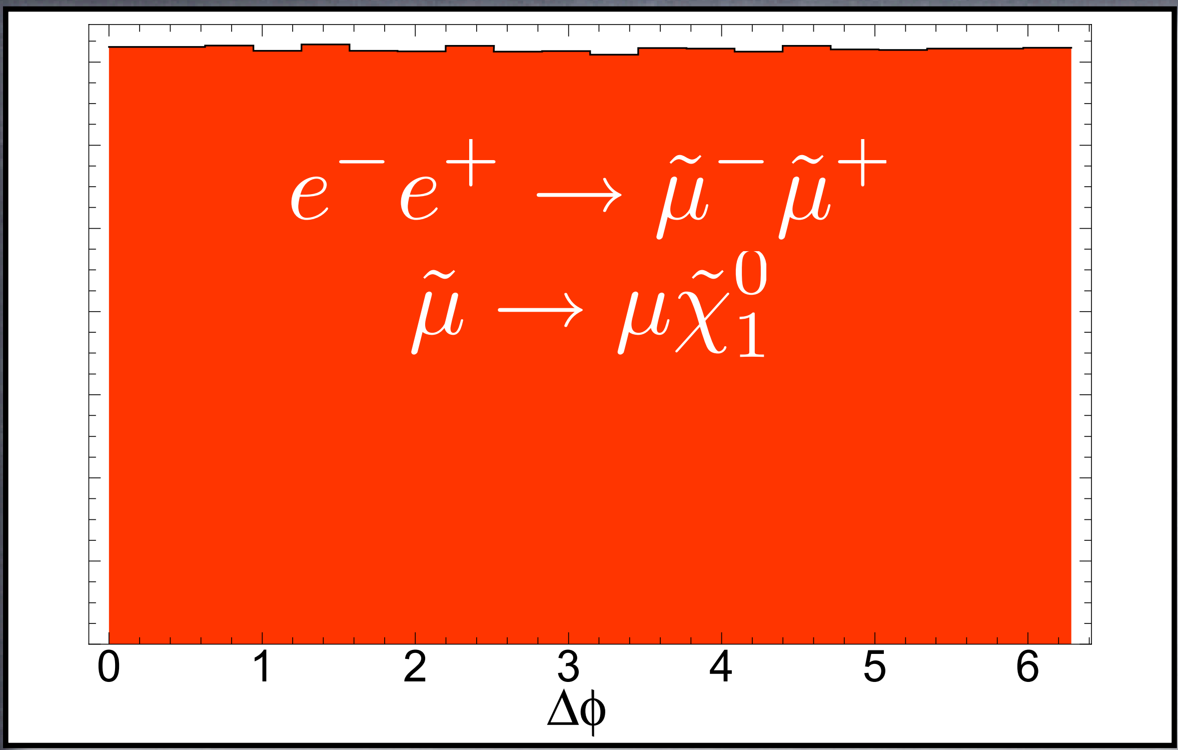
$$m_{\tilde{\chi}_1^0} = m_{B_1} = 50 \text{ GeV}$$

