MARMOSET:
The Physics of On-Shell Effective Theories

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hep-ph/0703088 www.marmoset-mc.net

MARMOSET @ Princeton

Nima	Path to the New Standard Model
Jesse	Physics of On-Shell Effective Theories
Philip (LHC Olympics)	MARMOSET in Practice (Cornell BB)
Natalia (MC4BSM)	An OSET Monte Carlo Tool
Johan (MC4BSM)	MadGraph and MARMOSET

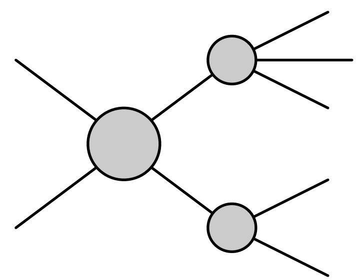
hep-ph/0703088 @ arXiv.org

Sec. 1	Path to the New Standard Model
Sec. 2 (App. A, B, C)	Physics of On-Shell Effective Theories
Sec. 4	MARMOSET in Practice (Michigan BB)
Sec. 3	An OSET Monte Carlo Tool
...	MadGraph and MARMOSET

MARMOSET:

Mass And Rate Modeling in On-Shell Effective Theories

OSET

LHC Signatures $\Leftrightarrow$  $\Leftrightarrow$ $\mathcal{L}$

$$\underbrace{\qquad\qquad\qquad\qquad\qquad\qquad}$$

$m \qquad \sigma \qquad \mathrm{Br} \qquad |\mathcal{M}|^2$

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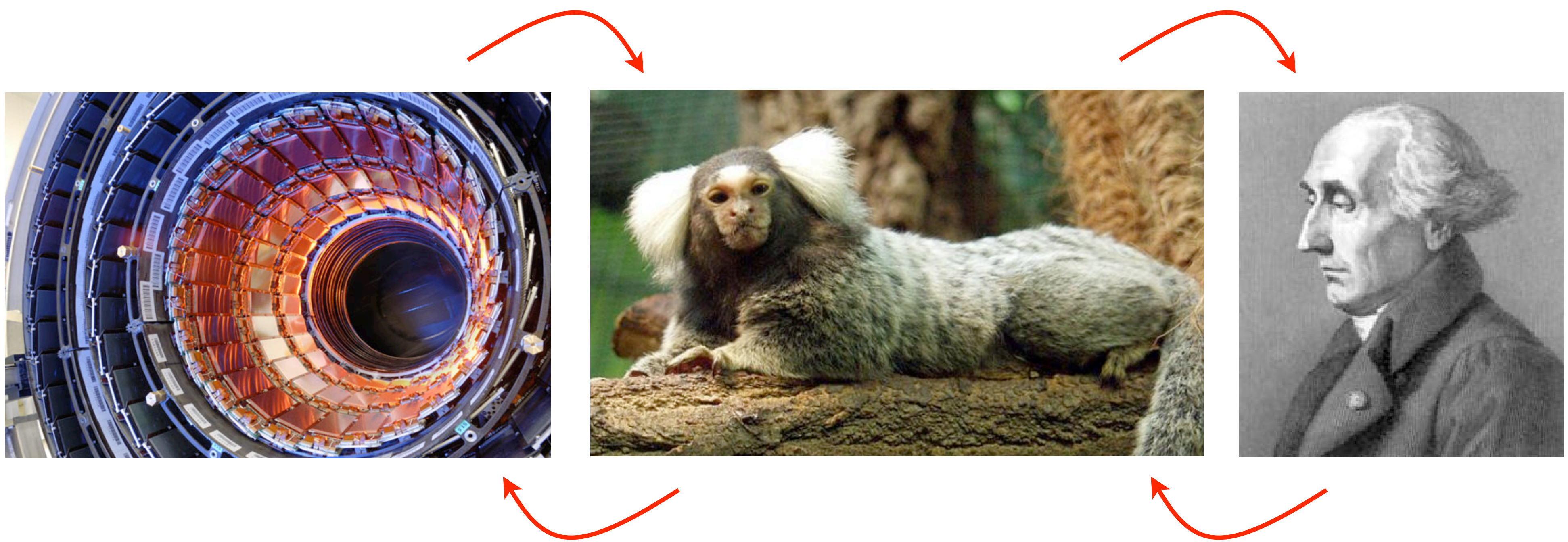
MARMOSET:

Mass And Rate Modeling in On-Shell Effective Theories



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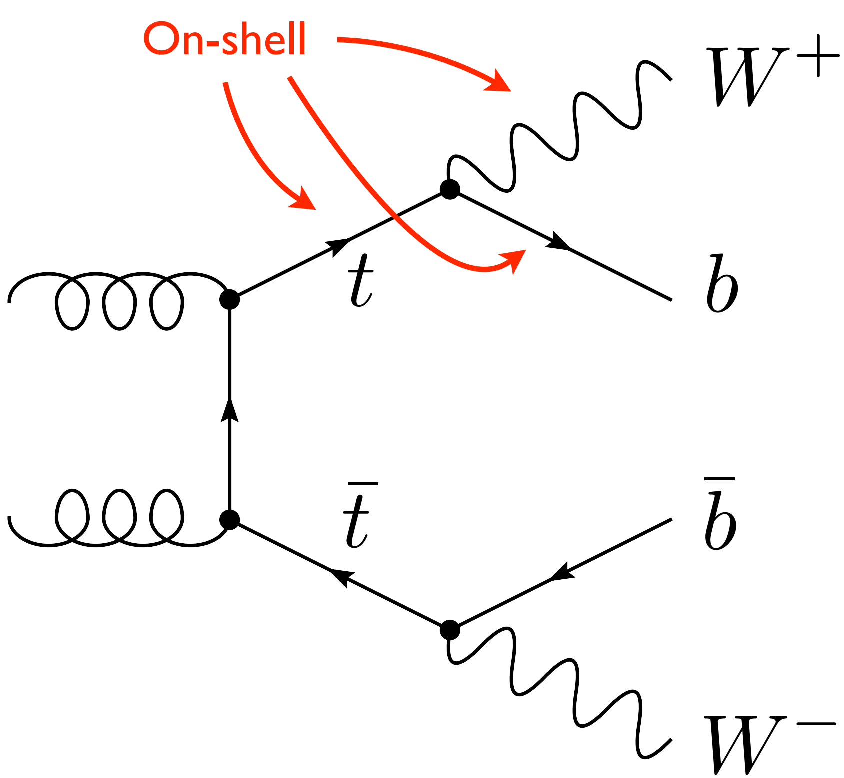
The Physics Behind MARMOSET

(Systematically Improvable) Approximate Monte Carlo Based on Narrow Widths and Phase Space

$m \qquad \sigma \qquad \mathrm{Br} \qquad |\mathcal{M}|^2$

E.g.: Top Quark

Masses, Rates, and Topology vs. Amplitudes



Dominant Top Properties:

$\sigma(gg \to t\bar{t})$

$\mathrm{Br}(t \to bW)$

m_t, m_W, m_b

Detailed Top Properties:

$d\sigma/d\hat{t}$

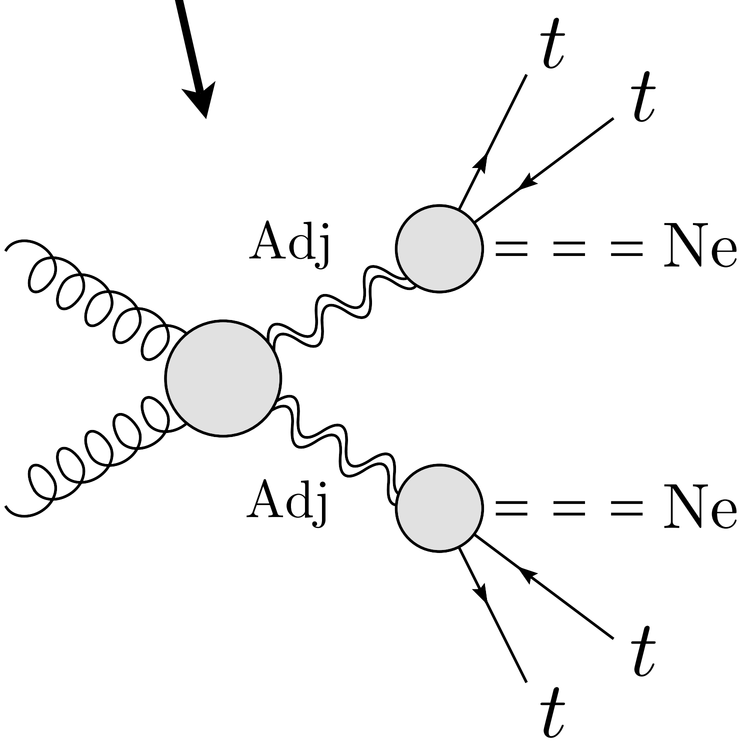
W helicity

t charge

Adjoints at the LHC?

