Determining Spin through Quantum Azimuthal-Angle Correlations

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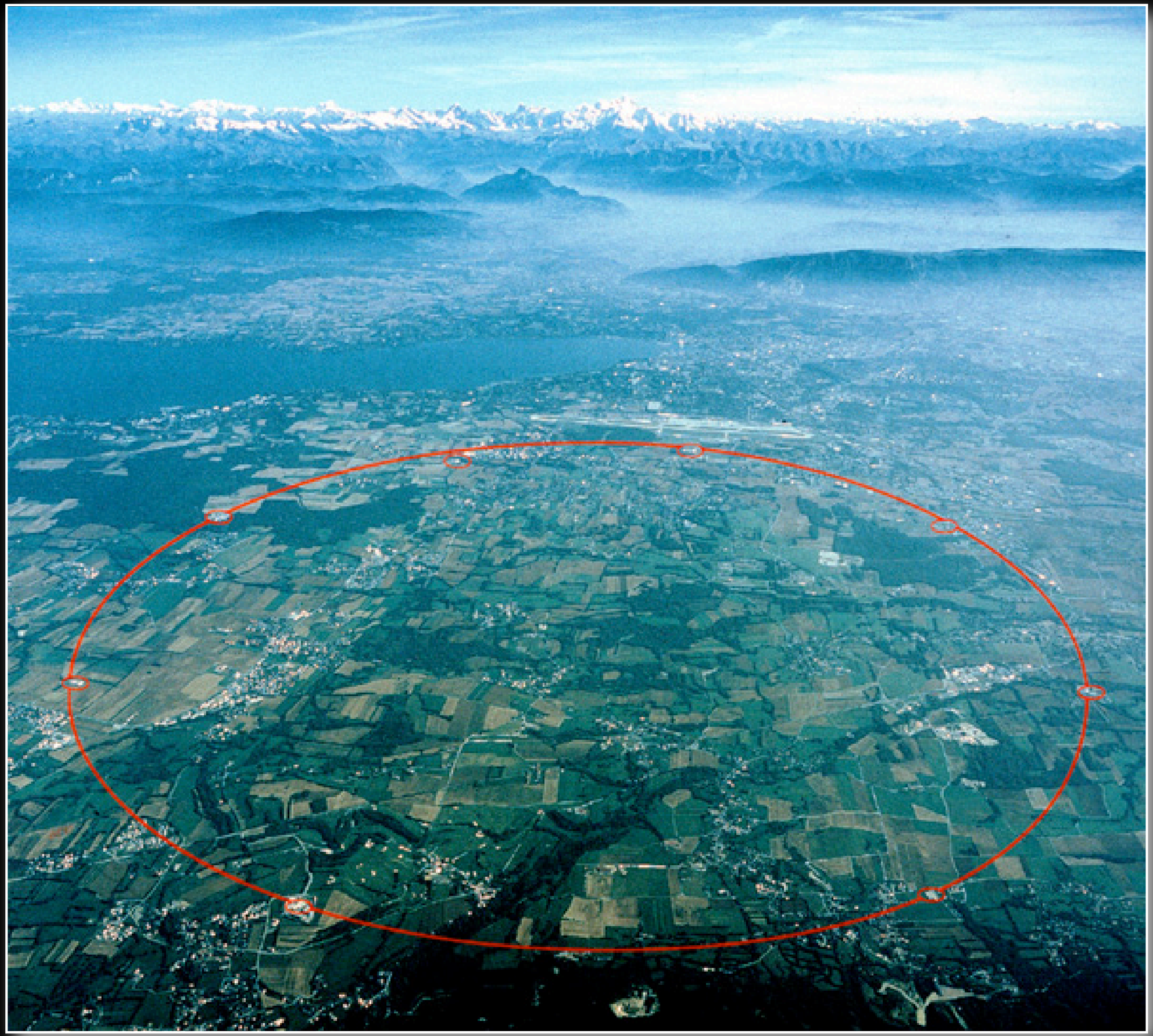
See previous works: 0711.0364, 0804.0476
with Heinemann, Klemm, Murayama, Rentala.

The LHC Era

- Finally have access to TeV-scale physics
  - Solution to the Hierarchy Problem?
  - Dark Matter?

  $\Longrightarrow$ New Particles
  - SUSY, Extra-Dimensions, Little Higgs? Something totally different?