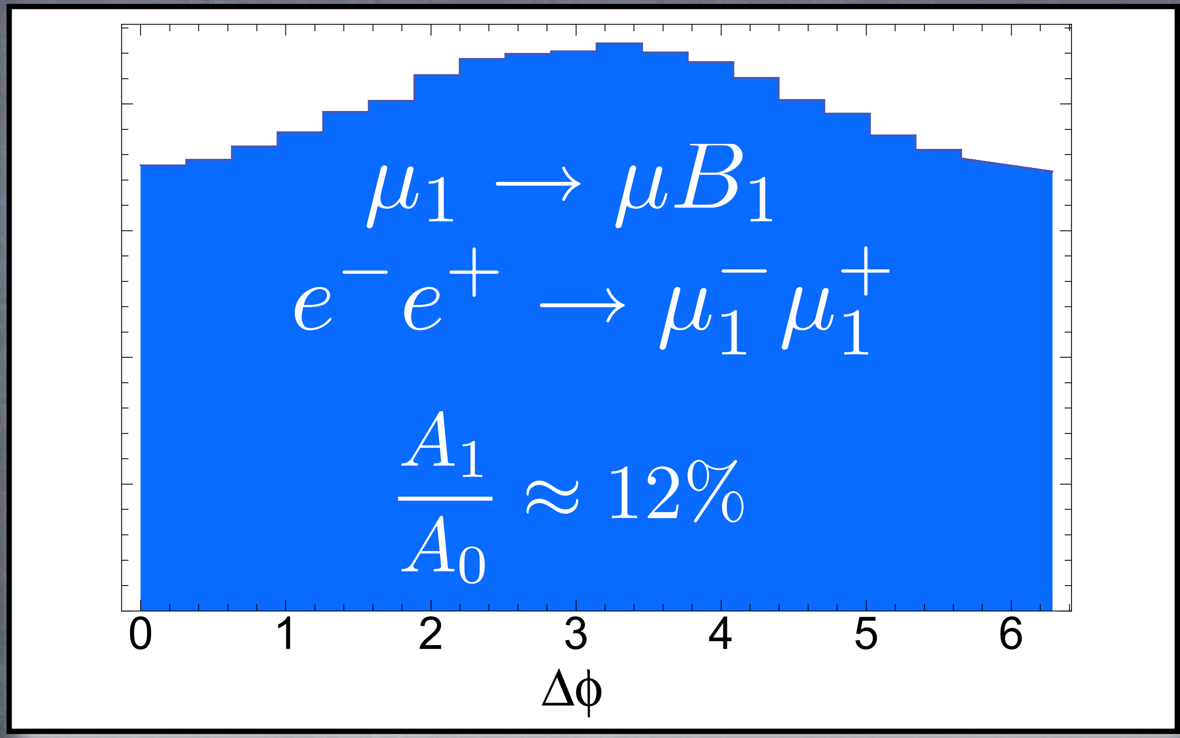
$$\sqrt{s} = 410 \text{ GeV}$$



Spin at the ILC

- Fit to $A_0 + A_1 \cos\phi + \cdots + A_4 \cos 4\phi$



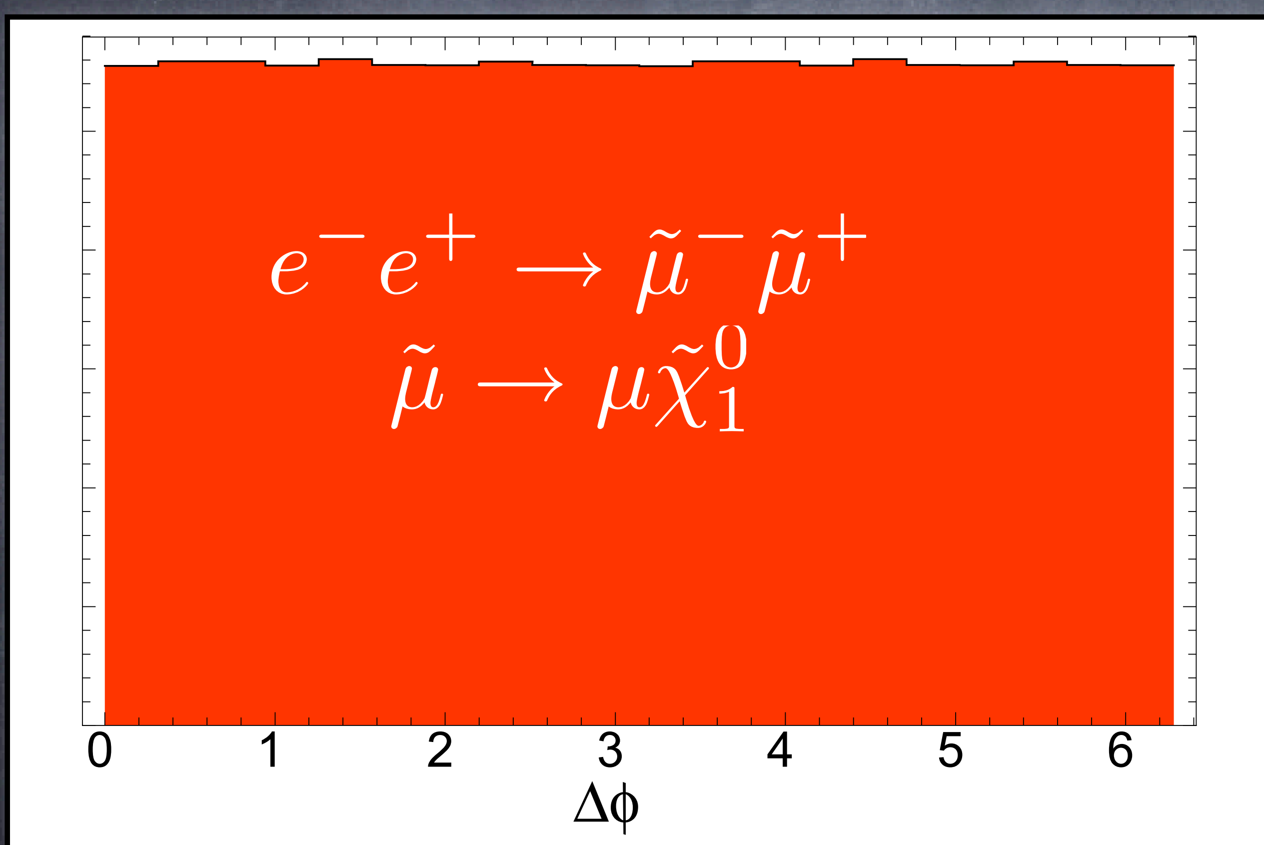


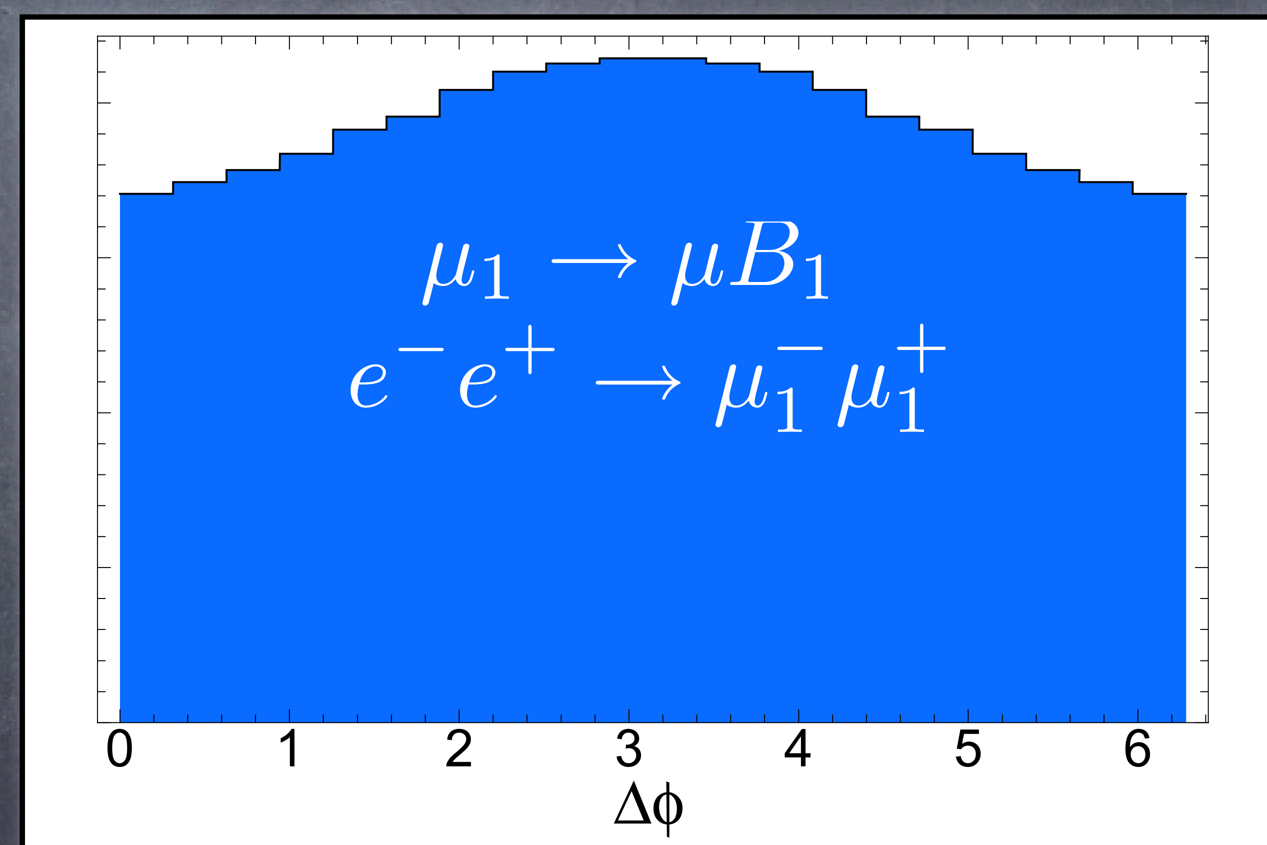
- For $m_{\tilde{\mu}^\pm/\mu_1} = 200$ GeV, $m_{\tilde{\chi}^0_1/B_1} = 100$ GeV, $\sqrt{s} = 405$ GeV

$$\frac{A_1}{A_0} \approx 5\%$$

Effects of Cuts

- Apply cuts on visible μ's and $\not{p}$: $|\eta| < 2.5$
- We find that these cuts do not introduce large spurious high-frequency modes