Excess of $4b\ 4\ell\ \not{E}_T$ → SUSY with $\tilde{g}\tilde{g} \to t\bar{t}t\bar{t}\tilde{N}\tilde{N}$?

(Through off-shell stop.)



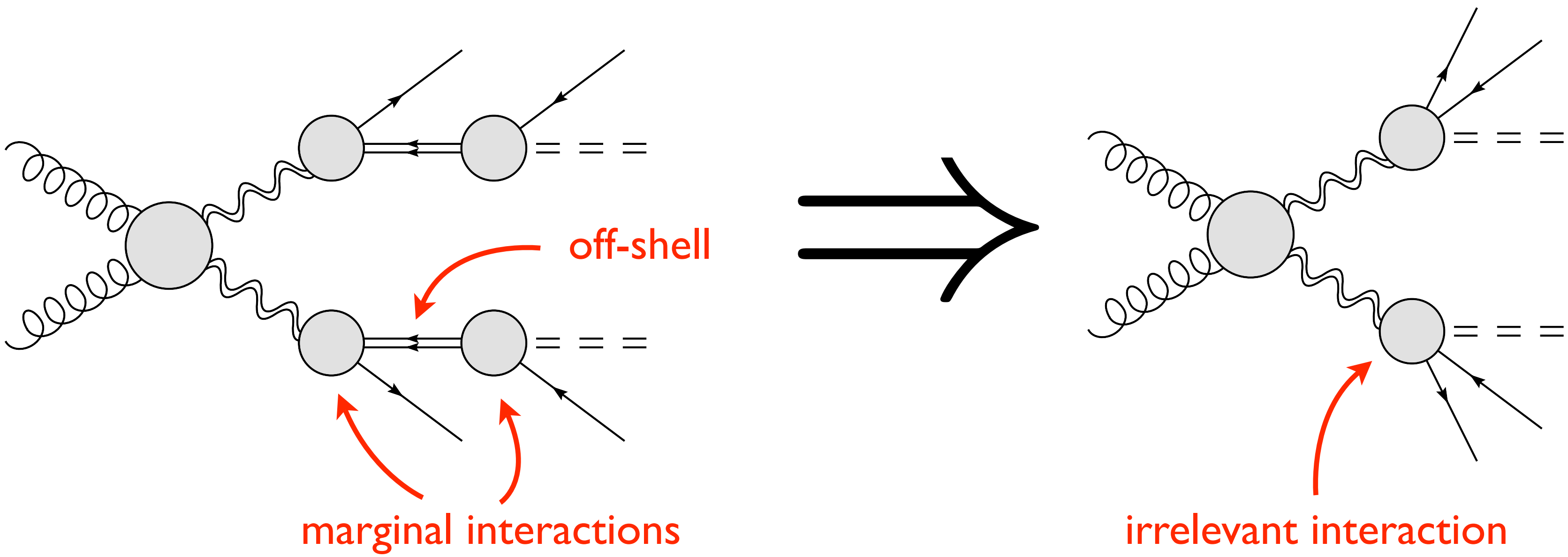
New Physics Properties:

$$m_{\mathrm{Adj}}, m_{\mathrm{Ne}}$$

$$\sigma(gg \to \mathrm{Adj\ Adj})$$

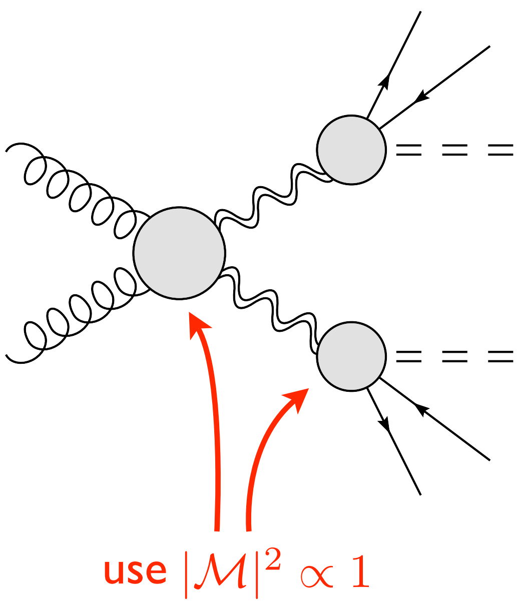
$$\mathrm{Br}(\mathrm{Adj} \to t\ t\ \mathrm{Ne})$$

The Effective Approach



Use narrow width approximation.
Integrate out off-shell particles at each decay stage.

