Studying spin through quantum interference

Hitoshi Murayama (Berkeley / IPMU Tokyo)

Focus week on LHC@IPMU, Dec 18, 2007

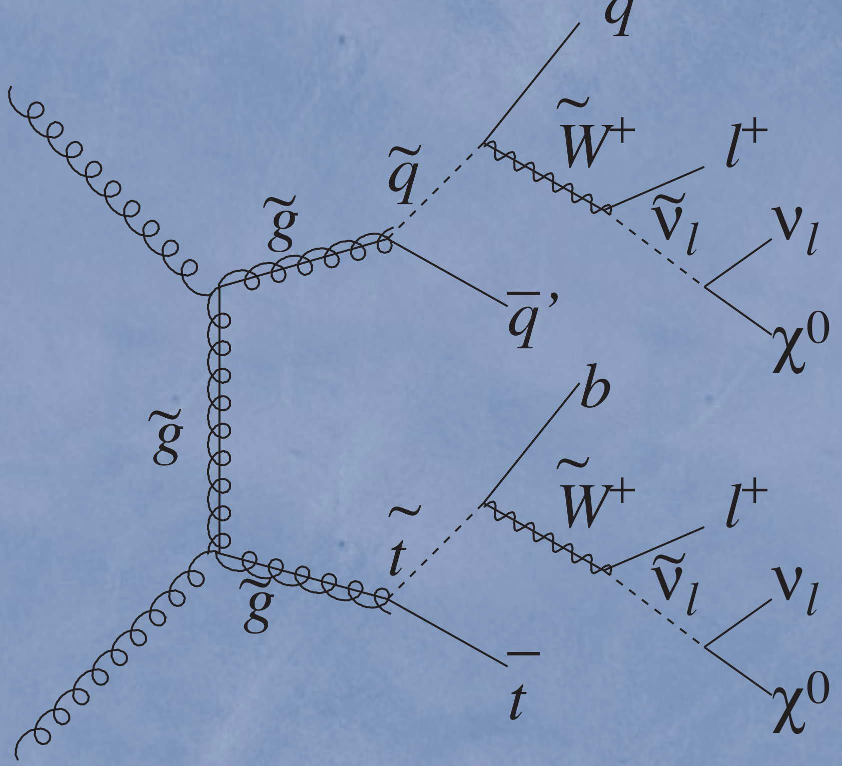
work with
Matt Buckley, Willie Klemm, Vikram Rentala

arXiv:0711.0364 and many more to follow

Motivation

New physics looks alike

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



SUSY

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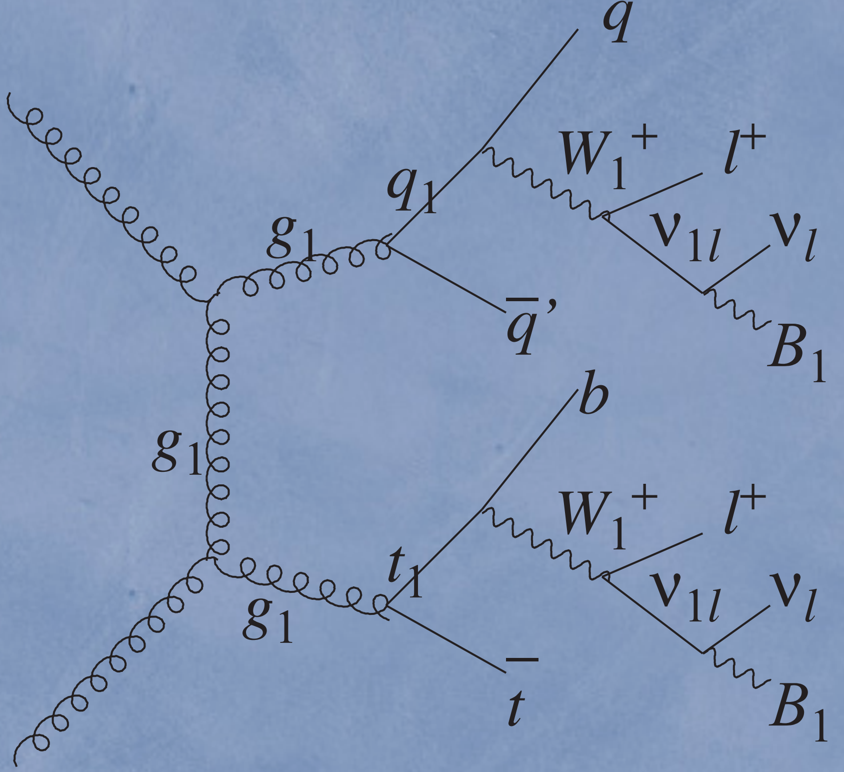
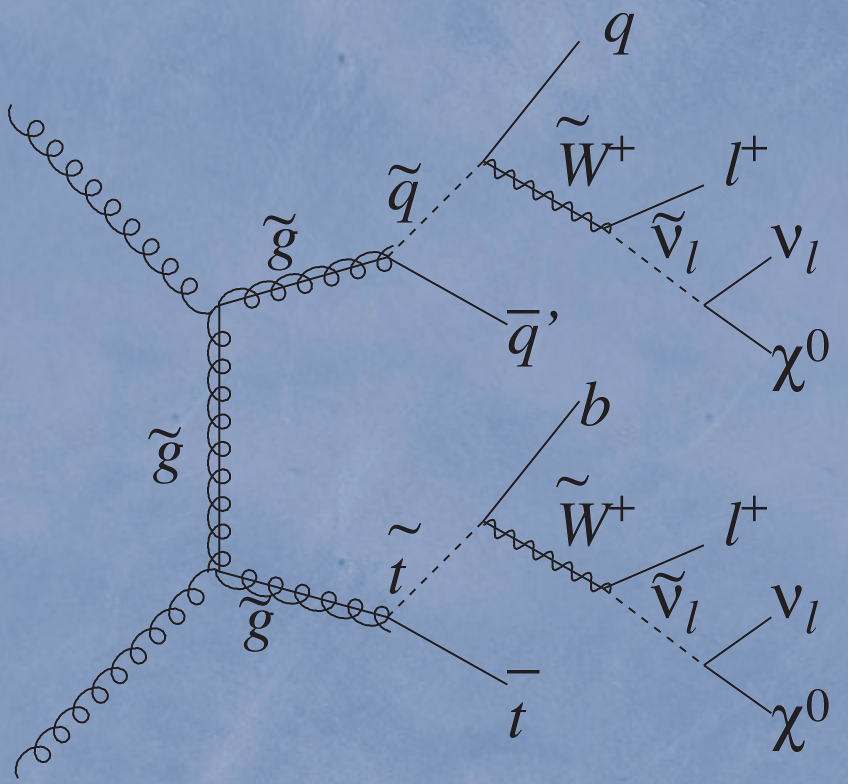


