A New Way to Measure Spin

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work with Michael Ramsey-Musolf, U. Wisconsin. arxiv:1008.5151

New Energies, New Particles

- What will we find at the Terascale?

- Most of the proposed UV completions have similar signatures at hadron colliders:
  - Strongly coupled states
  - Pair creation enforced by new symmetry
  - Missing energy from dark matter candidate

New Energies, New Particles

- What will we find at the Terascale?

  Supersymmetry?

  Extra Dimensions?

  Technicolor?

  None of the above?

- Most of the proposed UV completions have similar signatures at hadron colliders:
  - Strongly coupled states
  - Pair creation enforced by new symmetry
  - Missing energy from dark matter candidate

Breaking the Degeneracy

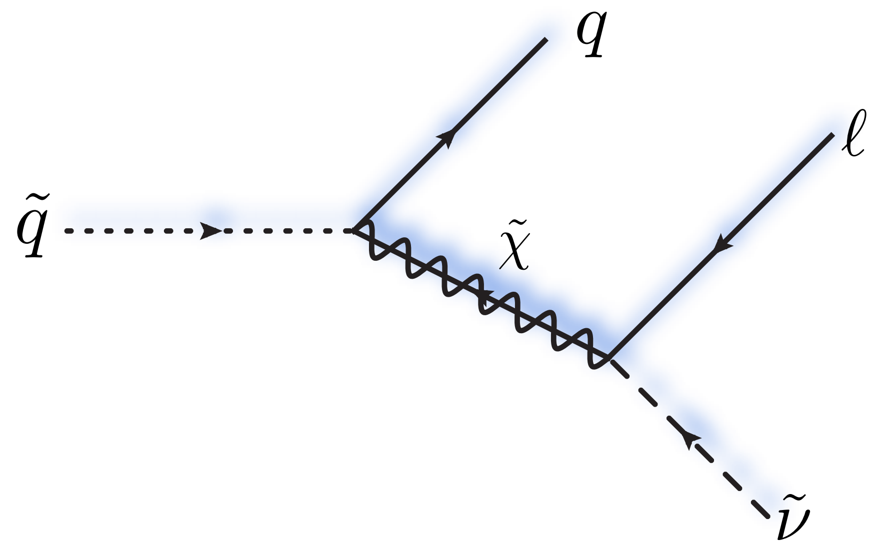
- To determine the underlying theory, we need to know the basic properties of the newly discovered particles:
  - Mass hierarchy
  - Decay channels
  - SM gauge charges
  - Spin

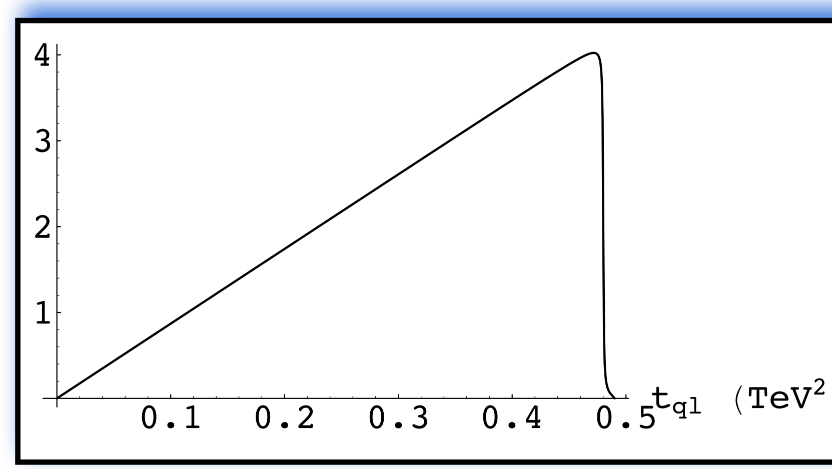
Spin Measurements

- Many techniques devised distinguish specific models from one another:
  - Total cross section: *i.e.* $\sigma_{\text{SUSY}} < \sigma_{UED}$
  - Spectrum of states: *i.e.* tower of Kaluza-Klein modes in UED
- If you had a linear collider, can use threshold scans,
  - Both scalars and vector bosons have $\sigma \propto \beta$

Spin Measurements

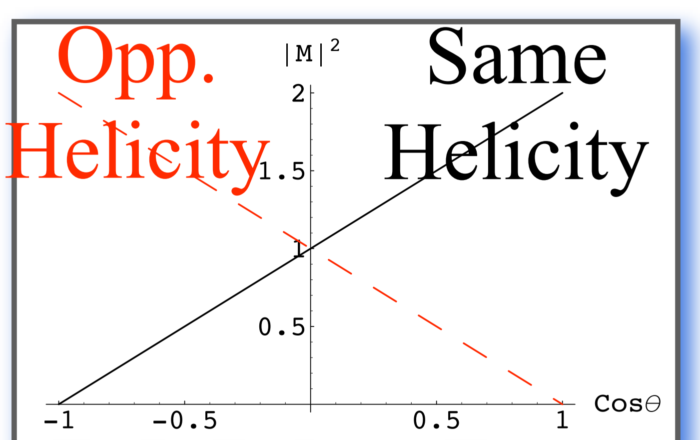
- Other techniques look at long decay chains



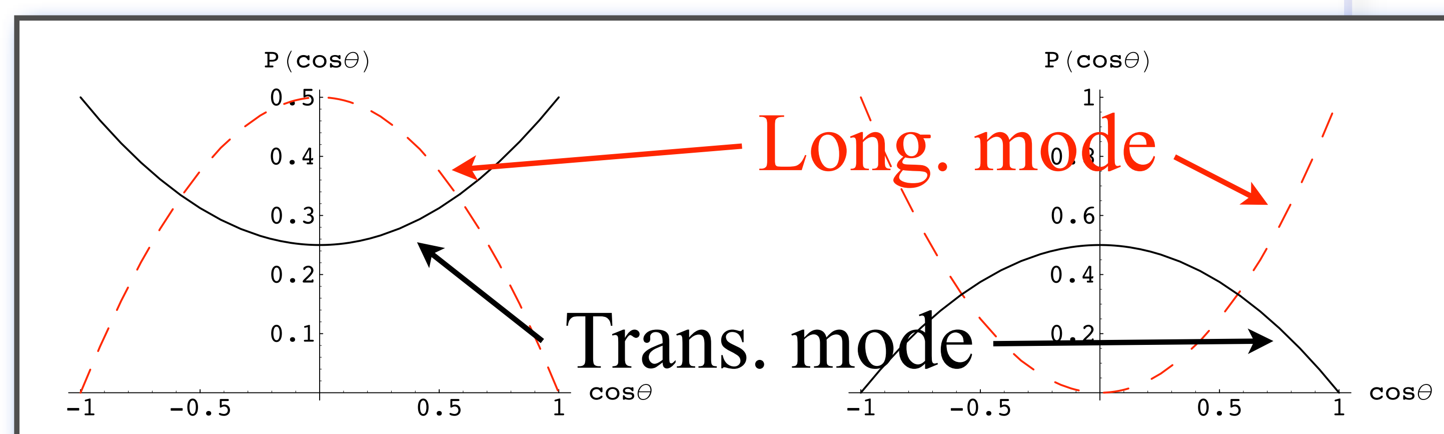


hep-ph/0605296

- But this requires chiral couplings, and depends on the spins of the final states (perhaps unknown).