The Effective^2 Approach

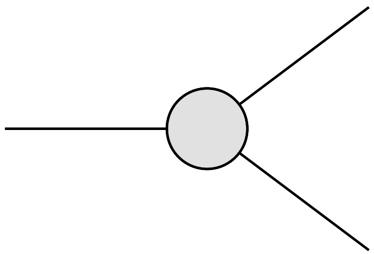


For almost all models, Matrix Elements well-approximated by Phase Space and Narrow Widths.

Dominant structures independent of Quantum Amplitudes.

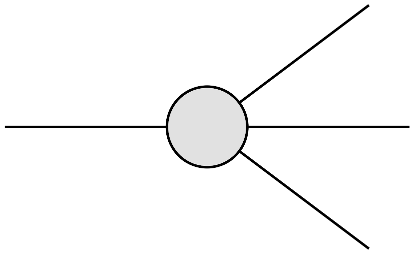
Not only can we integrate out off-shell particles à la Wilson, but we can often ignore detailed vertex structure!

Decay Folk Theorem



Two-Body Decays:

At most, lose angular correlations with other parts of the topology. (Kinematics correct.)



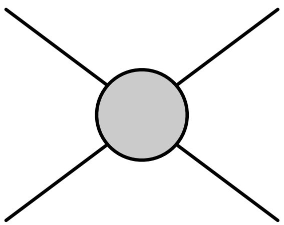
Multi-Body Decays:

Lose kinematic correlations among decay products. (Energy/momentum conserved.)

Pair-wise invariant masses have correct thresholds (i.e. edge/endpoint locations) but incorrect shapes.

(Use observable less sensitive to correlations, like single particle p_T.)

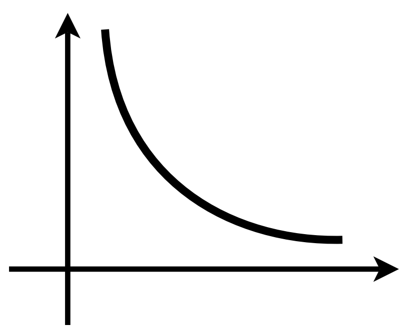
2→2 Folk Theorem



$$|\mathcal{M}|^2 = f\left(s, \xi\right) \qquad \xi = \frac{t-u}{s} = \beta\cos\theta$$

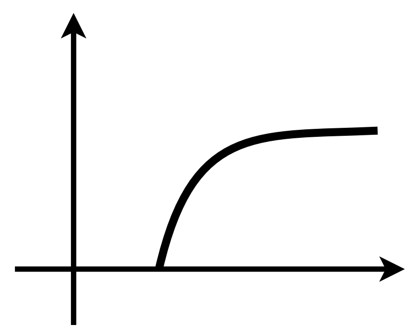
$$\frac{d\sigma}{d\hat{t}} = \int$$

Parton Luminosity



$\times$

Phase Space (Threshold)



$\times\, |\mathcal{M}|^2$

Well Approximated by Constant!

Cross Sections Dominated by Thresholds!

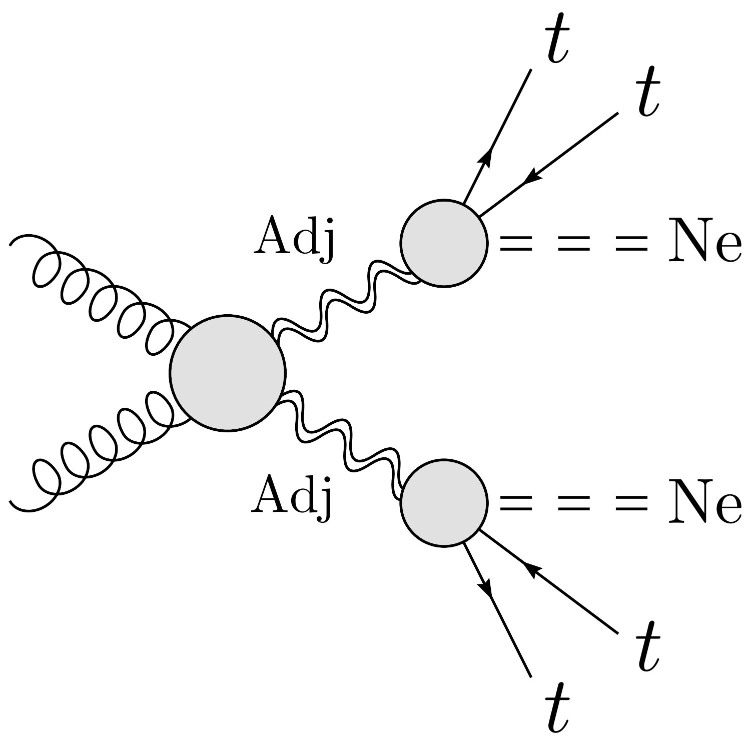
Further Considerations

Correlated/Detailed Structures Washed Out by...