UED



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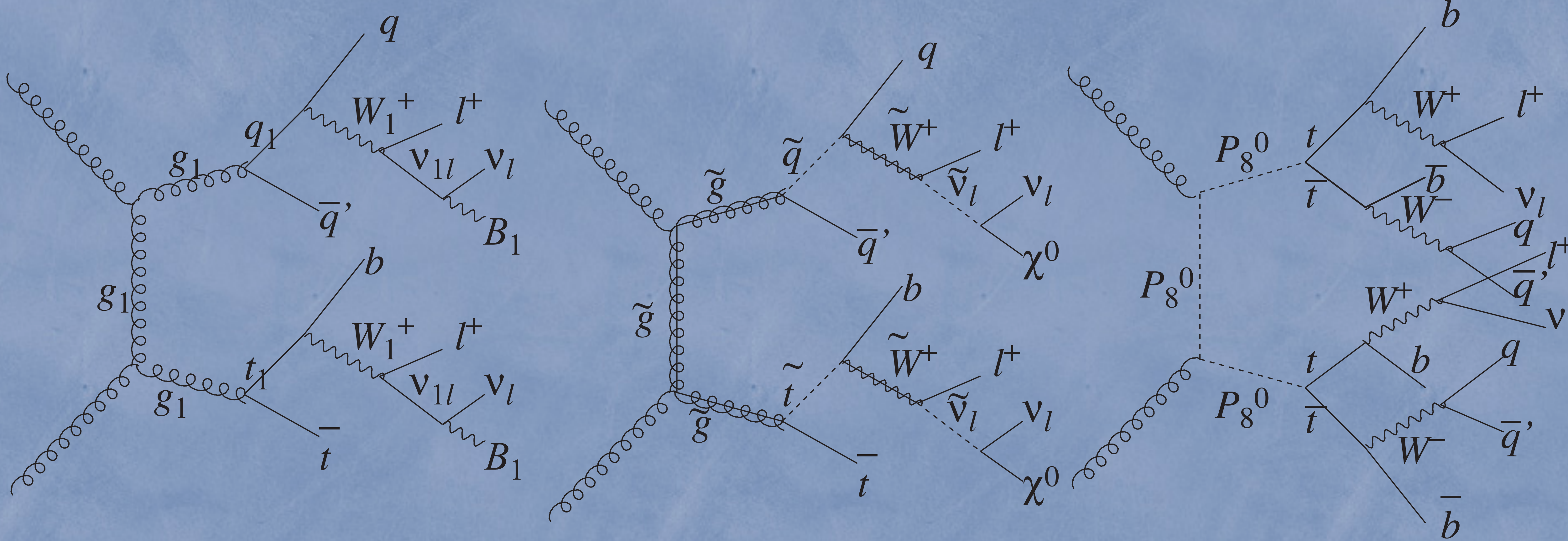

UED SUSY technicolor

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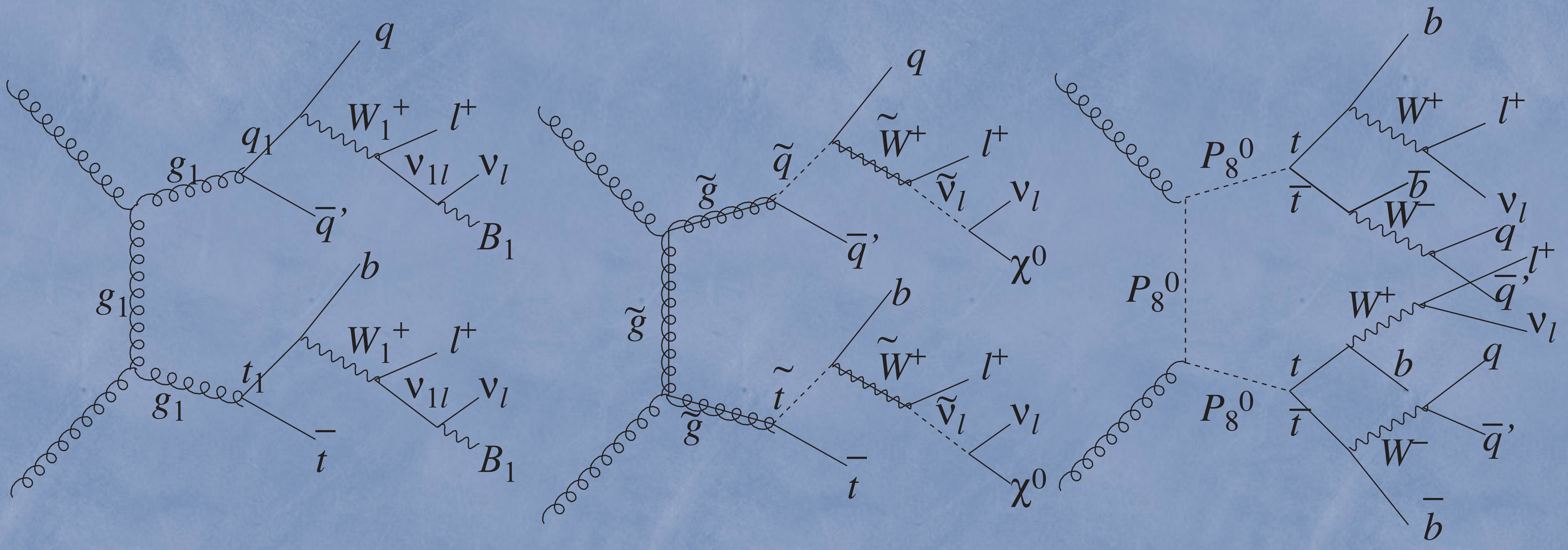

UED
spin 1

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
nMSSM
NMSSM
unnified SM
axigluon
sterile ν
6th gen
5th gen
4th gen
heavy Majorana
lepto quark
Z'LR
Z'ψ
Z'χ
Z'SM
Z'η
WR
X Y
S,T,U
vector-like family
fractionally charged
milli-charged
mono-pole
shadow matter
NOT YET THOUGHT OF
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triplet Higgs
doubly charged Higgs
Type I
Type II
general 2HDSM
mirror symmetry
N=2
N=4
N=8
Majoron
spontaneous CP
superweak
axion
saxion
axino
Weinberg's 3HD
milli-weak
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heterotic
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F
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- spectroscopy
- kinematic fits, partial wave analysis, Dalitz analysis, etc
- precision mass, BR measurements
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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 $\tan\beta = 3$. See Fig. 5 of the paper for other choices of A_0 and $\tan\beta$. 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 $\tan\beta = 5$.