Pol. Spinor Decay



Vector Boson Decay

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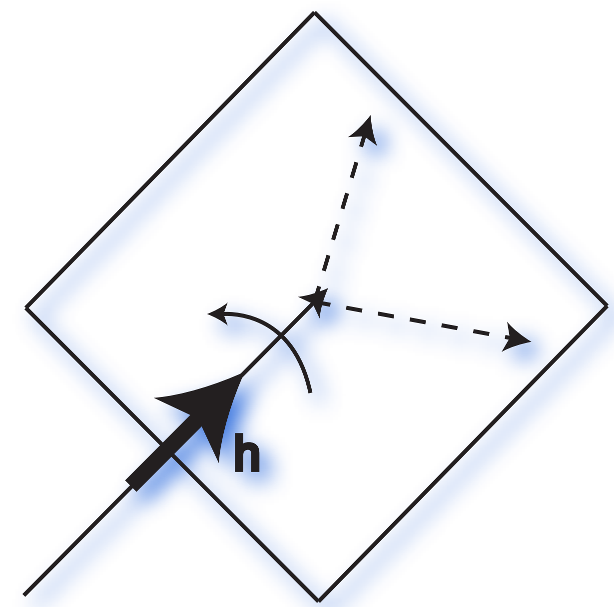
Model Independence

- Interfering helicity states of a decaying particle leave an imprint in the decay plane's distribution

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

$$\begin{aligned} |\mathcal{M}|^2 &= \left| \sum_h e^{ih\phi} \mathcal{M}_h(\phi = 0) \right|^2 \\ &= A_0 + \ldots + A_n \cos n\phi \end{aligned}$$

$$n = 2 \times \text{spin}$$

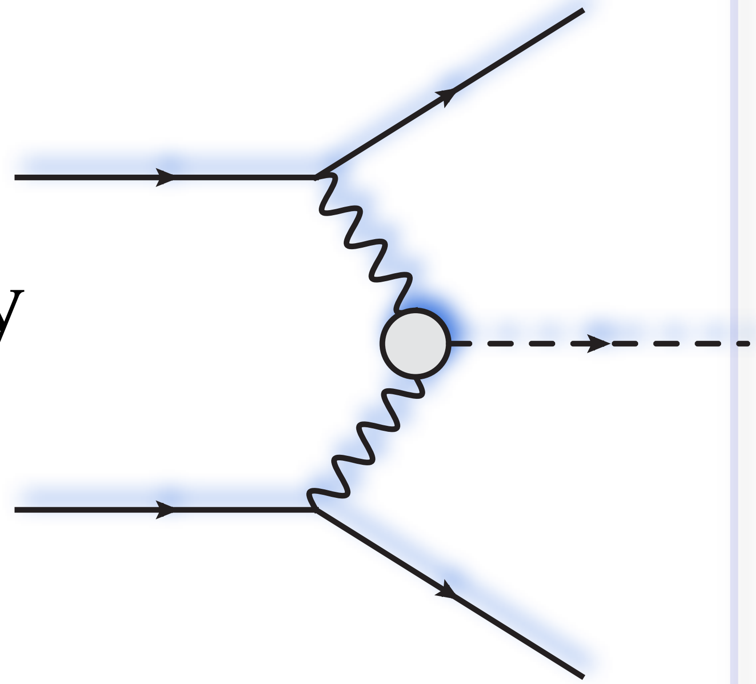


- 'Model Independent,' but still requires reconstruction of decay plane which is not always possible.

MRB with H. Murayama, V. Rentala, W. Klemm, B. Heinemann, S.Y. Choi and K. Mawatari
0711.0364, 0804.0476, 0811.3030, 0904.4561

Inspiration from Higgs Measurements

- Proposal from Zeppenfeld *et. al.*
- Consider on-shell Higgs production from Vector Boson Fusion (VBF)
  - Azimuthal angular dependence comes from gauge boson helicity
  - Presence of various cos/sin modes depends on how these helicities can be combined.
    - *i.e.* on the Lorentz structure of the matrix element for Higgs production



hep-ph/0105325, hep-ph/0605117, hep-ph/0703202

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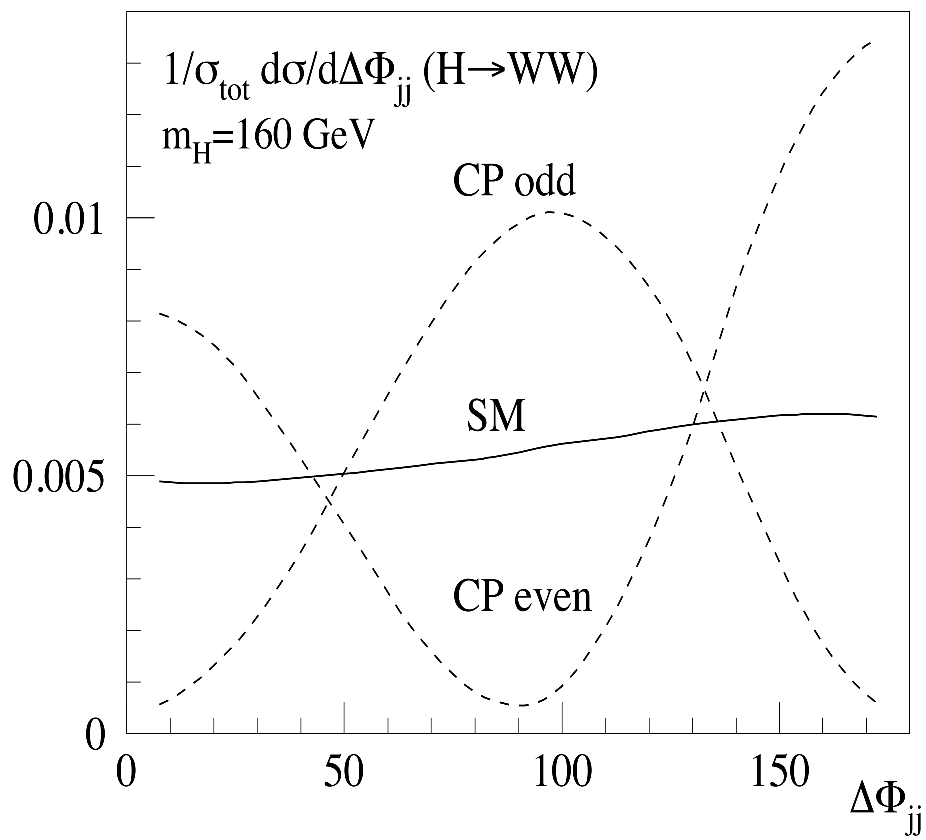
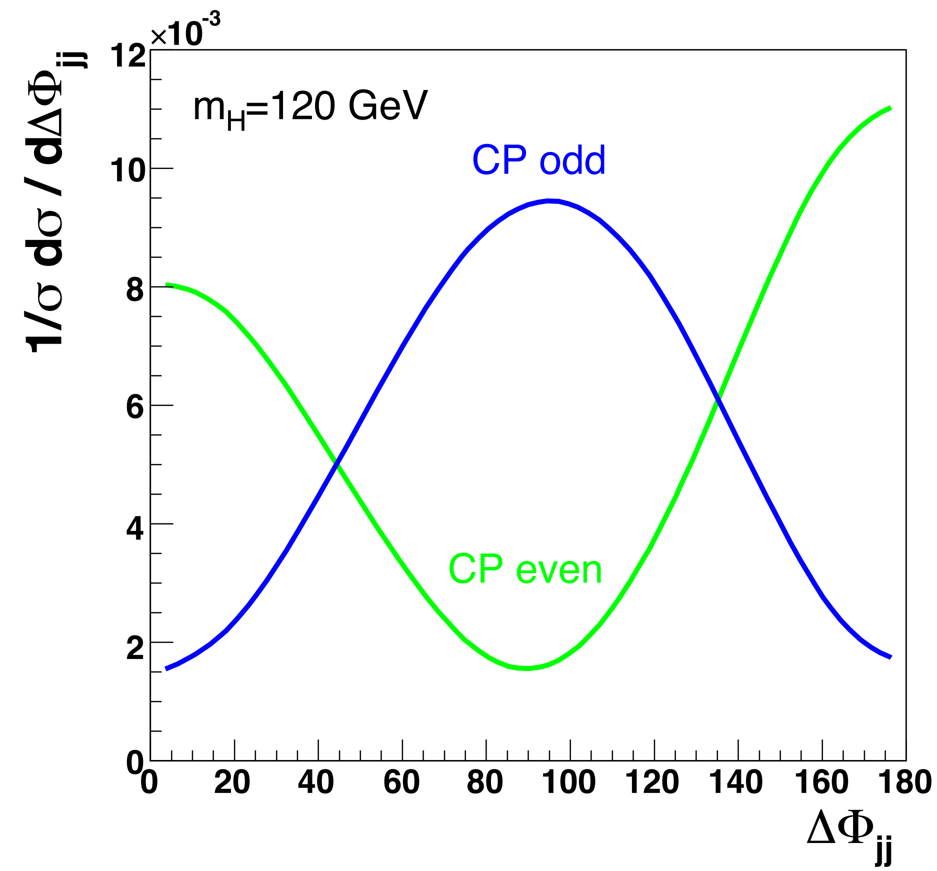
Inspiration from Higgs Measurements