- Low Statistics at Low Luminosity
- Finite Experimental Resolution
- Combinatoric Background
- Inability to Fully Reconstruct Events (especially with new stable neutral particles)

A Zeroth-Order Monte Carlo Tool need only be as Accurate as the Data to be Modeled.

On-Shell Effective Theories (v1)



New Physics Properties:

$$m_{\text{Adj}}, m_{\text{Ne}}$$

$$\sigma(gg \to \text{Adj Adj})$$

$$\text{Br}(\text{Adj} \to t\ t\ \text{Ne})$$

Characterize New Physics In Term of Production/Decay Topologies, Rates, and Masses

MC: m σ Br ~~$|\mathcal{M}|^2$~~

Beyond Zeroth-Order

To go beyond OSETs, do we need full Lagrangian?

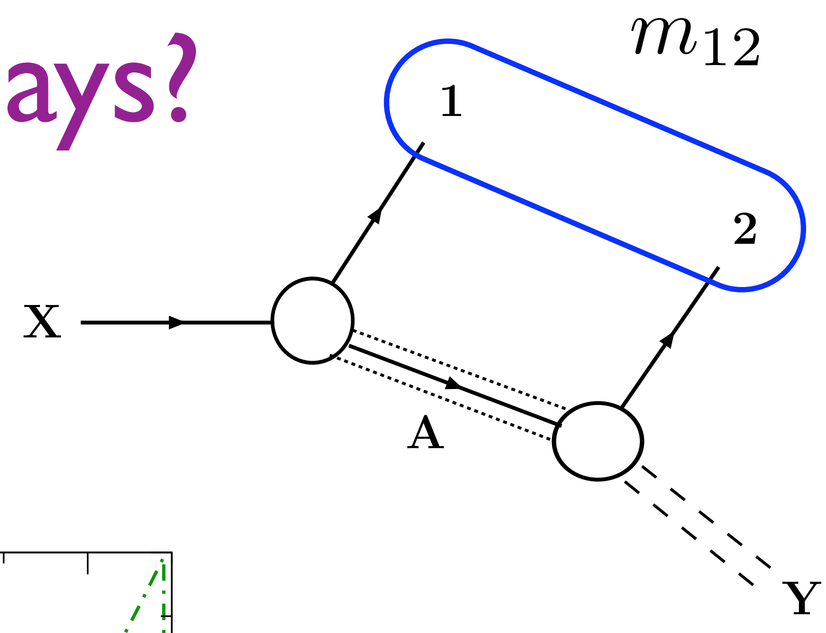
$$\cancel{|\mathcal{M}|^2} \Rightarrow |\mathcal{M}_{\text{approx}}|^2 \Rightarrow |\mathcal{M}_{\text{real}}|^2$$

We envision MARMOSET as a tool to interpolate between varying levels of theoretical sophistication.