[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	

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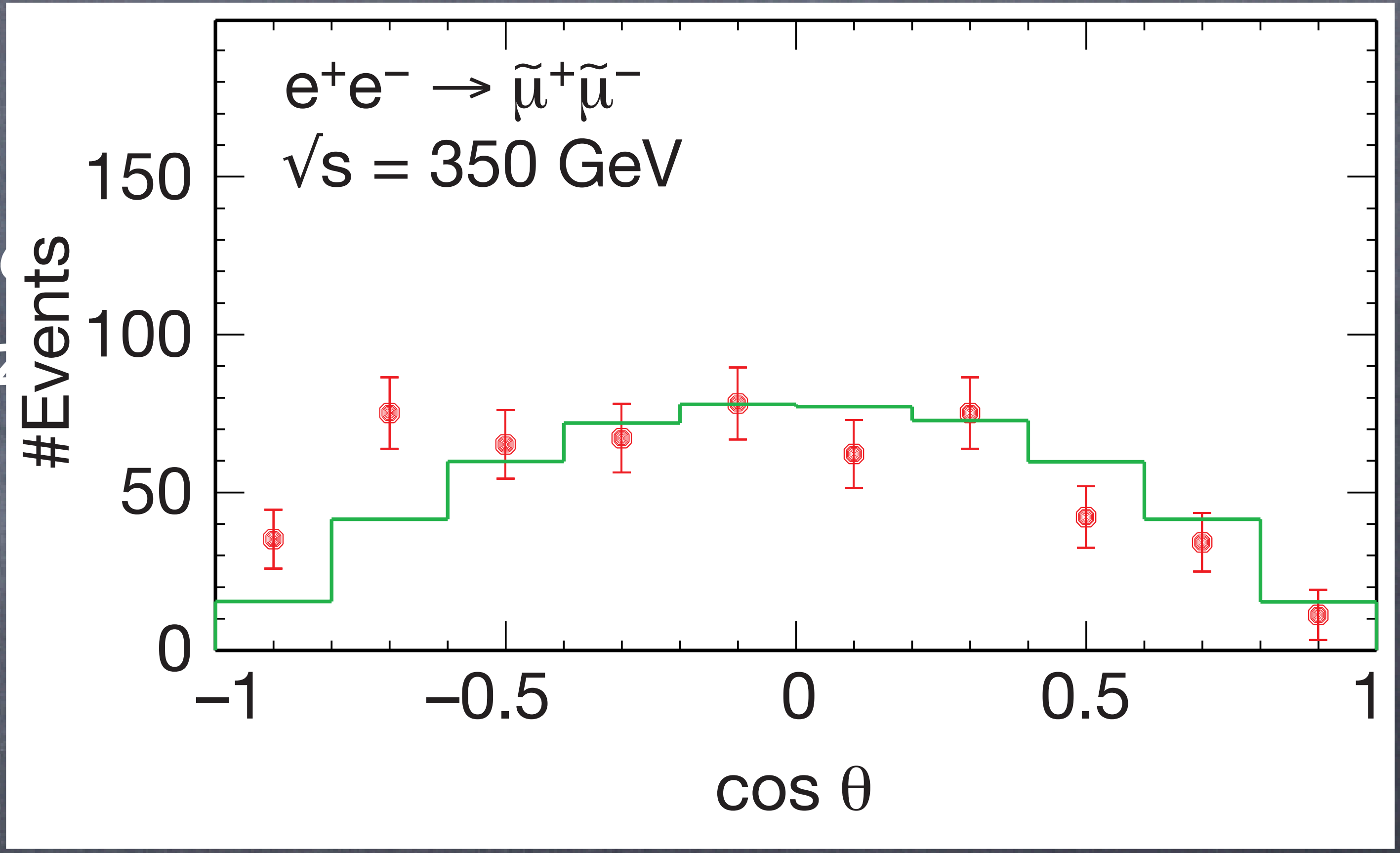
Spin 0?