Spin Measurements

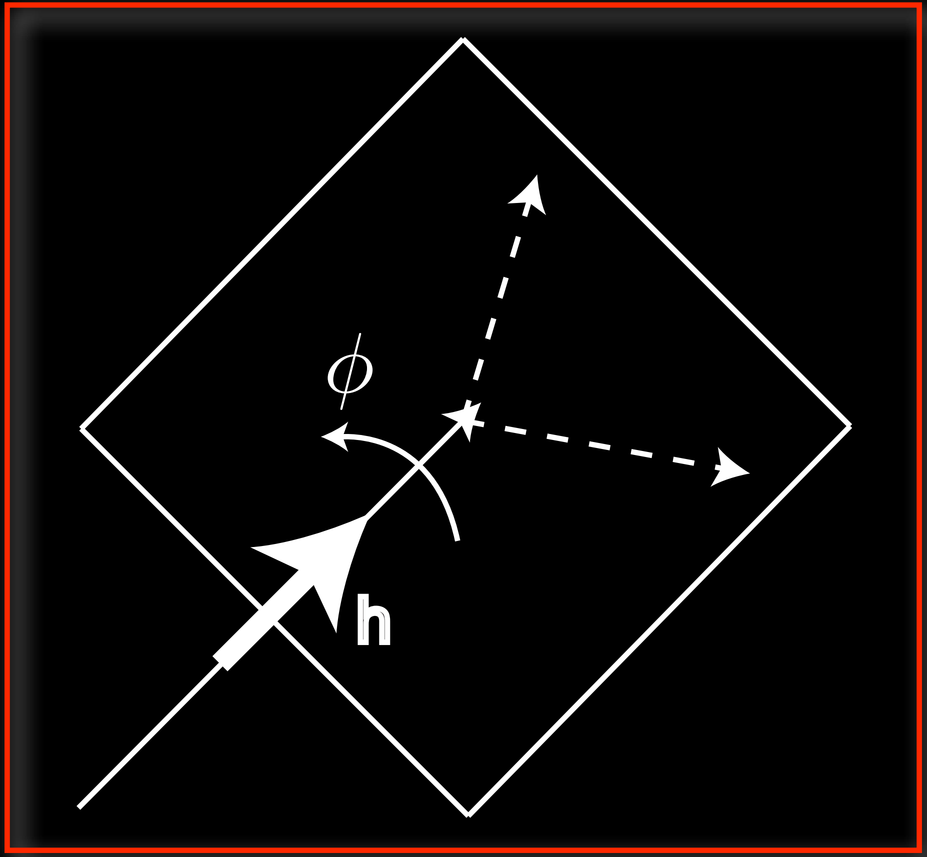
- Most techniques for next-generation colliders concentrate on distinguishing models:
  - Comparison of total cross section
  - Look for higher KK modes in UED
- At a linear collider can use threshold scans
  - Reconstruct production/polar decay angle
  - With long decay chains, can be used at hadron collider.

Spin and Quantum Interference

- Want a spin measurement with as few assumptions as possible.
- Back to Quantum Mechanics!

- Decay of particle with helicity h
  - Rotations about the z-axis (particle momentum) implies that

$$\mathcal{M}_{\mathrm{decay}} \propto e^{iJ_z\phi} = e^{ih\phi}$$



Spin and Quantum Interference

- If particle is produced in multiple helicity states and then decays, then decay amplitudes interfere coherently:

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

- Sum runs over all helicities produced, generically $h = -s, \cdots, s$ in which case