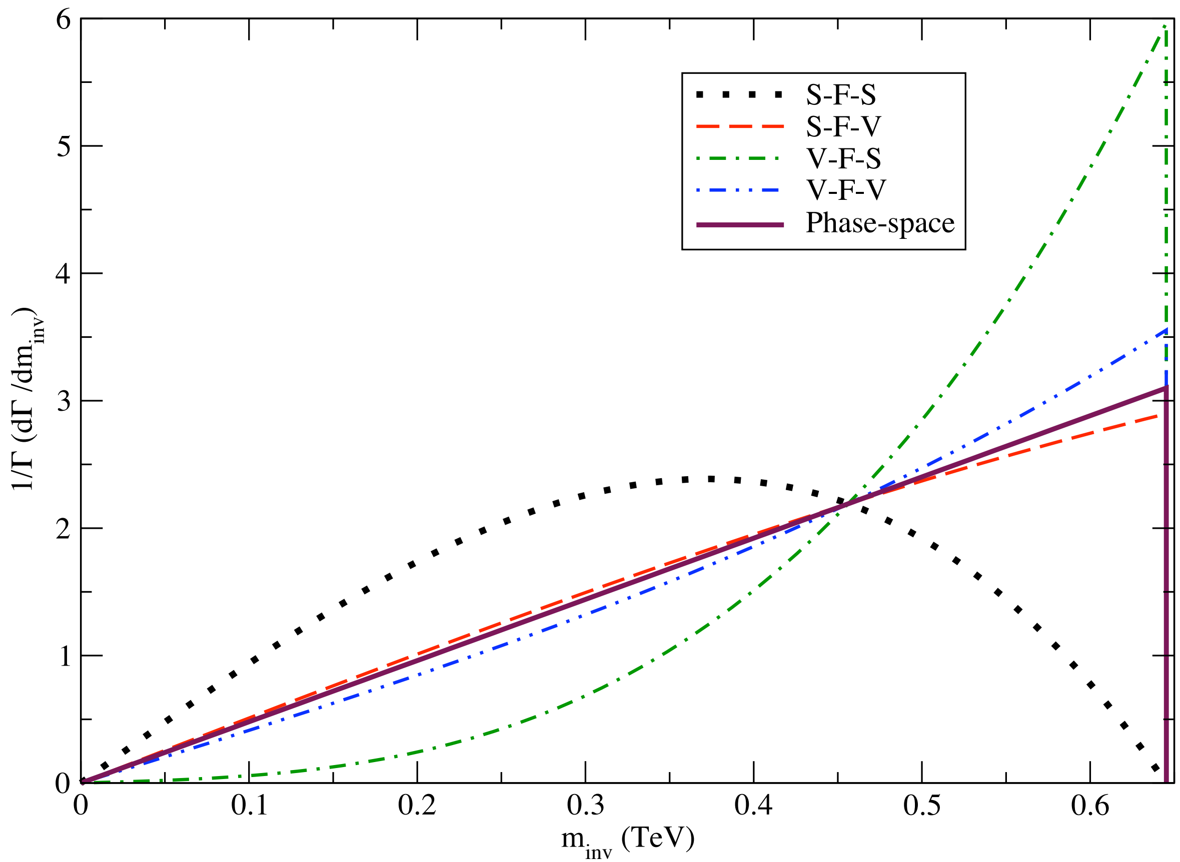
What are leading effects of Quantum Amplitudes?

Smallest "complete" parametrization of new physics?

$|\mathcal{M}|^2$ True for Decays?

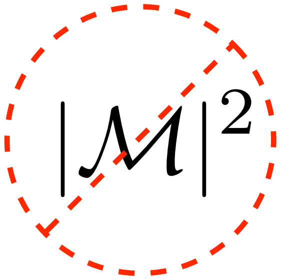


Di-object Distributions

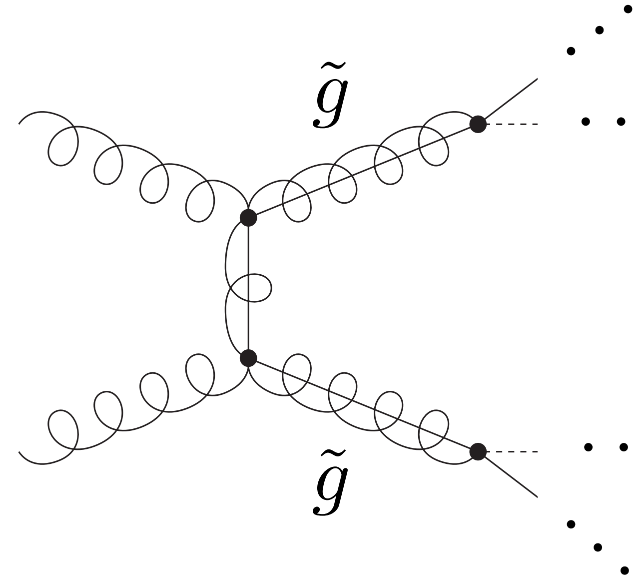


Angular correlations in cascade decays are known to be important!