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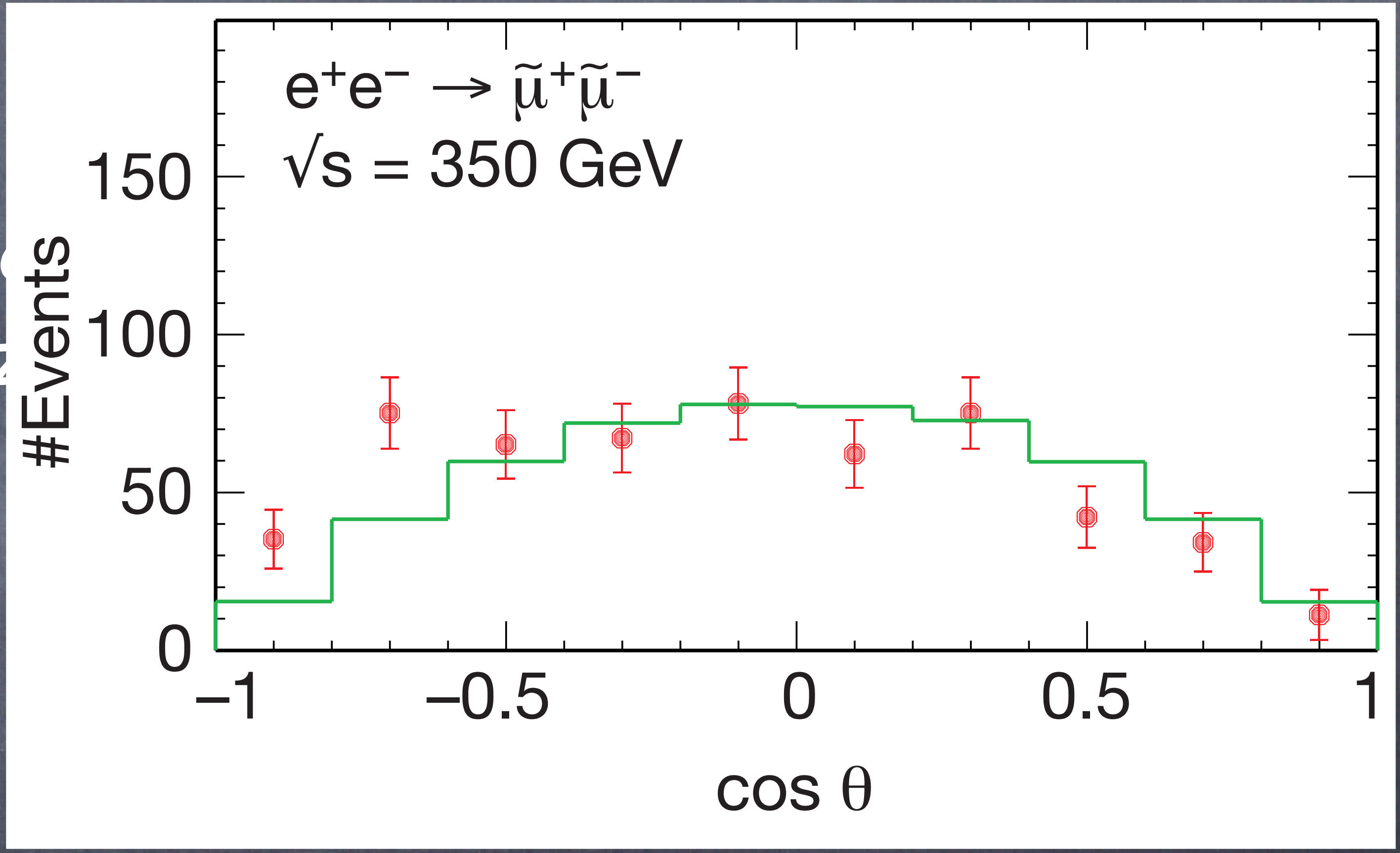


relies on the absence of t,u-channel!

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

General Principle

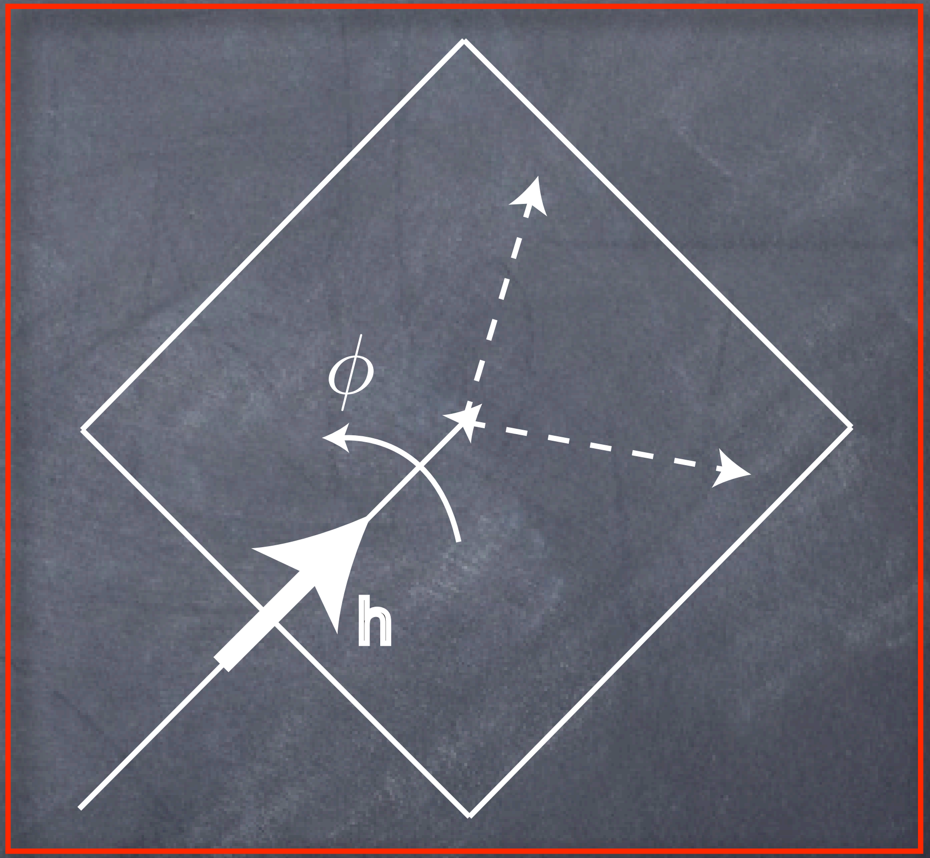
Helicity and phase

- 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



Quantum Interference among helicities

- If particles produced in multiple helicities:

$$\sigma \propto \left| \sum \mathcal{M}_{prod.} \mathcal{M}_{decay} \right|^2$$

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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)