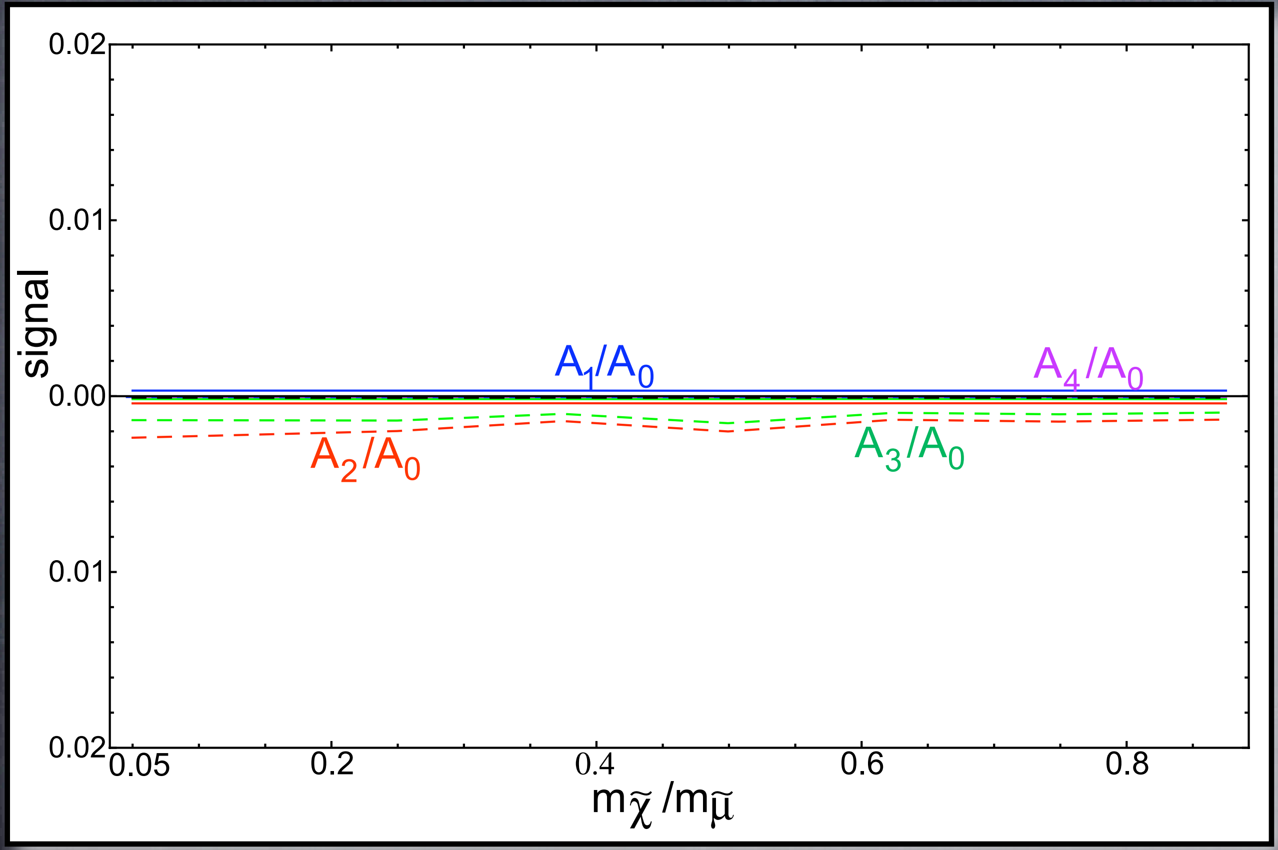


Effects of Cuts

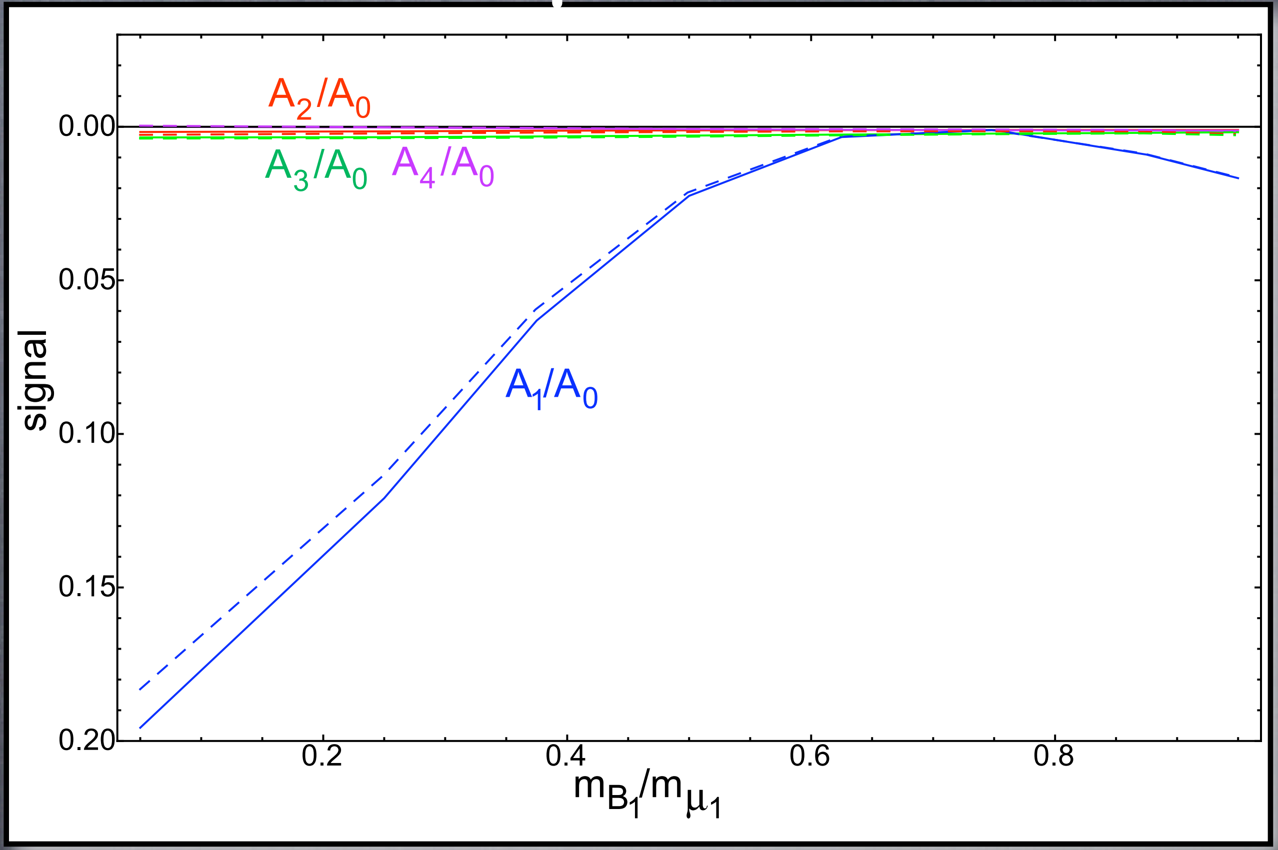
solid lines no cuts

dashed lines $|\eta| < 2.5$

Scalar



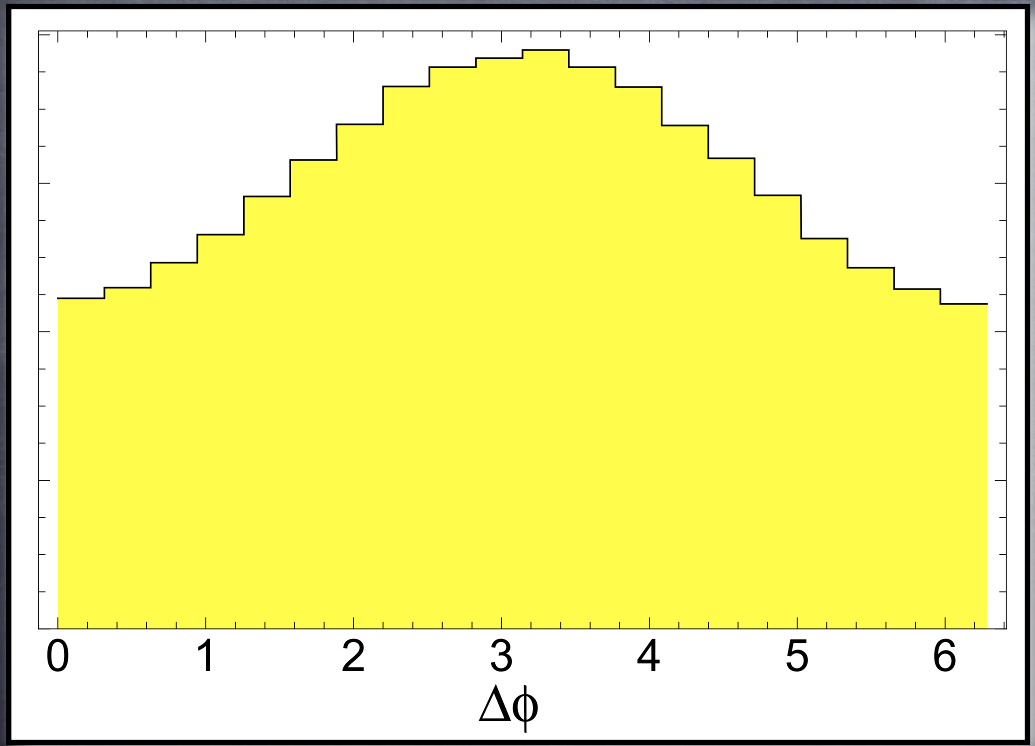
Spinor

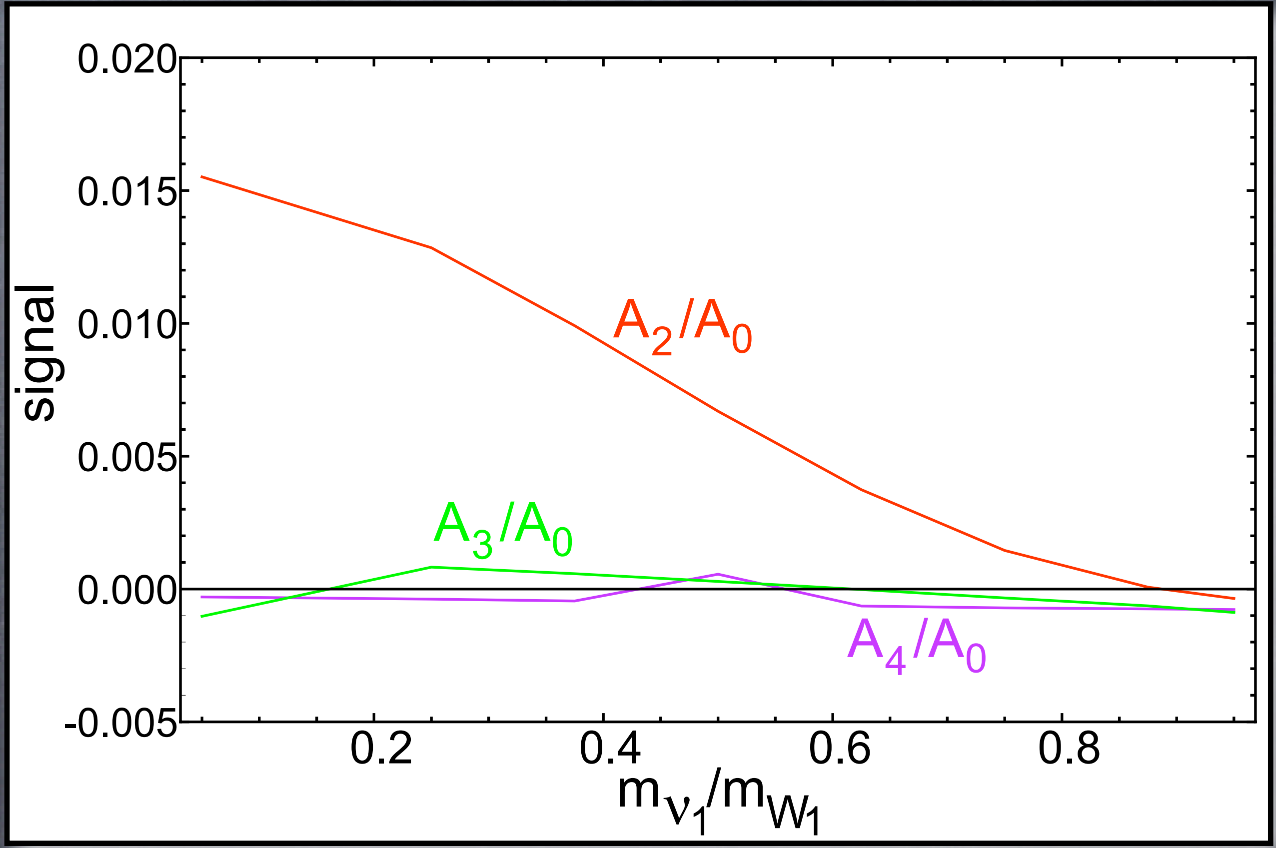


Higher Spin

$$e^- e^+ \to W_1^+ W_1^-, W^\pm \to \ell^\pm \nu_1$$

- $\cos 2\Delta\phi$ is present, but A_2/A_0 typically $1-2\%$
- Measurement possible, but would require high statistics $\sqrt{s} = 405$ GeV $\quad m_{W_1^\pm} = 200$ GeV