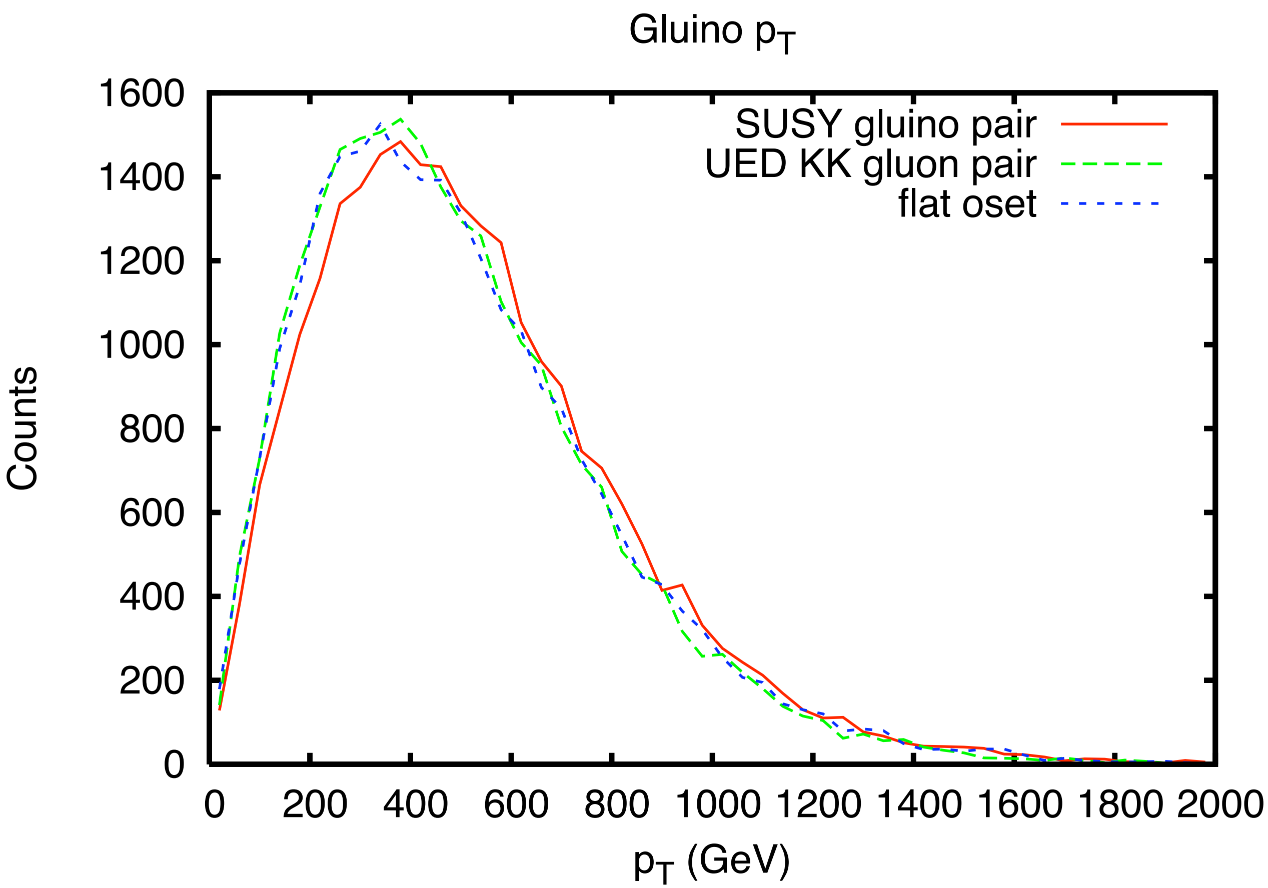
See Johan's talk about MadGraph/MARMOSET

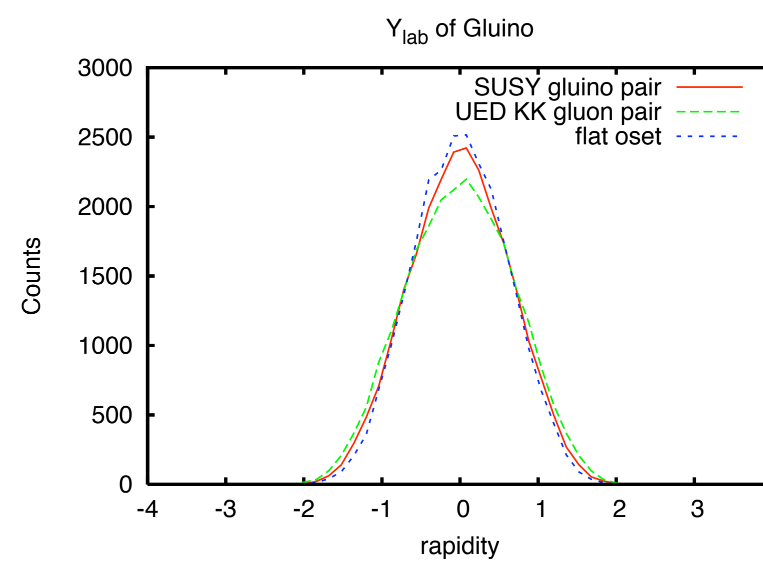


True for 2→2?