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

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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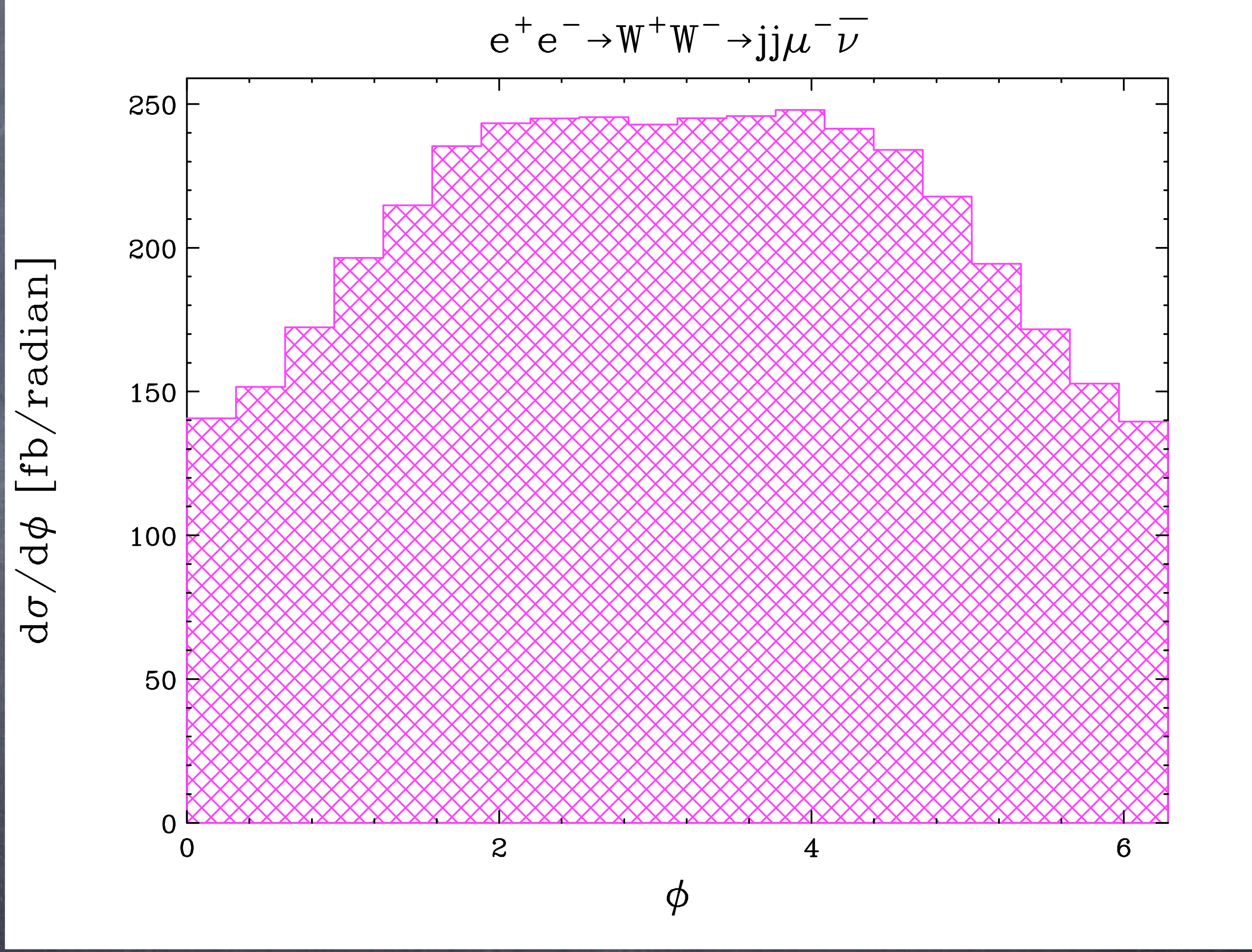