$$\boxed{\sigma = A_0 + A_1 \cos\phi + \cdots + A_n \cos n\phi, \;\; n = 2s}$$

New Physics

$$e^+e^- \to F^+F^- \to (\mu^+\chi)(\mu^-\chi) \to \mu^+\mu^-\not{E}$$

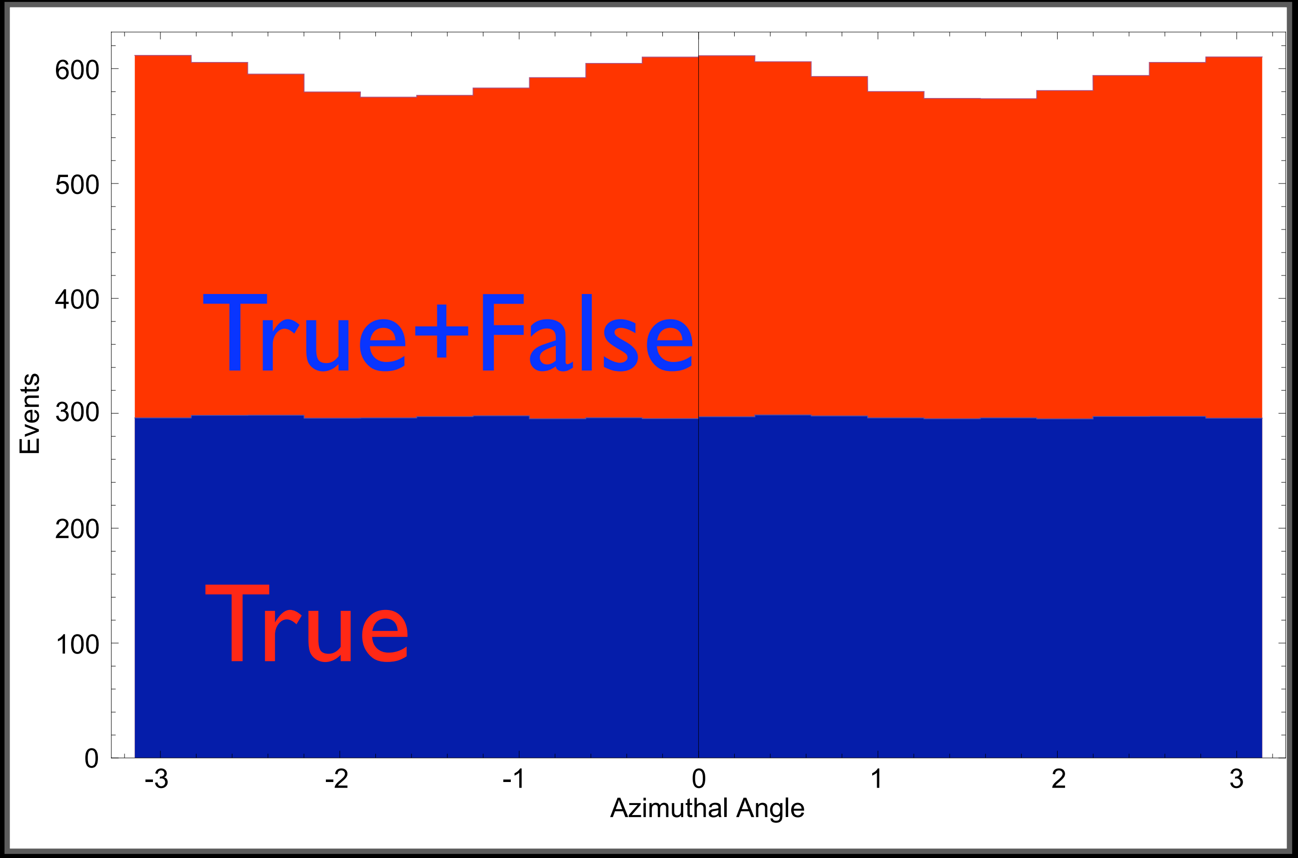
- i.e. $e^+e^- \to \tilde{\mu}^+\tilde{\mu}^- \to (\mu^+\tilde{\chi}_1^0)(\mu^-\tilde{\chi}_1^0)$ or
  $e^+e^- \to \mu_1^+\mu_1^- \to (\mu^+\gamma_1)(\mu^-\gamma_1)$

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

- 2-Fold ambiguity in reconstructing momenta & azimuthal angles ϕ_i (measured from production plane)