- It's been shown that $d\sigma/d\Delta\phi$ sensitive to CP-properties of Higgs coupling



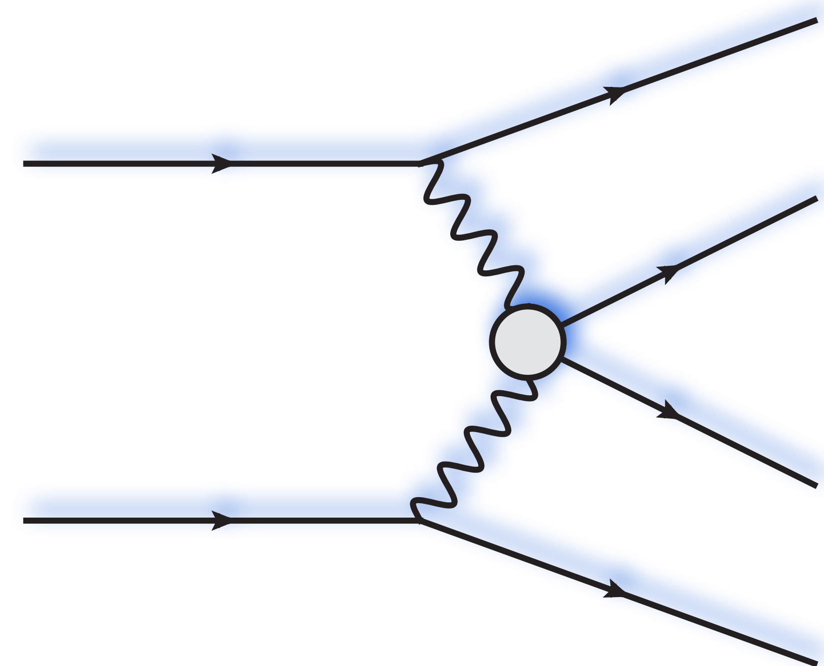


- SM background has no $\cos 2\Delta\phi$ mode.

hep-ph/0105325, hep-ph/0605117, hep-ph/0703202

A New Way to Measure Spin

- Generalize from single-particle production to pair-production.
  - Lorentz structure of pair-production matrix element fixes which combinations of vector boson polarizations can contribute to process



  - This is made measurable through the *difference* in azimuthal angle of the forward jets $\Delta\phi$

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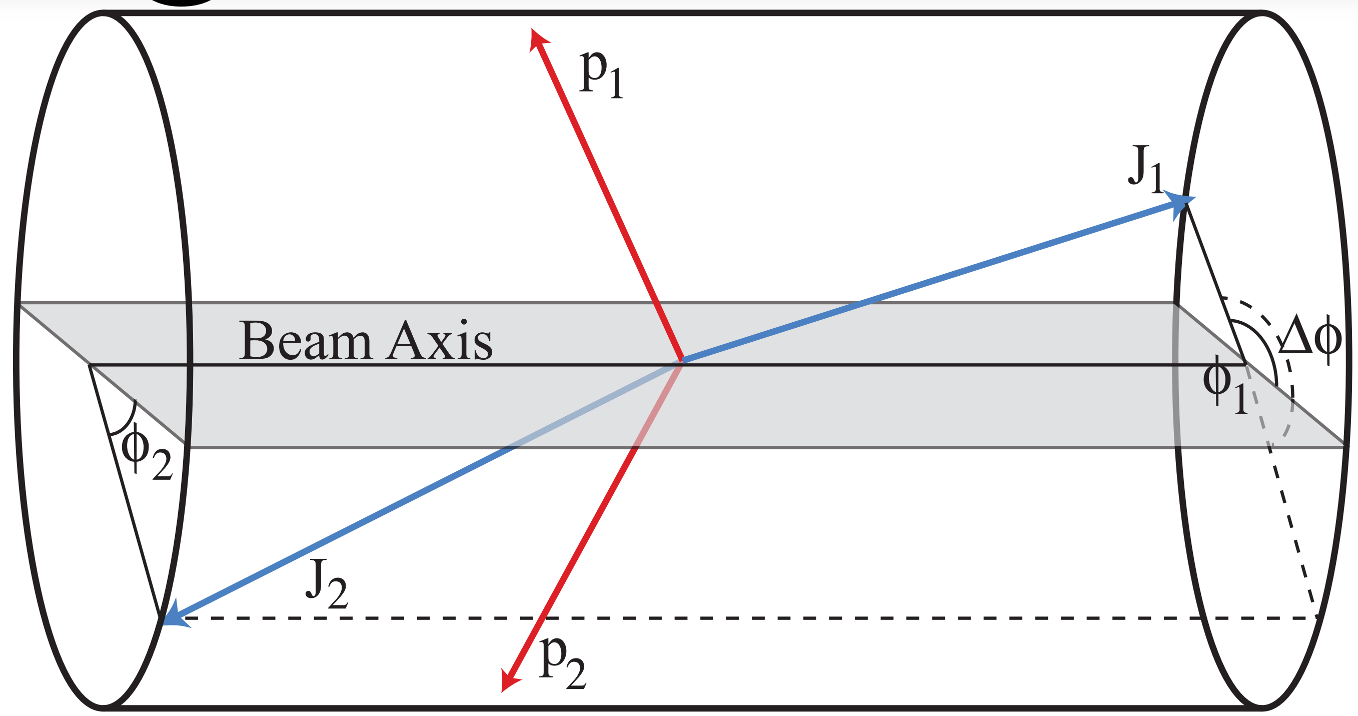
The Big Picture



- Since the spin measurement relies on the kinematics of jets J_1/J_2, the only requirements on new physics (p_1/p_2) is that we can trigger on it (and identify the forward jets)
- For this introductory study, we assume both these problems can be ignored
  - Clearly, we are not experimentalists.

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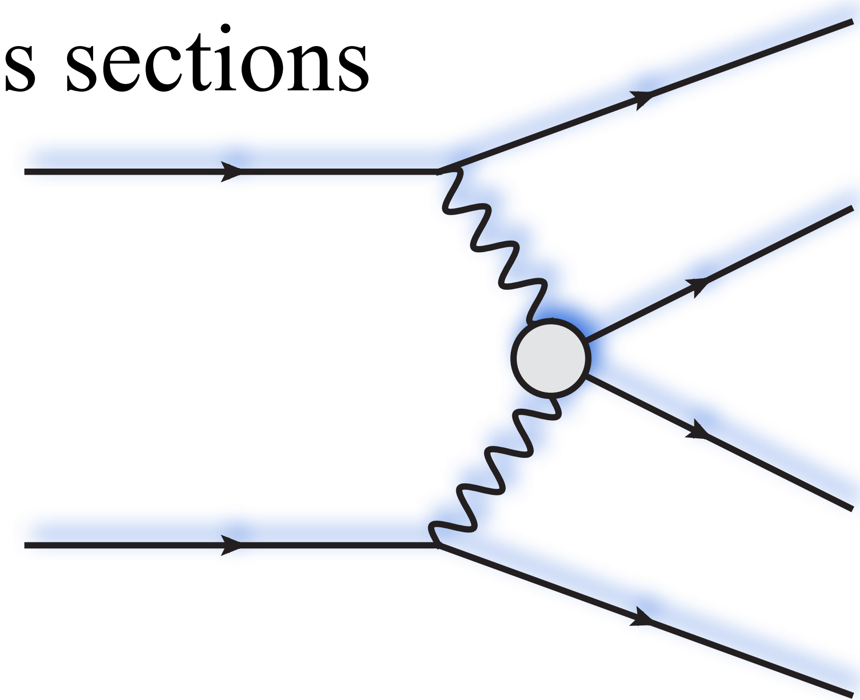
Scalars vs. Spinors