Tevatron

- p pbar → Z + gluon
- study Z → $l^+ \; l^-$
- A_1/A_0=6.0%
- A_2/A_0=12%

    used $p_T(g)$>7 GeV

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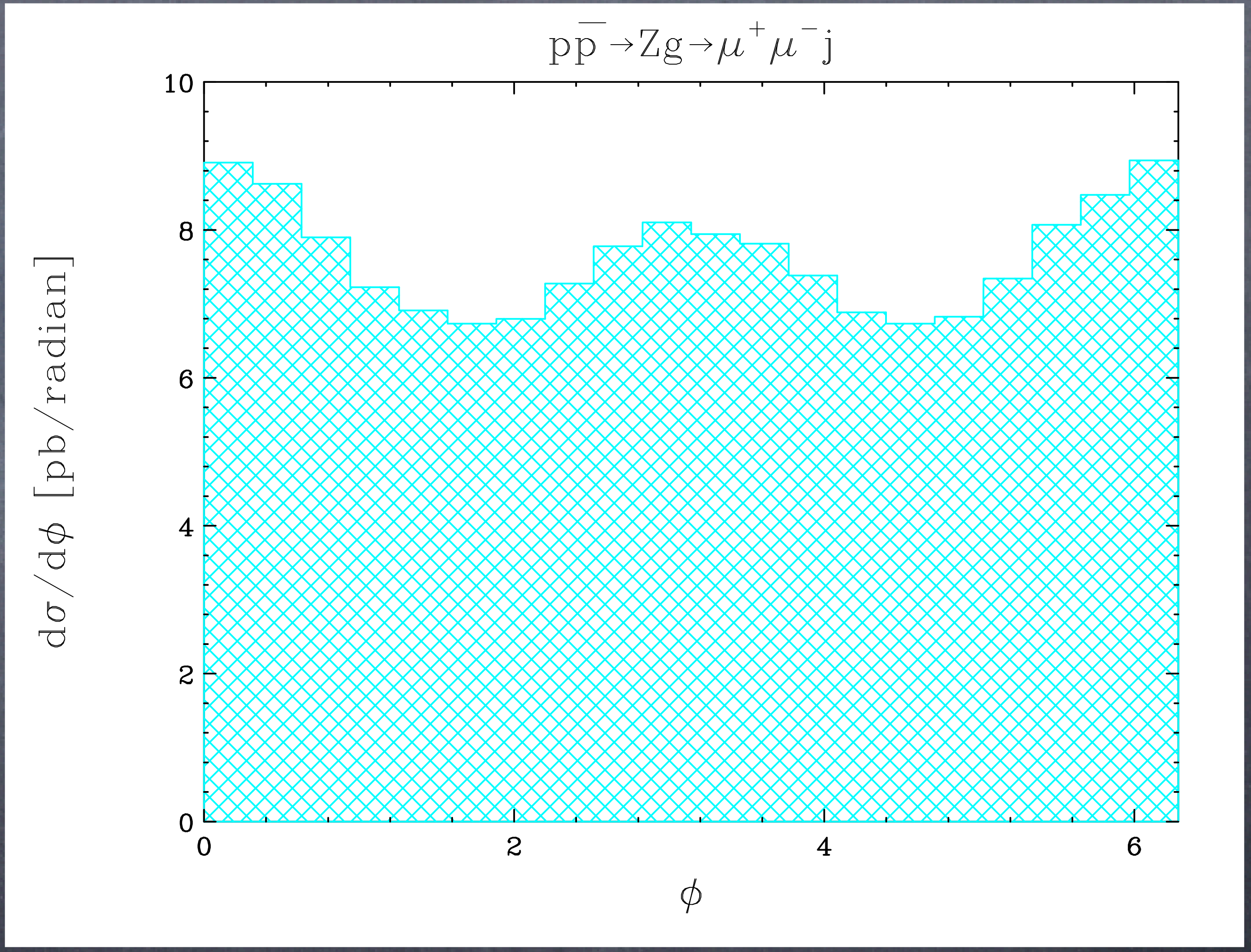
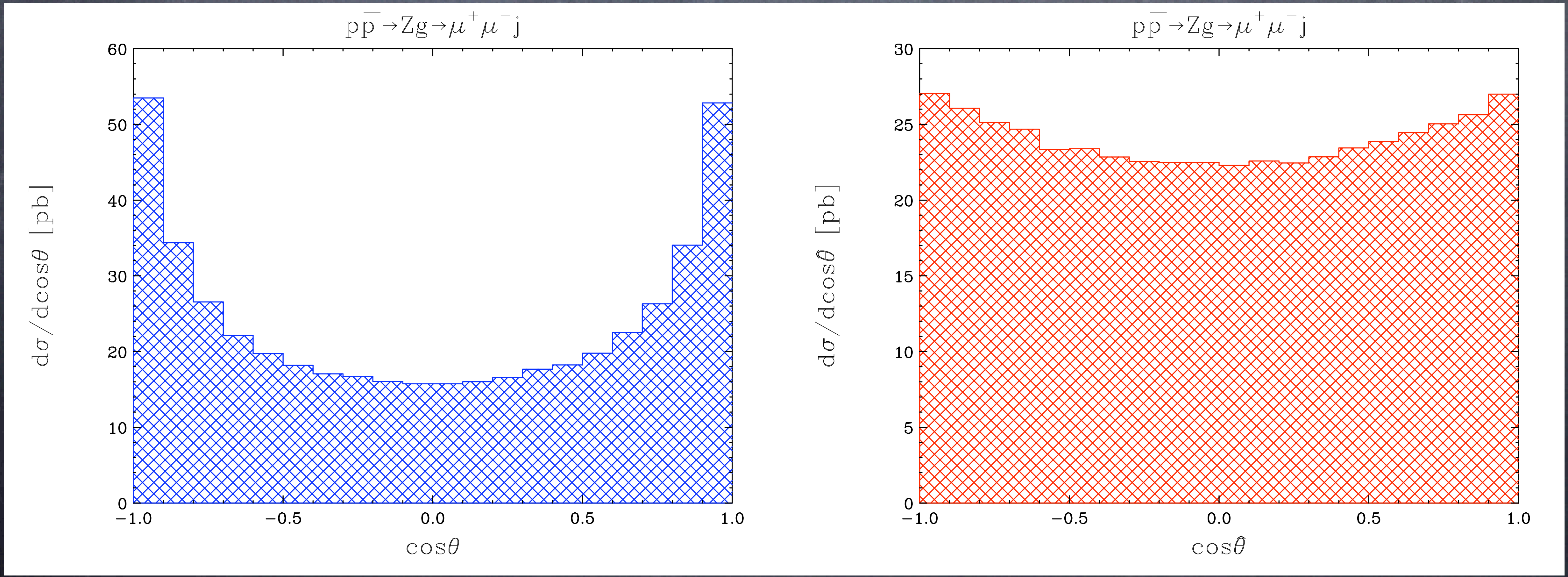


Other distributions

- 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



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

Challenges

partially reconstructible

- Many new physics scenarios have more than one invisible particle in their events

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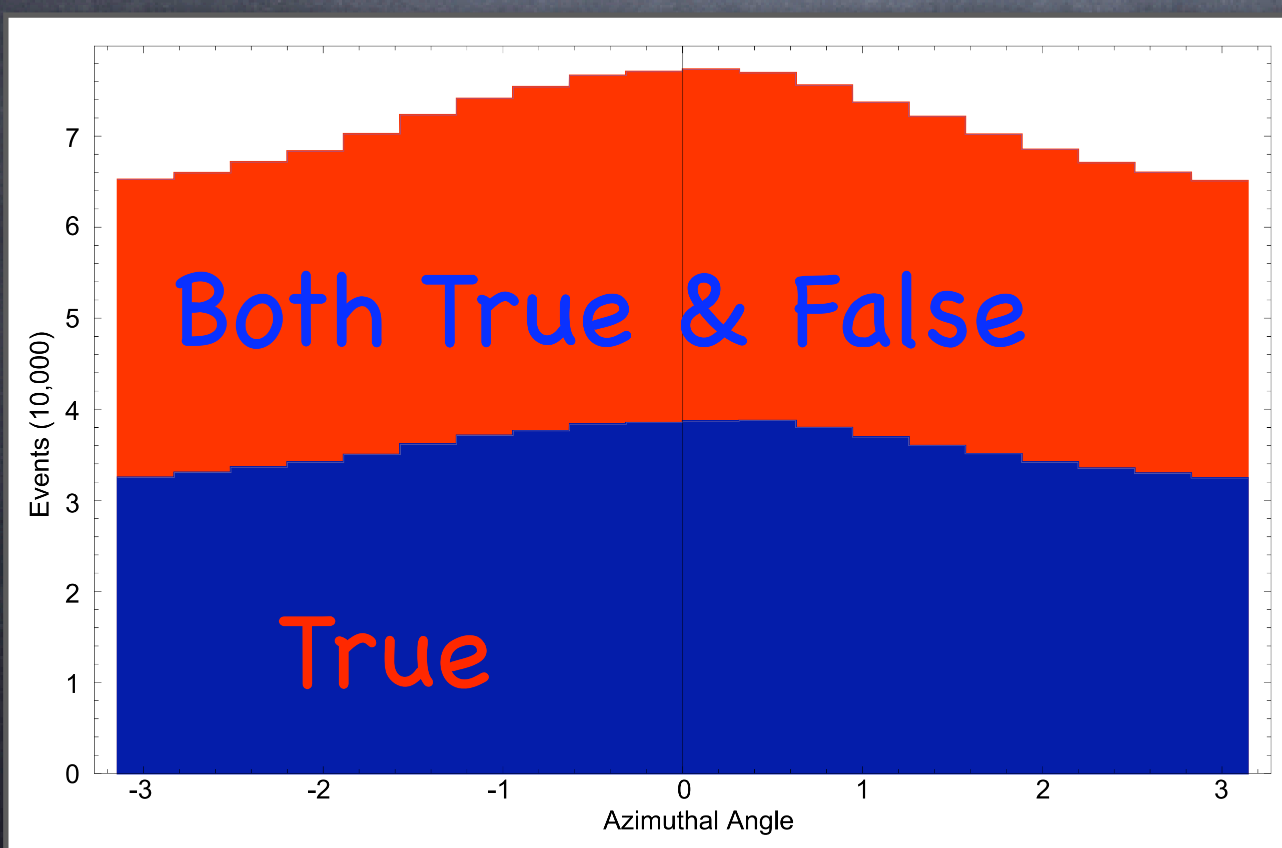
- ILC KK muon pair, KK $\mu_1 \to \mu$ + KK B_1
- ILC smuon pair, smuon $\to \mu$ + neutralino
- once masses measured, reconstructible up to a two-fold ambiguity