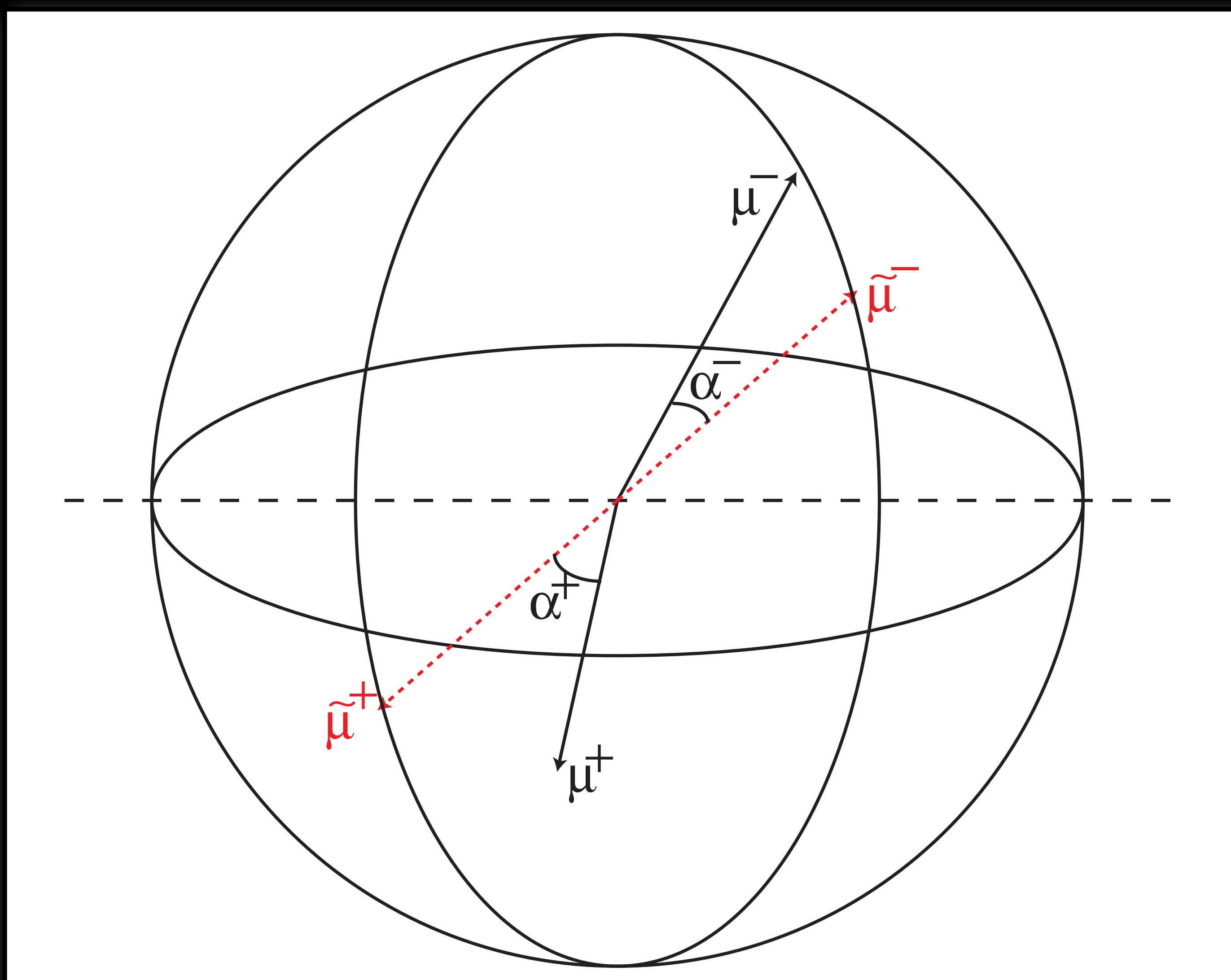
False Solutions

Scalar decay:



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

ϕ Reconstruction



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

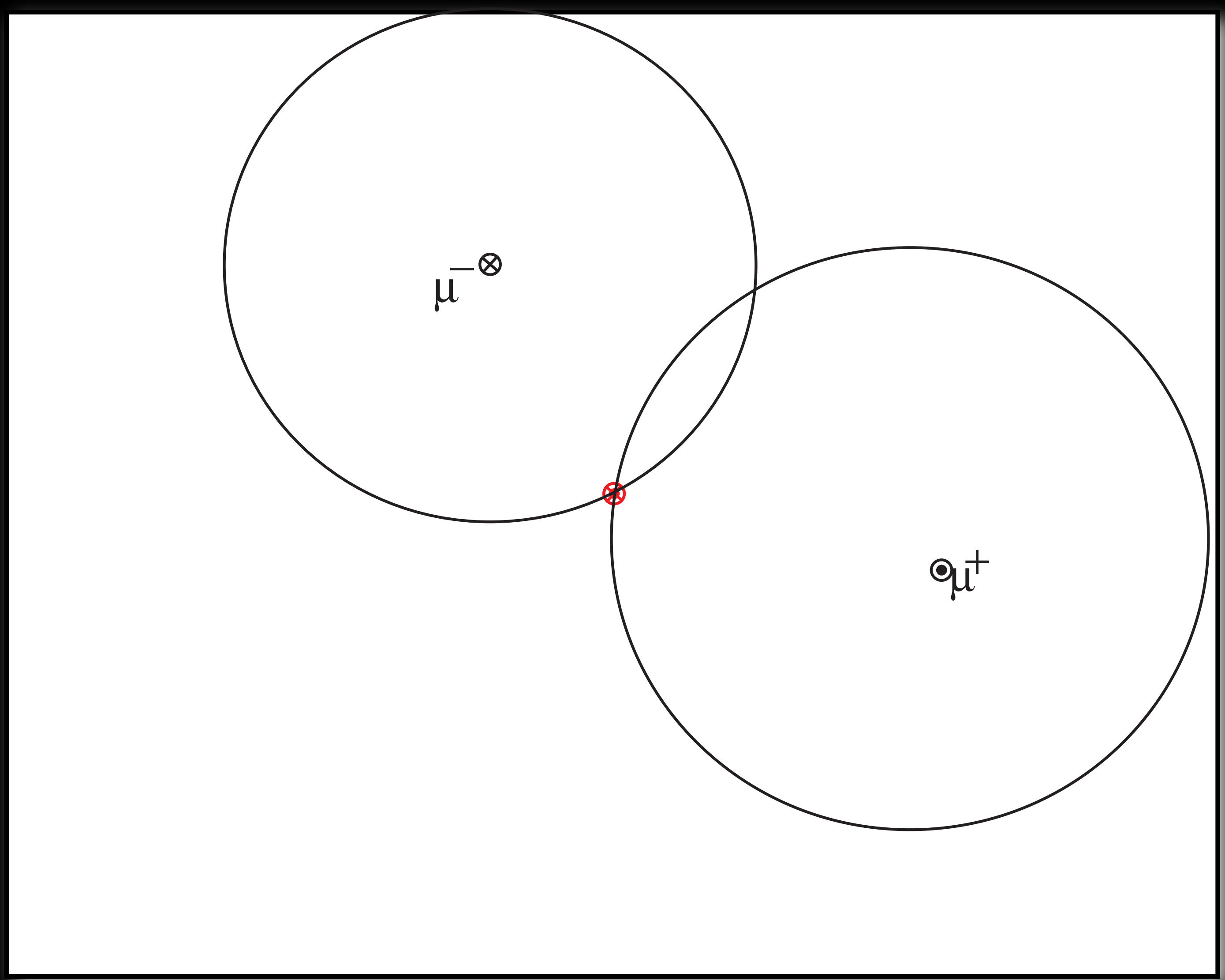
$$m_{\tilde{\mu}^{\pm}}^2 - m_{\tilde{\chi}}^2 = \sqrt{s} E_{\tilde{\mu}^{\pm}} (1 - \beta_{\tilde{\mu}^{\pm}} \cos\alpha^{\pm})$$