- Choose simple models: 500 GeV 'R-hadron' $SU(3)_C$ triplets with spin-0 or spin-1/2
  - Looking at 2 R-hadrons + 2 jet events
  - Avoids trigger and background problems
  - Large production cross sections

We'll consider the VBF production matrix elements



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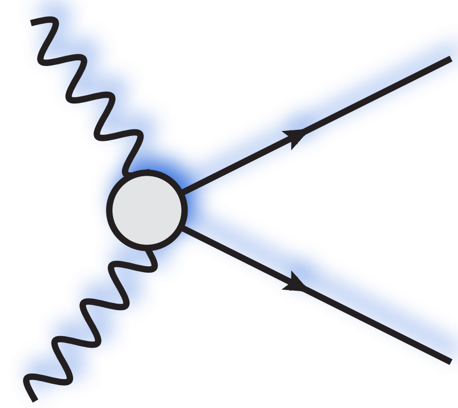

(This turns out to be an over-simplification)

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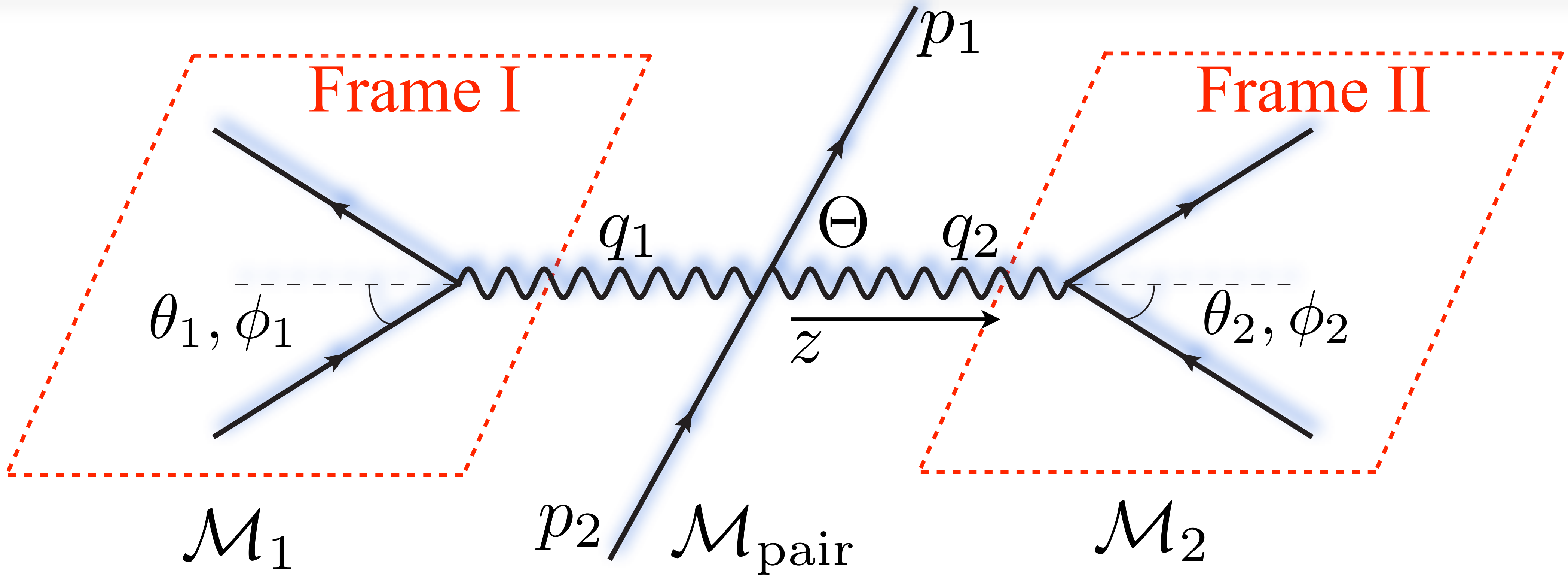
VBF Kinematics



- With these choices, ϕ dependence made clear:

$$\epsilon_{1/2} \propto e^{+i\phi_{1/2}}, e^{-i\phi_{1/2}}, e^{0\times i\phi_{1/2}}$$

- I've drawn quark initial states only, but anti-quark and gluon contribute as well.

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Azimuthal Angle

- Can expand out dependence on ϕ_1, ϕ_2:

$$|\mathcal{M}|^2 = \left| \sum_{h_1, h_2 = \pm, 0} \mathcal{M}_1 \mathcal{M}_2 \mathcal{M}_{\mathrm{pair}} e^{i(h_1\phi_1 + h_2\phi_2)} \right|^2$$

$$\begin{aligned}
|\mathcal{M}|^2 \quad = \quad & f_1 + f_2 \cos\phi_1 + f_3 \cos\phi_2 + f_4 \cos 2\phi_1 + f_5 \cos 2\phi_2 \\
& + f_6^+ \cos(\phi_1 + \phi_2) + f_6^- \cos(\phi_1 - \phi_2) + f_7^+ \cos(2\phi_1 + \phi_2) + f_7^- \cos(2\phi_1 - \phi_2) \\
& + f_8^+ \cos(\phi_1 + 2\phi_2) + f_8^- \cos(\phi_1 - 2\phi_2) + f_9^+ \cos 2(\phi_1 + \phi_2) + f_9^- \cos 2(\phi_1 - \phi_2) \\
& + \bar{f}_2 \sin\phi_1 + \bar{f}_3 \sin\phi_2 + \bar{f}_4 \sin 2\phi_1 + \bar{f}_5 \sin 2\phi_2 \\
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Azimuthal Angle

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$$|\mathcal{M}|^2 = \left| \sum_{h_1,h_2=\pm,0} \mathcal{M}_1 \mathcal{M}_2 \mathcal{M}_{\text{pair}} e^{i(h_1\phi_1 + h_2\phi_2)} \right|^2$$

$$|\mathcal{M}|^2 \quad = \quad f_1 + f_6^- \cos\Delta\phi + f_9^- \cos 2\Delta\phi$$

After integrating out

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f_9^-

- We will show that f_6^- gets a contribution from cuts.
- Look at the coefficient of $\cos 2\Delta\phi$ instead.
  - From

$$|\mathcal{M}|^2 = \left| \sum_{h_1, h_2 = \pm, 0} \mathcal{M}_1 \mathcal{M}_2 \mathcal{M}_{\text{pair}} e^{i(h_1\phi_1 + h_2\phi_2)} \right|^2$$

we're interested in

$$f_9^- = (\mathcal{PS}) \sum_{\substack{h_1, h_1', h_2, h_2' \\ |h_i - h_i'| = 2}} \Big(\mathcal{M}_1(h_1) \mathcal{M}_2(h_2) \mathcal{M}_{\text{pair}}(h_1, h_2) \Big) \times \Big(\mathcal{M}_1(h_1') \mathcal{M}_2(h_2') \mathcal{M}_{\text{pair}}(h_1', h_2') \Big)^*$$

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VBF Cuts

- Our measurement technique requires that we isolate VBF events from other production
- Use the cuts from Zeppenfeld *et. al.*
  - R-hadron cuts to ensure they remain in the barrel

$$\eta_{j_1} \cdot \eta_{j_2} < 0,\ |\eta_j| \leq 5,\ |\eta_{j_1} - \eta_{j_2}| \geq 4.2$$
$$p_{T,j_1} \geq 30 \text{ GeV},\ p_{T,j} \geq 20 \text{ GeV},\ M_{jj} \geq 500 \text{ GeV}$$
$$|\eta_{R-\text{hadron}}| < 2.1,\ \ p_{T,R-\text{hadron}} > 50 \text{ GeV}$$