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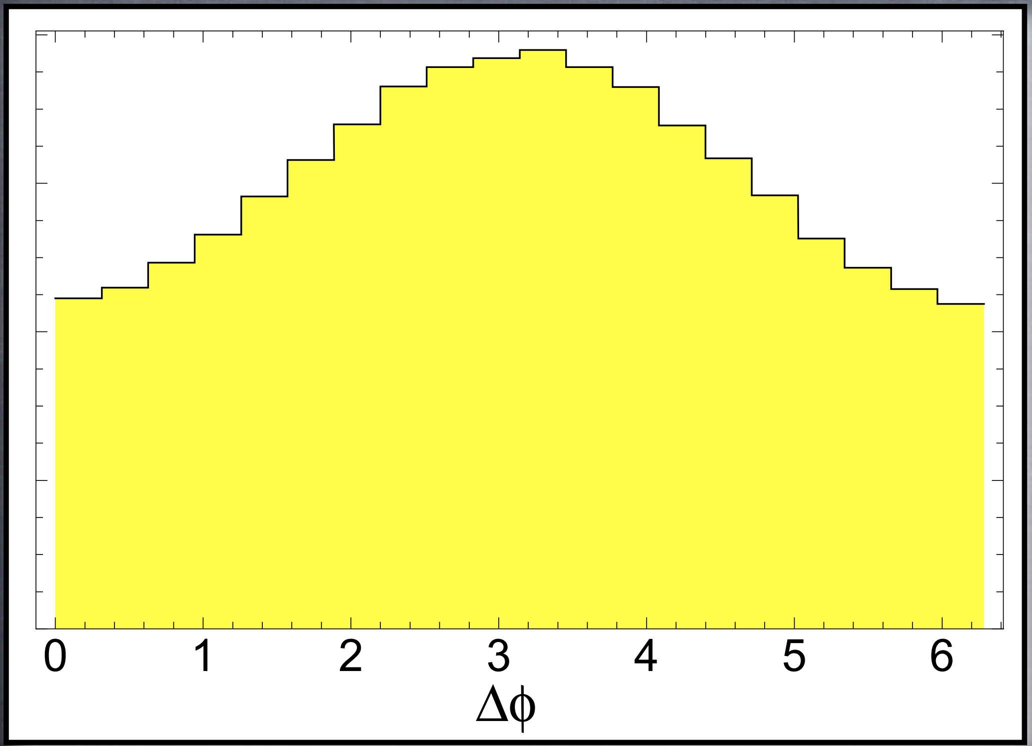
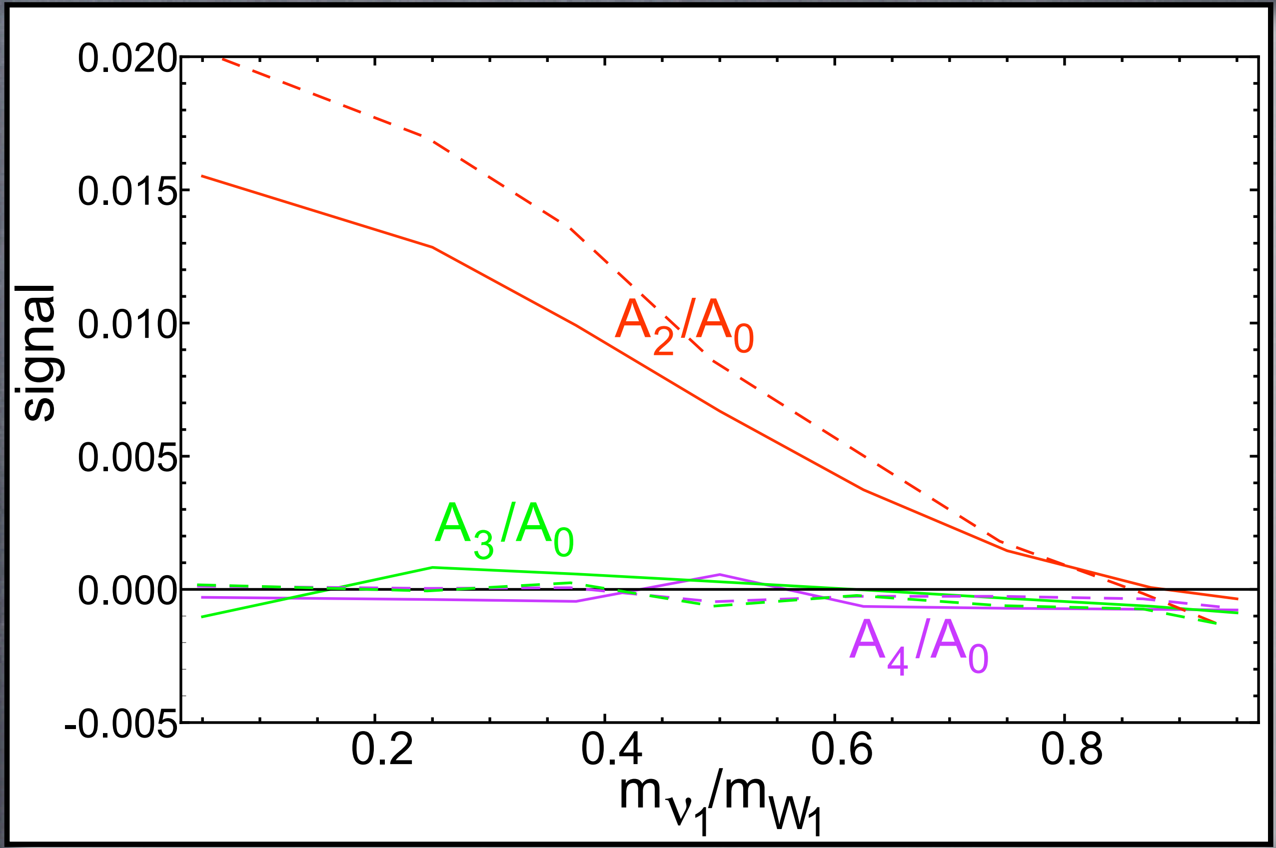