Straightforwardly,

$$\phi \equiv \phi_T = \phi_F$$

Since interference argument only needs *some* reference plane, we expect same expansion in $\cos n\phi_i$ and $\cos n\phi$

ϕ Reconstruction



Opening angles defined by

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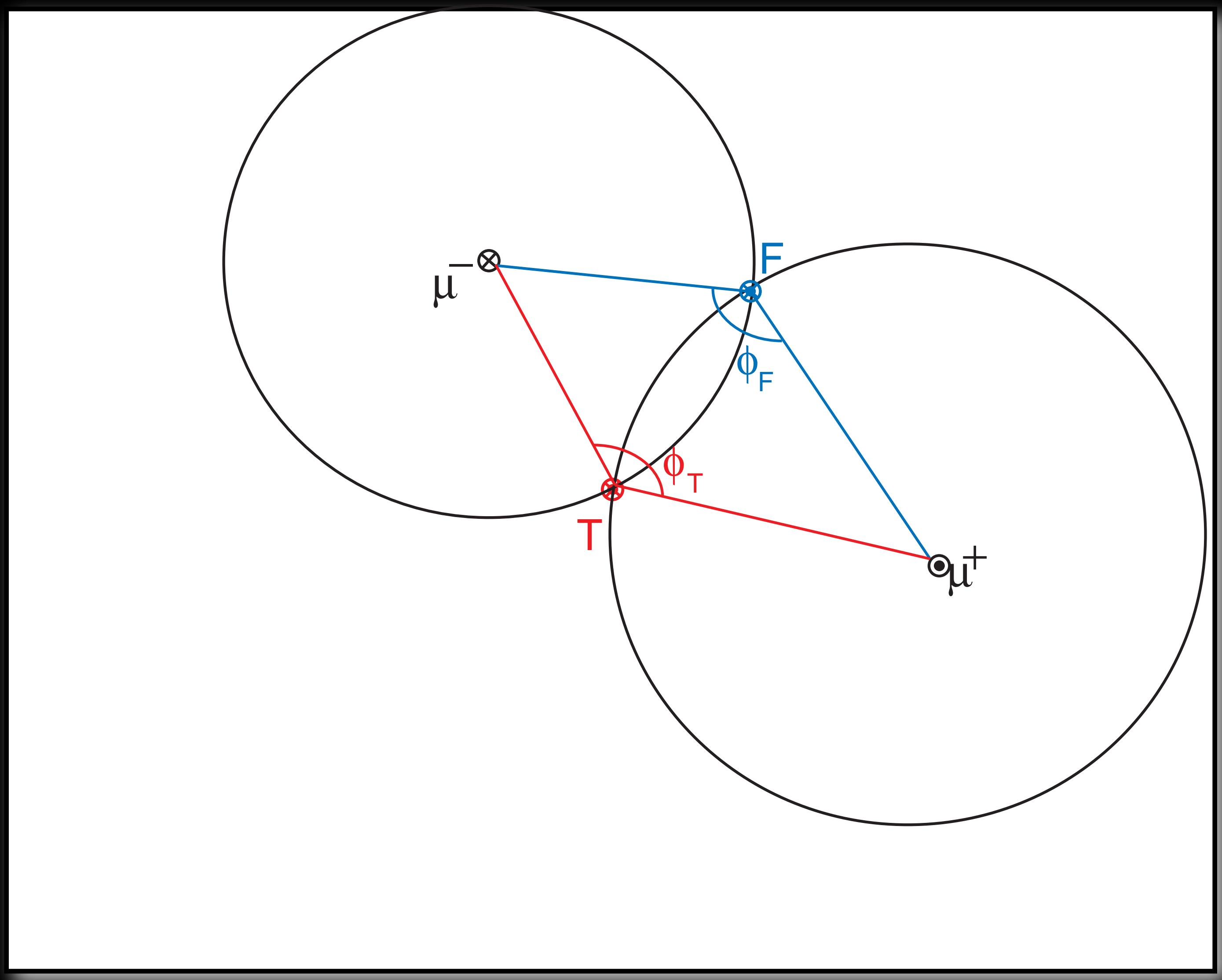