Scalars

- Factoring out production matrix elements:

$$\begin{aligned} f_9^- &= (\mathcal{PS})\mathcal{M}_1(+1)\mathcal{M}_1(-1)^*\mathcal{M}_2(-1)\mathcal{M}_2(+1)^* \\ &\times \Big[\mathcal{M}_{\rm pair}(+1,-1)\mathcal{M}_{\rm pair}(-1,+1)^* + (1 \leftrightarrow -1)\Big] \end{aligned}$$

- In an abelian theory, easy to write down the matrix elements for transverse polarizations:

$$\mathcal{M}_{\rm scalar} \propto (\epsilon_1 \cdot \epsilon_2) - 4\Big[\frac{(p_1 \cdot \epsilon_1)(p_1 - q_1)\cdot \epsilon_2}{q_1^2 - 2p_1 \cdot q_1} + \frac{(p_1 \cdot \epsilon_2)(p_1 - q_2)\cdot \epsilon_1}{q_2^2 - 2p_1 \cdot q_2}\Big]$$

- Invariant under $\epsilon^+_{1/2} \leftrightarrow \epsilon^-_{2/1}$
- (Also true in non-abelian calculation)

Scalars

- Since $\mathcal{M}(+1,-1) = \mathcal{M}(-1,+1)$,

$$f_9^- \propto \mathcal{M}(+1,-1)\mathcal{M}(-1,+1)^* > 0$$

- Prediction: $\cos 2\Delta\phi$ mode for scalars must be positive

- Recall this is a consequence of how polarization vectors enter into $\mathcal{M}_{\mathrm{pair}}$ calculation
  - *i.e.* Lorentz structure

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Spinors

- Need to repeat the calculation for spinors
  - (Spoiler: f_9^- will be negative)
- Straightforward for on-shell abelian example:

$$\mathcal{M}(\pm 1, \mp 1) = i\bar{u}\left[\frac{\not{\epsilon}_1^{\pm}(\not{p}_1 - \not{q}_1 + M)\not{\epsilon}_2^{\mp}}{q_1^2 - 2p_1 \cdot q_1} + \frac{\not{\epsilon}_2^{\mp}(\not{p}_1 - \not{q}_2 + M)\not{\epsilon}_1^{\pm}}{q_2^2 - 2p_1 \cdot q_2}\right] v$$

- After lots of tediousness, you can prove that

$$f_9^- \propto -\frac{64m^2}{s}\left(1 + \frac{4m^2}{s\sqrt{1-4m^2/s}}\tanh^{-1}\sqrt{1-4m^2/s}\right) < 0$$

(Remember: Abelian)

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Non-abelian Spinors

- Can divide $\mathcal{M}(+1,-1)\mathcal{M}(-1,+1)^*$ into symmetric ($d_{abc}d_{abd}T^cT^d$) and antisymmetric ($f^{abc}f^{abd}T^cT^d$) parts
  - Symmetric part reproduces the abelian example:

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  - Simulations of full process find $f_9^- < 0$
  - Naive calculation of antisymmetric part finds positive and *large* contribution

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WHAT?

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Non-abelian Spinors

- Naive calculation ignores cuts (integrates over all of phase space) and only used VBF *t*- and *s*-channel diagrams (not gauge invariant)
  - Analytic calculation can't easily take into account the cuts
    - *i.e.* 4-body phase space is hard
  - Full calculation involves hundreds of diagrams

- Rather than reinvent the wheel, use Calchep!

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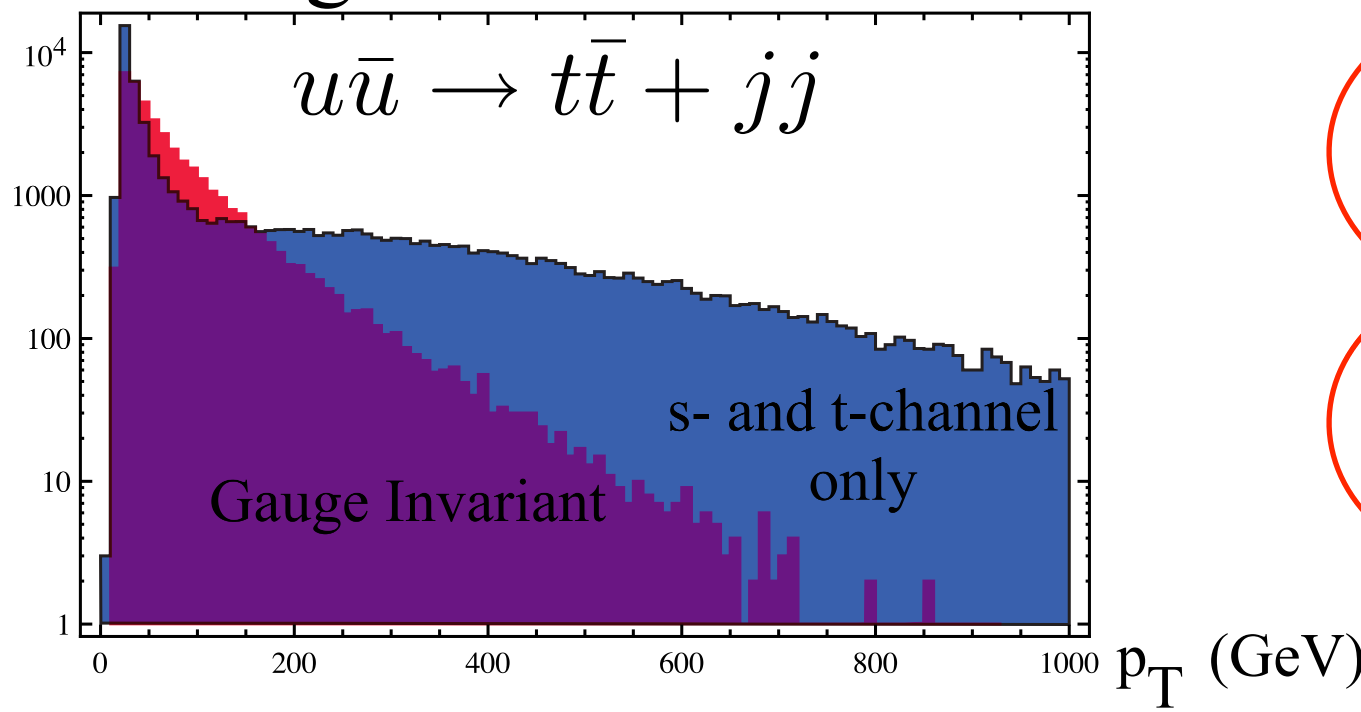
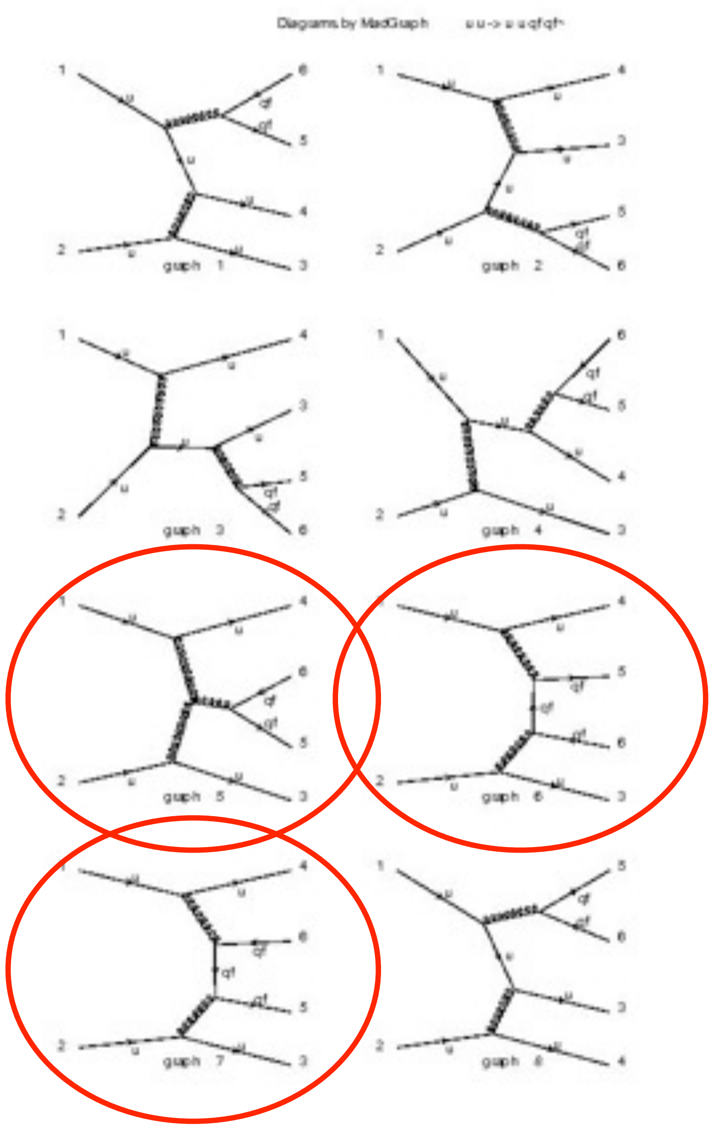
Gauge Invariance