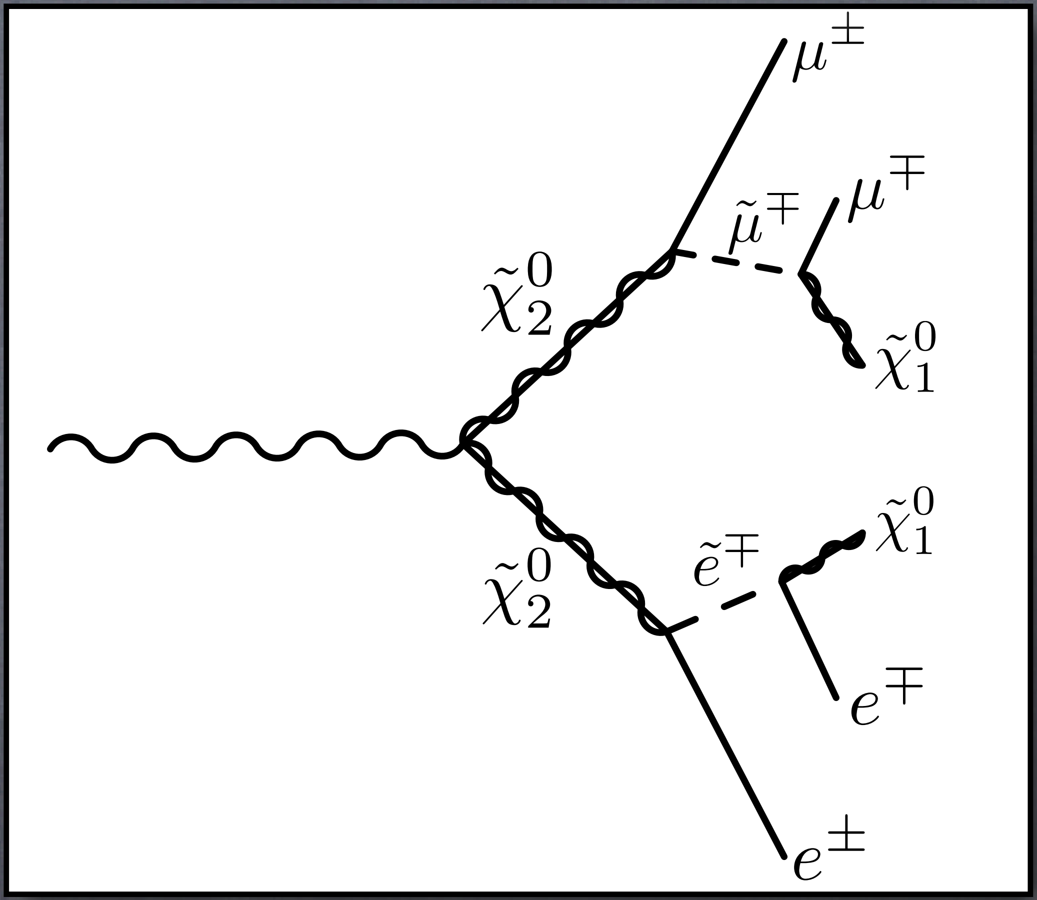


Fully Reconstructable Events

- Longer decay chains provide additional mass constraints.
  - All investigated possibilities at the ILC suffered from low statistics.

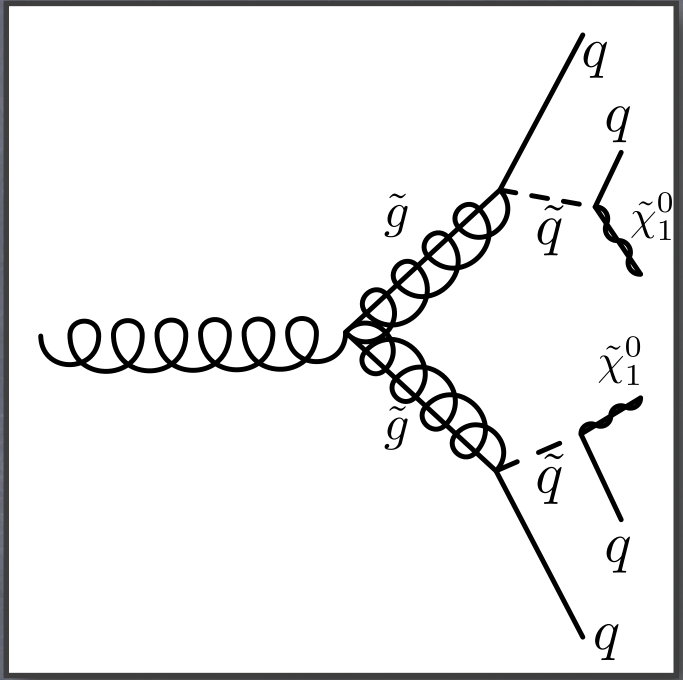
$\sigma_{UED} \times BR \sim 1 \text{ fb}$