Azimuthal Distributions

- Sum ϕ_1 and ϕ_2 distributions. $\sqrt{s} = 370\ \mathrm{GeV}$
- 183 GeV decaying into muon and 161 GeV

UED distribution



SUSY distribution

Fake solution

- We do not fully understand yet how exactly the fake solutions contribute to the apparent $\cos(n\phi)$ dependence
- Obviously it can be studied within a model
- but we wish to subtract the fake contribution with as little model-dependent assumptions as possible

Spin at LHC

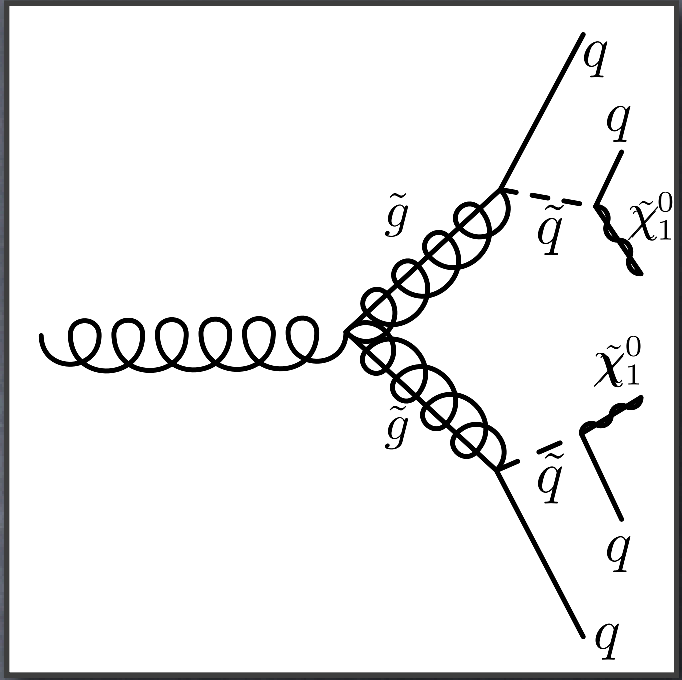
- Lose two constraints: center of momentum frame and $\sqrt{\hat{s}}$
  - Still can reconstruct up to two-fold ambiguity

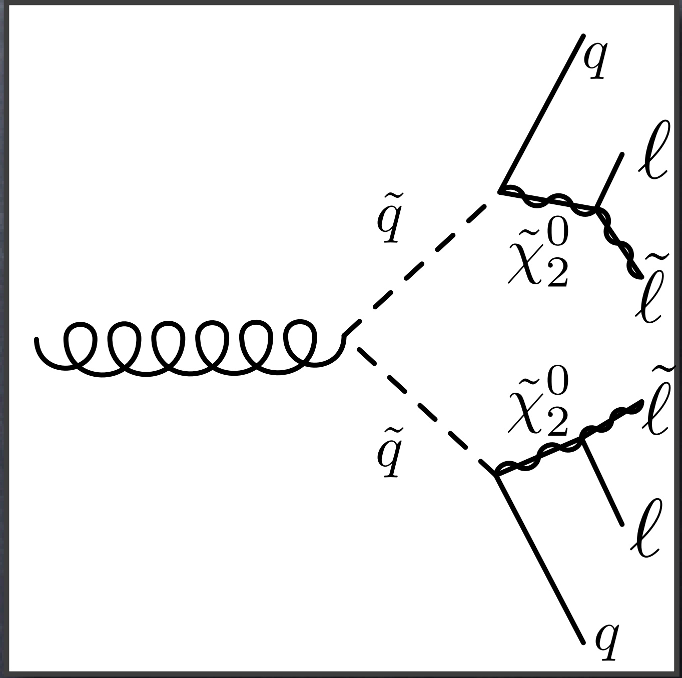
4+4 unknown LSP/LKP momenta
-2 measured $\not{p}_T$
-6 mass relations

- Much higher statistics available;