- We were calculating only *s*- and *t*-channel diagrams
- This is not a gauge invariant quantity.
- Using Calchep, can compare distributions with and without all diagrams.





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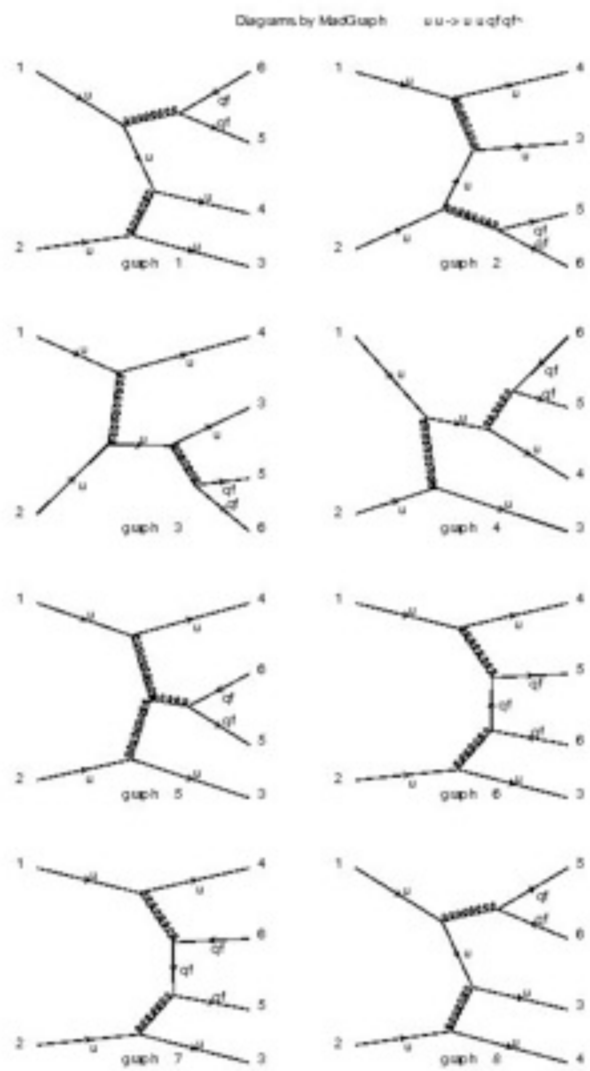
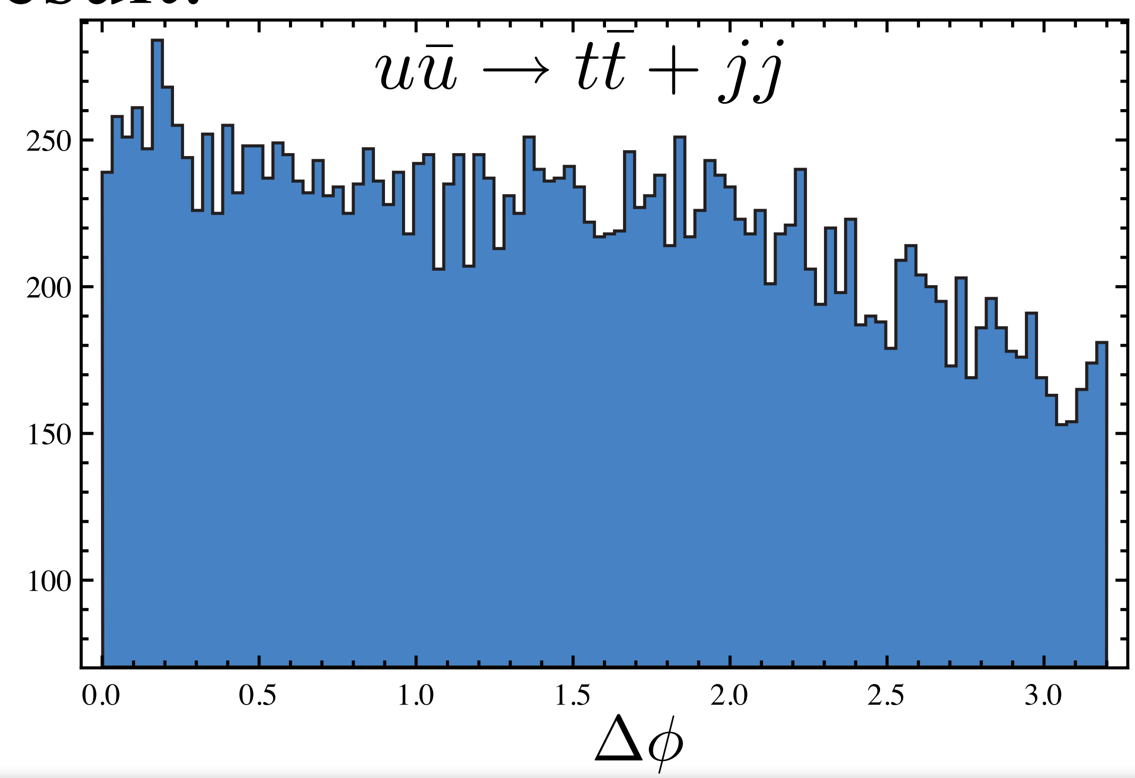
Tuesday, September 14, 2010

Gauge Invariance

- Lesson learned: gauge invariance is important!
  - Need to include all diagrams, not just the ones that 'look like VBF'
  - Cancellations between all diagrams remove spurious high p_T tail, as a result:





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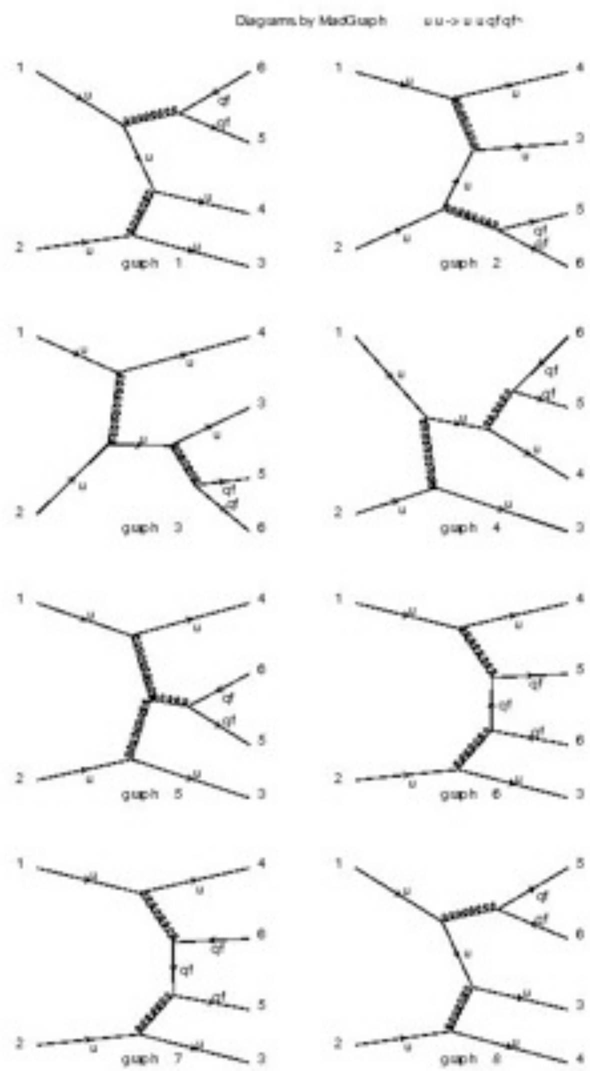
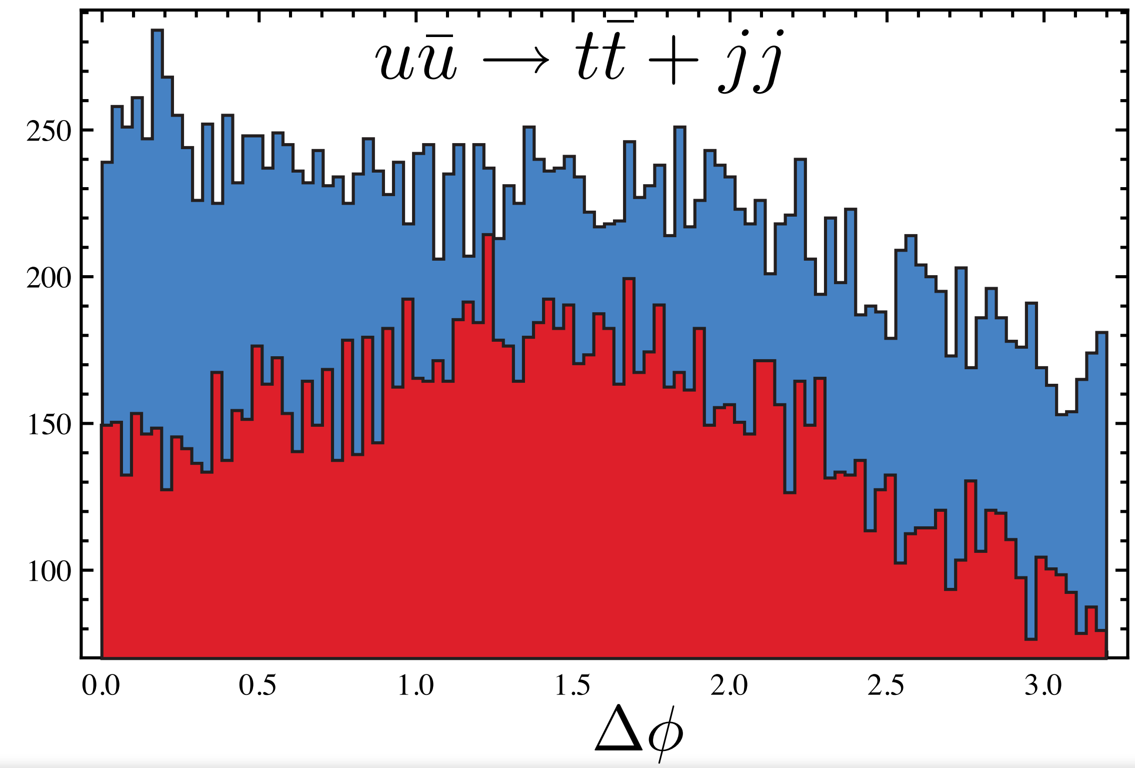




Results

- Use MadGraph/MadEvent for background-free simulation:

$$pp \to 2(\mathrm{R-hadrons}) + jj$$

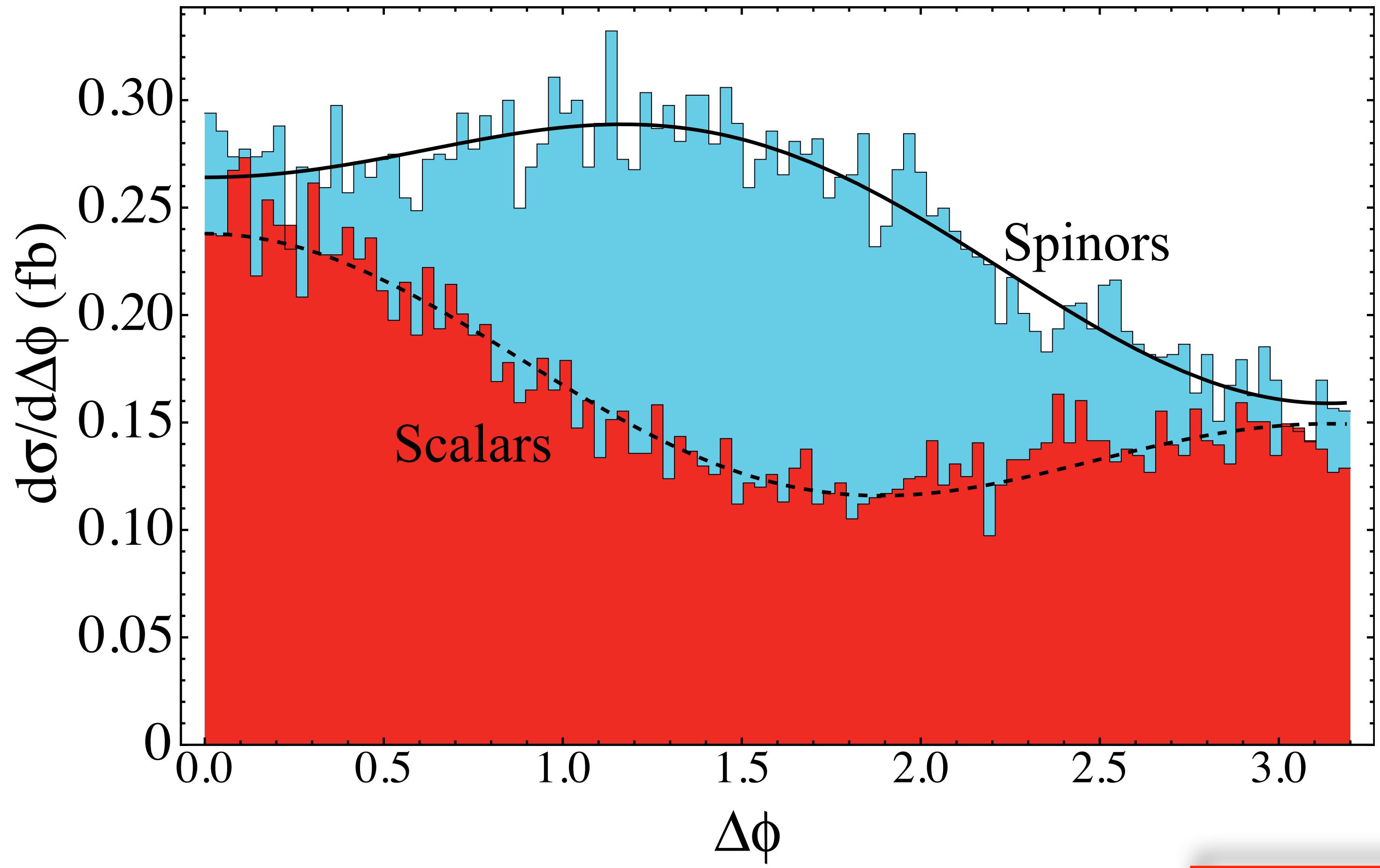
- Apply VBF-isolating cuts:

$$\eta_{j_1} \cdot \eta_{j_2} < 0,\ |\eta_j| \leq 5,\ |\eta_{j_1} - \eta_{j_2}| \geq 4.2$$
$$p_{T,j_1} \geq 30\ \mathrm{GeV},\ p_{T,j} \geq 20\ \mathrm{GeV},\ M_{jj} \geq 500\ \mathrm{GeV}$$
$$|\eta_{R-\mathrm{hadron}}| < 2.1,\ \ p_{T,R-\mathrm{hadron}} > 50\ \mathrm{GeV}$$