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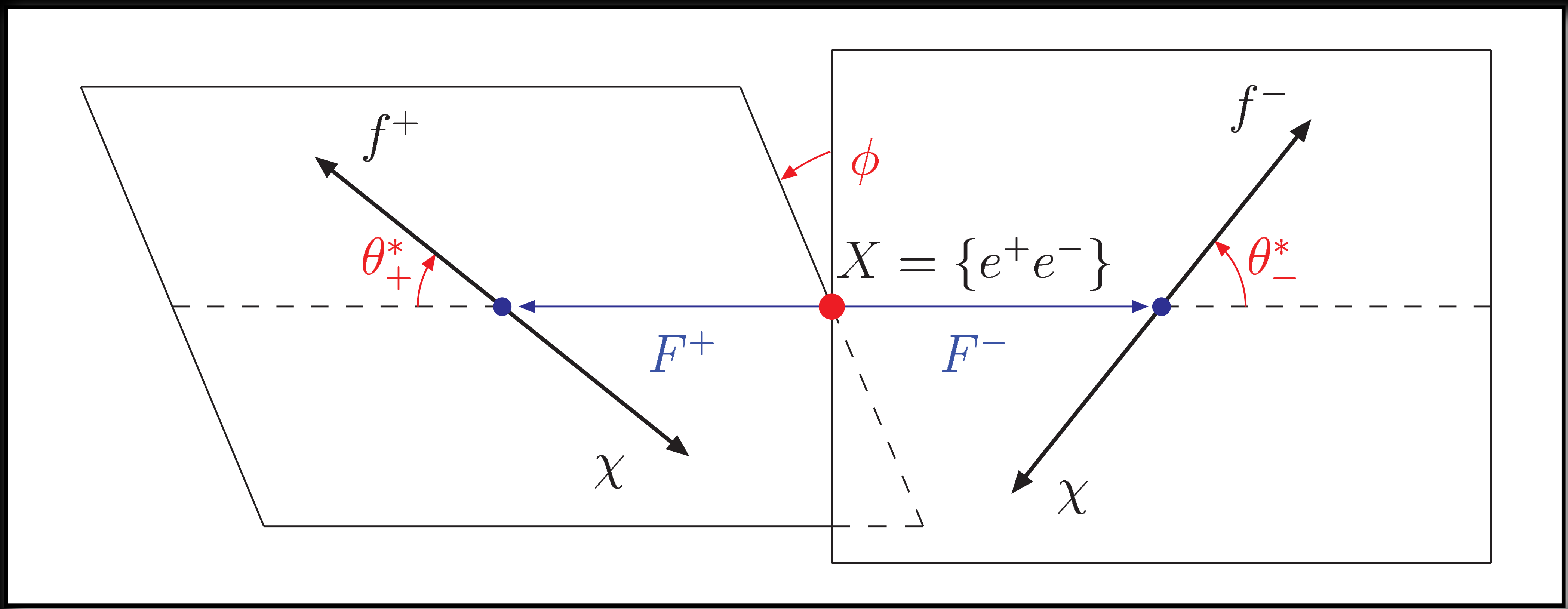


$$\cos\phi = \frac{\hat{n}_+ \cdot \hat{n}_- + \cos\alpha_+ \cos\alpha_-}{\sin\alpha_+ \sin\alpha_-}$$

$$(m_\pm^2 - m_0^2) = \sqrt{s} E_{f\pm} \left(1 - \sqrt{1 - \frac{4m_\pm^2}{s}} \cos\alpha_\pm\right)$$