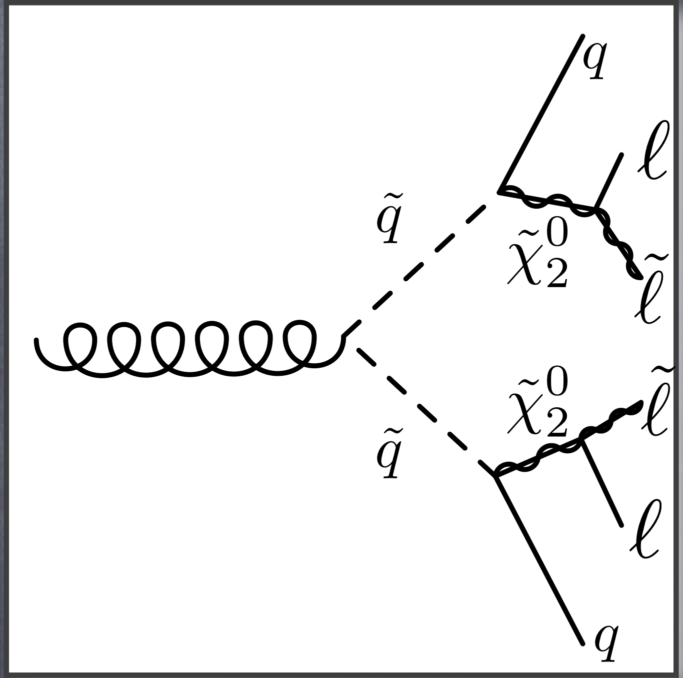
$\sigma_{SUSY} \times BR \sim 0.1 \text{ fb}$



Spin at the LHC

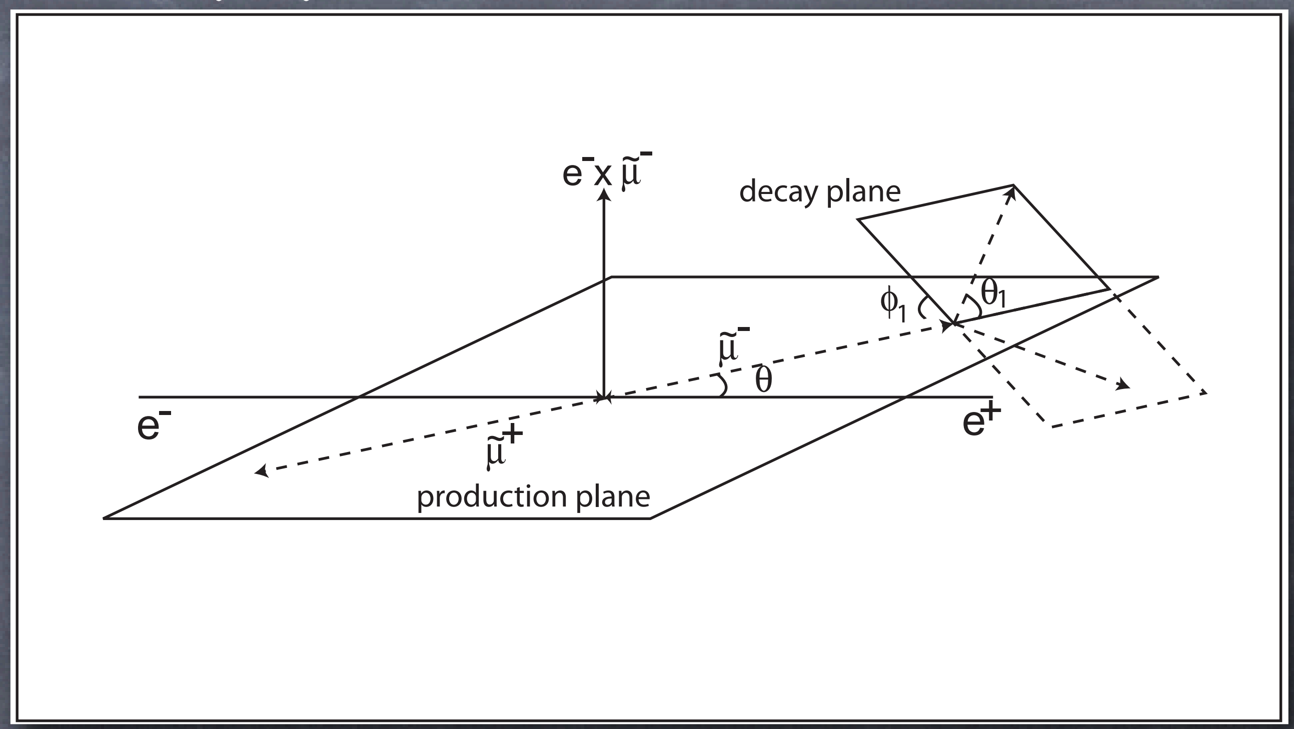
- If all masses are known:
  - 4+4 unknown momenta
  - −2 measured $\not{p}_T$
  - −6 mass relations
- If near/far ambiguity can be overcome, system specified up to two-fold ambiguity
  - Still not clear whether this ambiguity has equal $\Delta\phi$





Spin at LHC

- In e+e- or p pbar collisions:



- Sign ambiguity with identical beams $\phi \longrightarrow \phi + \pi$
  - Makes odd $\cos n\phi$ non-physical
  - Work-around in study
  - But maybe cos4ϕ for KK graviton?

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- Really works if full reconstructable
- partial reconstruction can be used as well
- Can be used to decipher new physics!