- Total cross sections ($\sqrt{s} = 10\ \mathrm{TeV}, m = 500\ \mathrm{GeV}$):

$$\sigma_{\mathrm{spinor}} = 33\ \mathrm{fb}, \sigma_{\mathrm{scalar}} = 21\ \mathrm{fb}$$

Results



$$\frac{d\sigma_{\rm scalar}}{d\Delta\phi} = 0.16 + 0.044\cos\Delta\phi + 0.035\cos 2\Delta\phi \quad \text{(fb)}$$

$$\frac{d\sigma_{\rm spinor}}{d\Delta\phi} = 0.24 + 0.053\cos\Delta\phi - 0.033\cos 2\Delta\phi \quad \text{(fb)}$$

$$(f_9^- / f_1)_{\rm scalar} = 0.22$$

$$(f_9^- / f_1)_{\rm spinor} = -0.14$$

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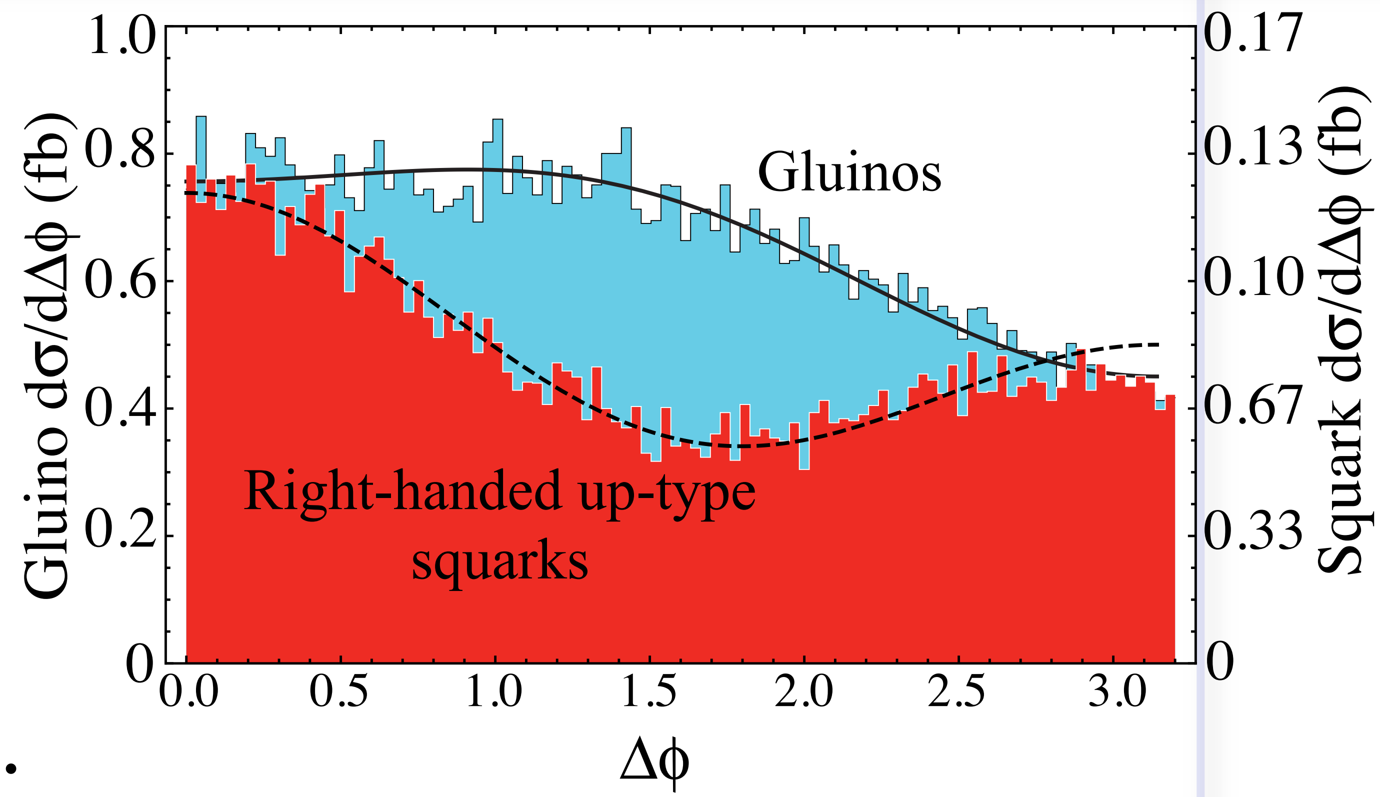
SUSY Applications

- We picked a "background free" model
  - No central jets that can be confused with the forward jets that constitute our observables
- Obvious next step: SUSY gluino pairs/squark pairs
- What we have done:
  - Background-free, trigger/tagging free MadGraph/Calchep study (*i.e.* is there a signal?)

Gluinos and Squarks



- Demonstrates that a signal is present, and that the majorana nature of the gluinos isn't a problem.
- What needs to be done:
  - Background (naive expectation: flat in $\cos 2\Delta\phi$)
  - Trigger analysis, cut optimization
  - Jet ID, including decays of gluinos/squarks

Future Work

- Top spin measurements
  - Negative f_9^- confirmed in simulations
  - Might be a background to New Physics searches
    - b-tagging necessary?
  - Tevatron search possible?
- Weak VBF events
  - Rate will be low, but signal should be present
- Vector Boson final states
  - Expectation is a positive f_9^-
  - If so, how to distinguish from scalars?

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Future Work

- Other modes:

$$
\begin{aligned}
|\mathcal{M}|^2 \;=\;& f_1 + f_2\cos\phi_1 + f_3\cos\phi_2 + f_4\cos 2\phi_1 + f_5\cos 2\phi_2 \\
&+ f_6^+\cos(\phi_1+\phi_2) + f_6^-\cos(\phi_1-\phi_2) + f_7^+\cos(2\phi_1+\phi_2) + f_7^-\cos(2\phi_1-\phi_2) \\
&+ f_8^+\cos(\phi_1+2\phi_2) + f_8^-\cos(\phi_1-2\phi_2) + f_9^+\cos 2(\phi_1+\phi_2) + f_9^-\cos 2(\phi_1-\phi_2) \\
&+ \bar{f}_2\sin\phi_1 + \bar{f}_3\sin\phi_2 + \bar{f}_4\sin 2\phi_1 + \bar{f}_5\sin 2\phi_2 \\
&+ \bar{f}_6^+\sin(\phi_1+\phi_2) + \bar{f}_6^-\sin(\phi_1-\phi_2) + \bar{f}_7^+\sin(2\phi_1+\phi_2) + \bar{f}_7^-\sin(2\phi_1-\phi_2) \\
&+ \bar{f}_8^+\sin(\phi_1+2\phi_2) + \bar{f}_8^-\sin(\phi_1-2\phi_2) + \bar{f}_9^+\sin 2(\phi_1+\phi_2) + \bar{f}_9^-\sin 2(\phi_1-\phi_2)
\end{aligned}
$$

- If we can identify some plane in the event, we can use ϕ_1, ϕ_2 modes, not just $\Delta\phi$
  - Not as 'model independent'
  - Probably very hard

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Conclusions

- Azimuthal angular correlations of associated forward jets in pair-production events carry spin information.
  - Demonstrated in a “best case scenario.”
- Technique has significant advantages:
  - Works regardless of decay modes or structure of couplings
  - Does not require reconstruction of heavy particle kinematics
- A lot of work remains to realize this measurement at Tevatron or the LHC

Non-Relativistic Version

- Consider the symmetries of the final state radiation in QM (rather than QFT)
  - The combination $\psi_{\text{spatial}}\psi_{\text{color}}$ needs to be symmetric
  - Limiting case of forward jets going down the beam, $\ell = 0$ and so ψ_{spatial} symmetric
  - Thus, the color indices must be symmetric
- Only $d_{abc}d_{abd}T^cT^d$ (negative f_9^-), no $f^{abc}f^{abd}T^cT^d$ (positive f_9^-)

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