Spinor-Scalar Measurement

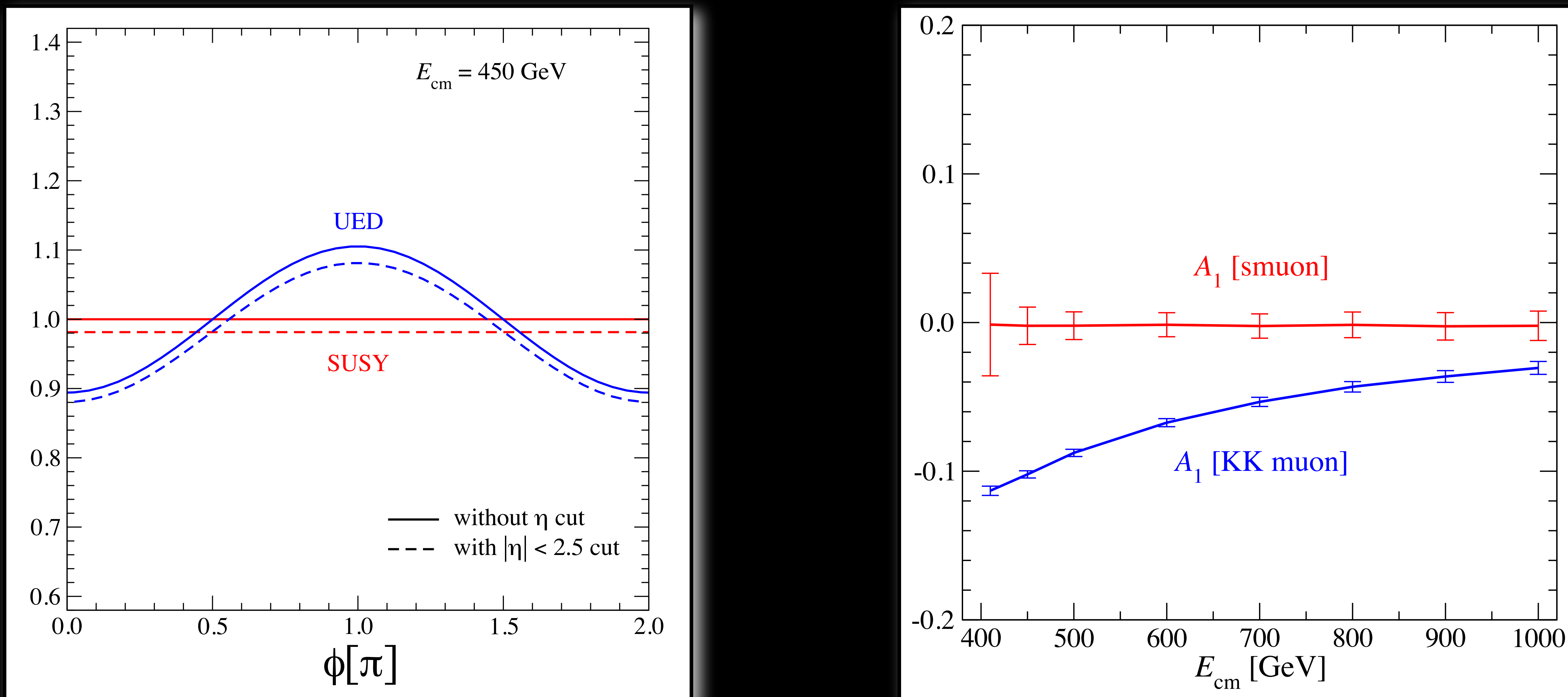
$$e^+e^- \to \tilde{\mu}_R^+\tilde{\mu}_R^- \to (\mu^+\tilde{\chi}_1^0)(\mu^-\tilde{\chi}_1^0)$$
$$e^+e^- \to \mu_{R1}^+\mu_{R1}^- \to (\mu^+\gamma_1)(\mu^-\gamma_1)$$

- Choose mass spectrum

$$m_\pm = m_{\tilde{\mu}_R^\pm} = m_{\mu_{R1}^\pm} = 200 \text{ GeV}$$
$$m_0 = m_{\tilde{\chi}_1^0} = m_{\gamma_1} = 50 \text{ GeV}$$

- Assume 500 fb^{-1} of luminosity and $\sqrt{s} \leq 1 \text{ TeV}$
- Model detector acceptance cuts with $|\eta_\mu|, |\eta_{\not{E}}| \leq 2.5$
- Simulated using HELAS/BASES

Spinor-Scalar Measurement



$$A_1 = \frac{\pi^2 m^2_{\mu^\pm_{R1}}}{8(s+2m^2_{\mu^\pm_{R1}})}\left(\frac{1-2m^2_{\gamma_1}/m^2_{\mu^\pm_{R1}}}{1+2m^2_{\gamma_1}/m^2_{\mu^\pm_{R1}}}\right)^2 \leq \pi^2/48 \approx 0.206$$