$$\sigma \sim 1 \text{ pb}$$

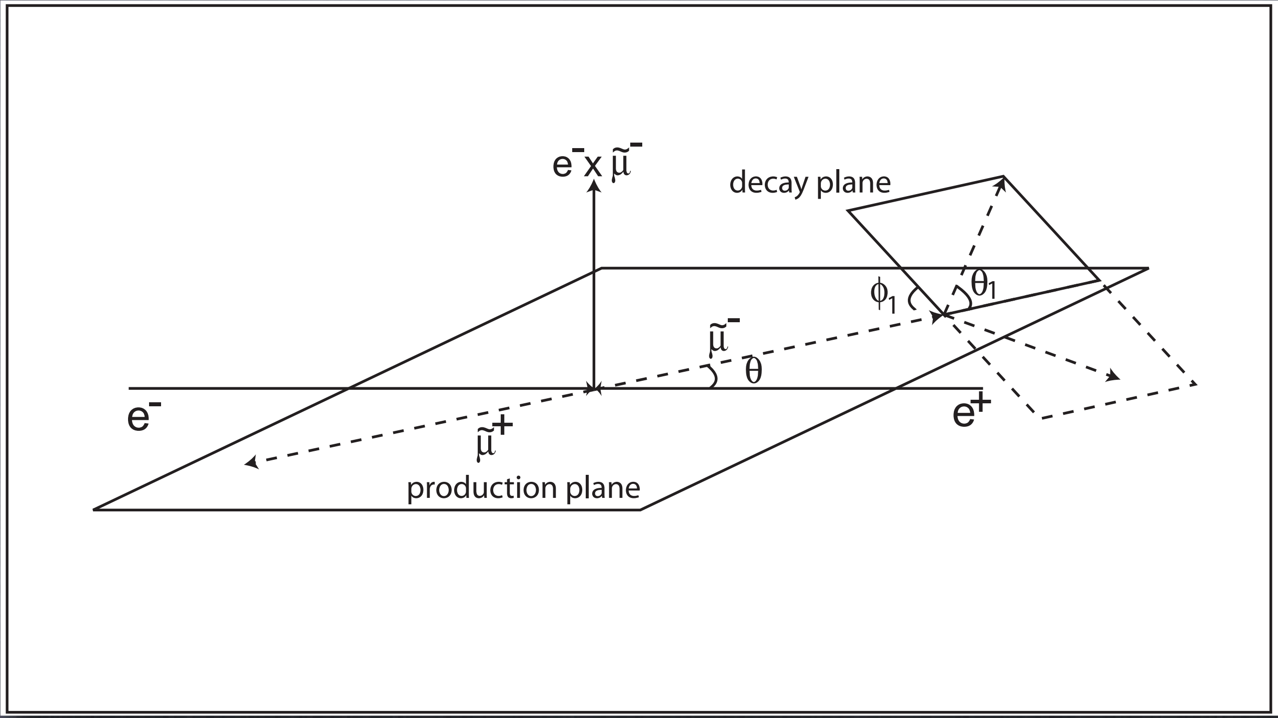
- Not studied yet!





Spin at LHC

- In e^+e^- or p pbar collisions:



- Sign ambiguity with identical beams

$$\phi \to \phi + \pi$$

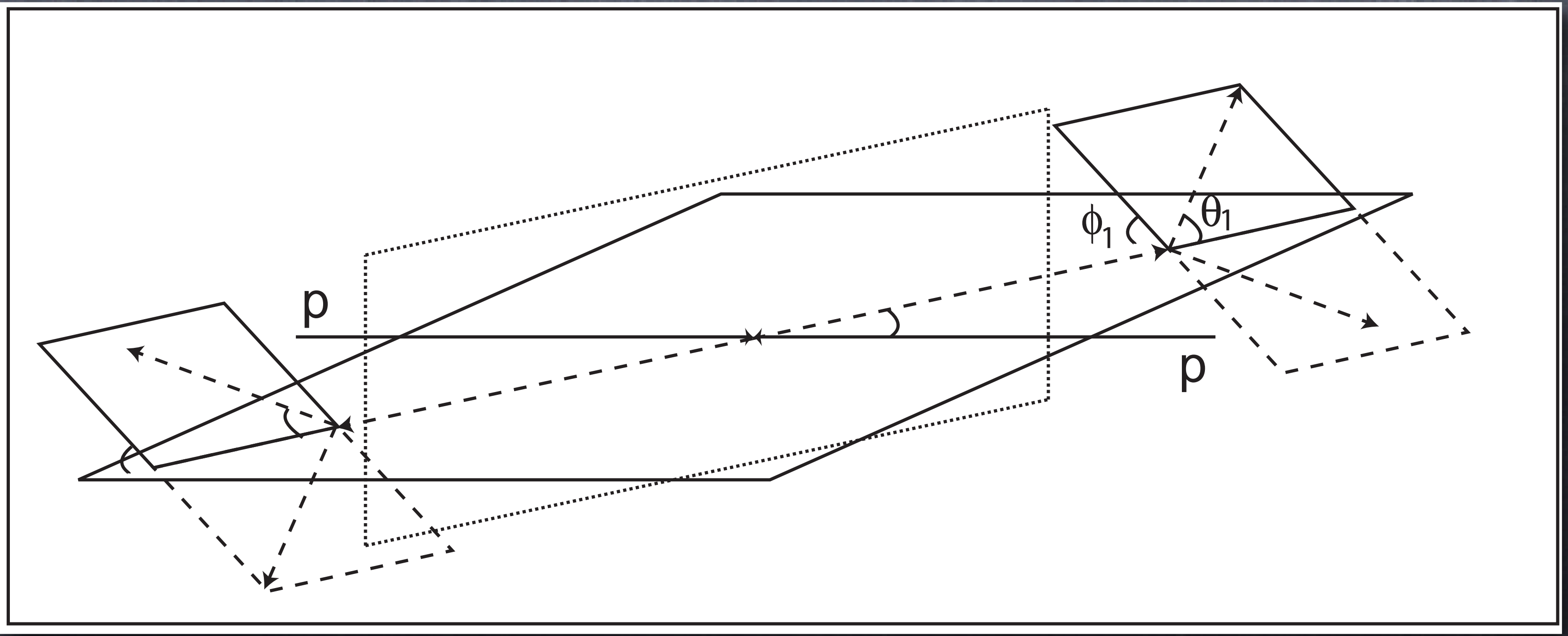
  - Makes odd $\cos n\phi$ non-physical

Spin at LHC

- Can still determine cos ϕ contribution from correlations of ϕ_1, ϕ_2

$$\langle \cos\phi_1 \cos\phi_2 \rangle \propto A_1^2/A_0^2$$

- Look at sign asymmetry between ϕ_1, ϕ_2



$p\ p \to t\ \bar{t}$

- dominated by $gg \to t\ \bar{t}$ at LHC
- $\langle \cos\phi_1 \cos\phi_2 \rangle = 0.8\%$
- small but statistically possible at LHC (>1M/year)
- systematics in reconstruction, background, "cross talk" between two tops via gluon exchange, etc
- W spin effect has only $\cos\phi$ in top rest frame because $t \to bW^+$ decay has only h=0,−1 for W^+

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- Should be demonstrable in the existing LEP-II and Tevatron data
- particularly useful near threshold when other spin correlations are not very prominent
- Full reconstruction really helps
- partial reconstruction may be used, but more studies needed