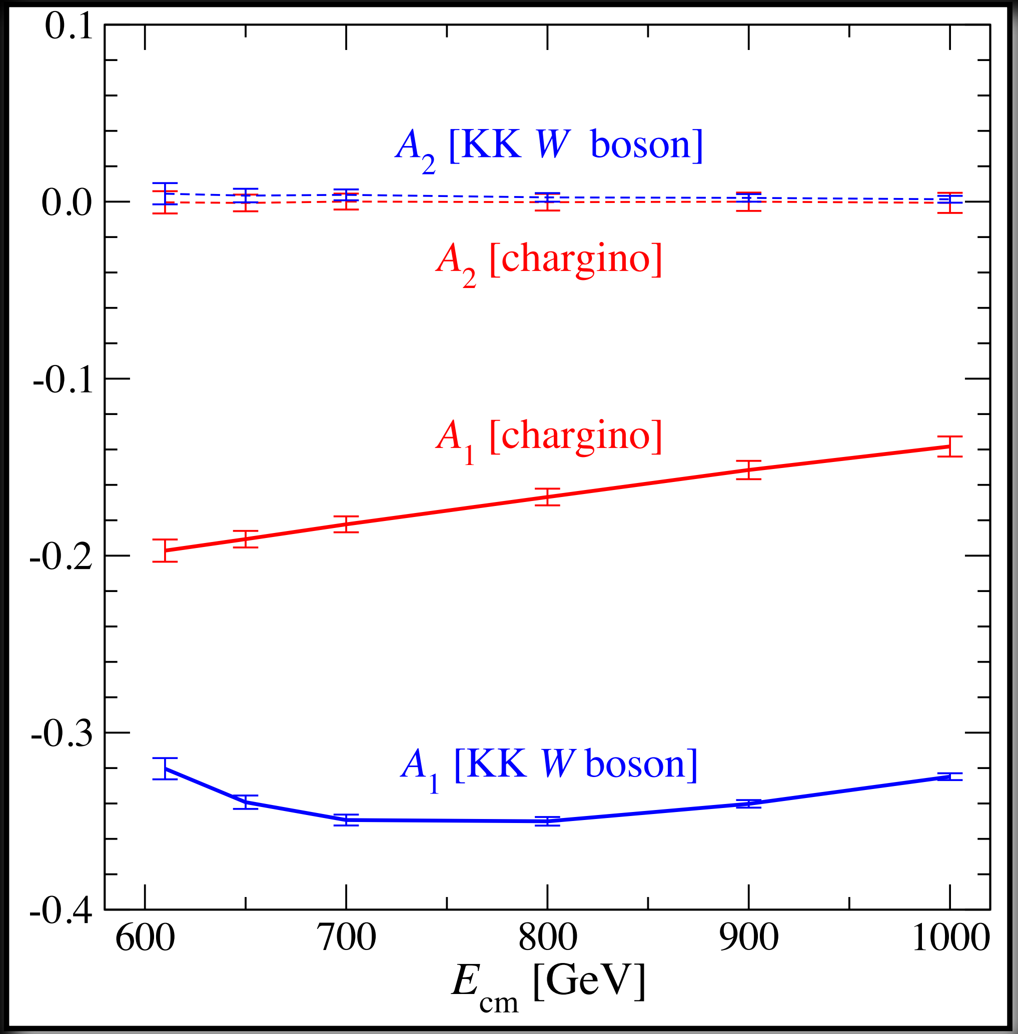
Vector-Spinor Measurement

$$e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^- \to (\ell^+\tilde{\nu}_\ell)(\ell^-\tilde{\nu}_\ell^*)$$
$$e^+e^- \to W_1^+W_1^- \to (\ell^+\nu_{\ell 1})(\ell^-\bar{\nu}_{\ell 1})$$

- Choose

$$m_\pm = m_{\tilde{\chi}_1^\pm} = m_{W_1^\pm} = 300\ \mathrm{GeV}$$
$$m_0 = m_{\tilde{\nu}_\ell} = m_{\nu_{\ell 1}} = 200\ \mathrm{GeV}$$

Production amplitudes suppressed by $\sim m_{W_1^\pm}^2/s$ leads to $A_2 \lesssim 0.5\%$



Conclusions

- Measurement of azimuthal angular dependence offers model-independent measurement of spin.
- Reconstruction of azimuthal angles ϕ_i impossible for most interesting new physics.
- We have demonstrated that $\Delta\phi \equiv \phi$ is both measurable and contains spin information
  - This technique successful in discerning spin 0 and spin-1/2 particles
  - Spin-1/2 vs. spin-1 more difficult.