Remarkable insensitivity!



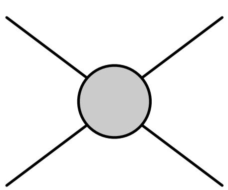


The Physics of OSETs

Because of homogeneity of Parton Luminosities (and assuming equal final state masses): $(\xi = \beta \cos\theta)$

$$\frac{d\sigma}{dp_T} \text{ invariant under } |\mathcal{M}|^2 = s^p \to s^p \xi^q \ !$$

For "reasonable" matrix elements, Transverse Structure of 2→2 scattering well described by:

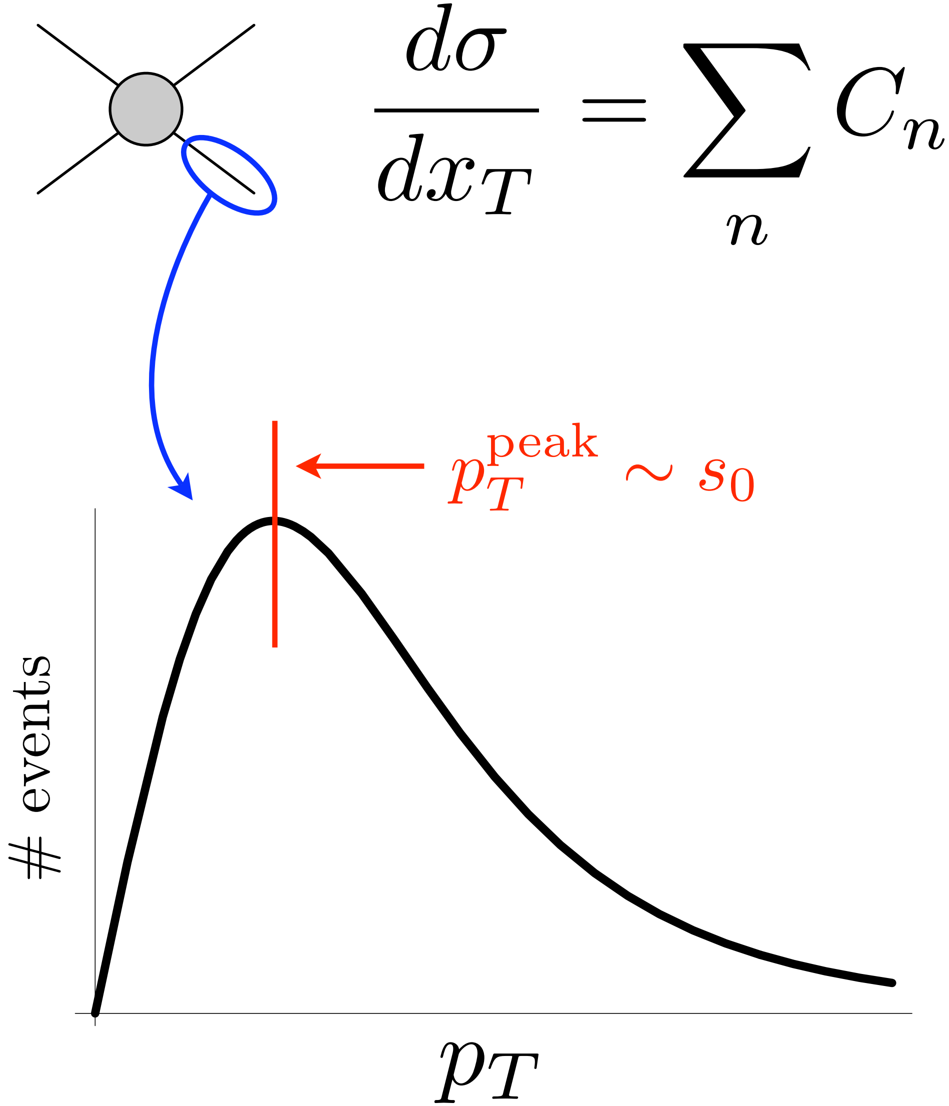


$$|\mathcal{M}_{\rm approx}|^2 = A + B\frac{s_0}{s} + C\frac{s}{s_0}$$

Similar results for Rapidity Structure.

The Physics of OSETs

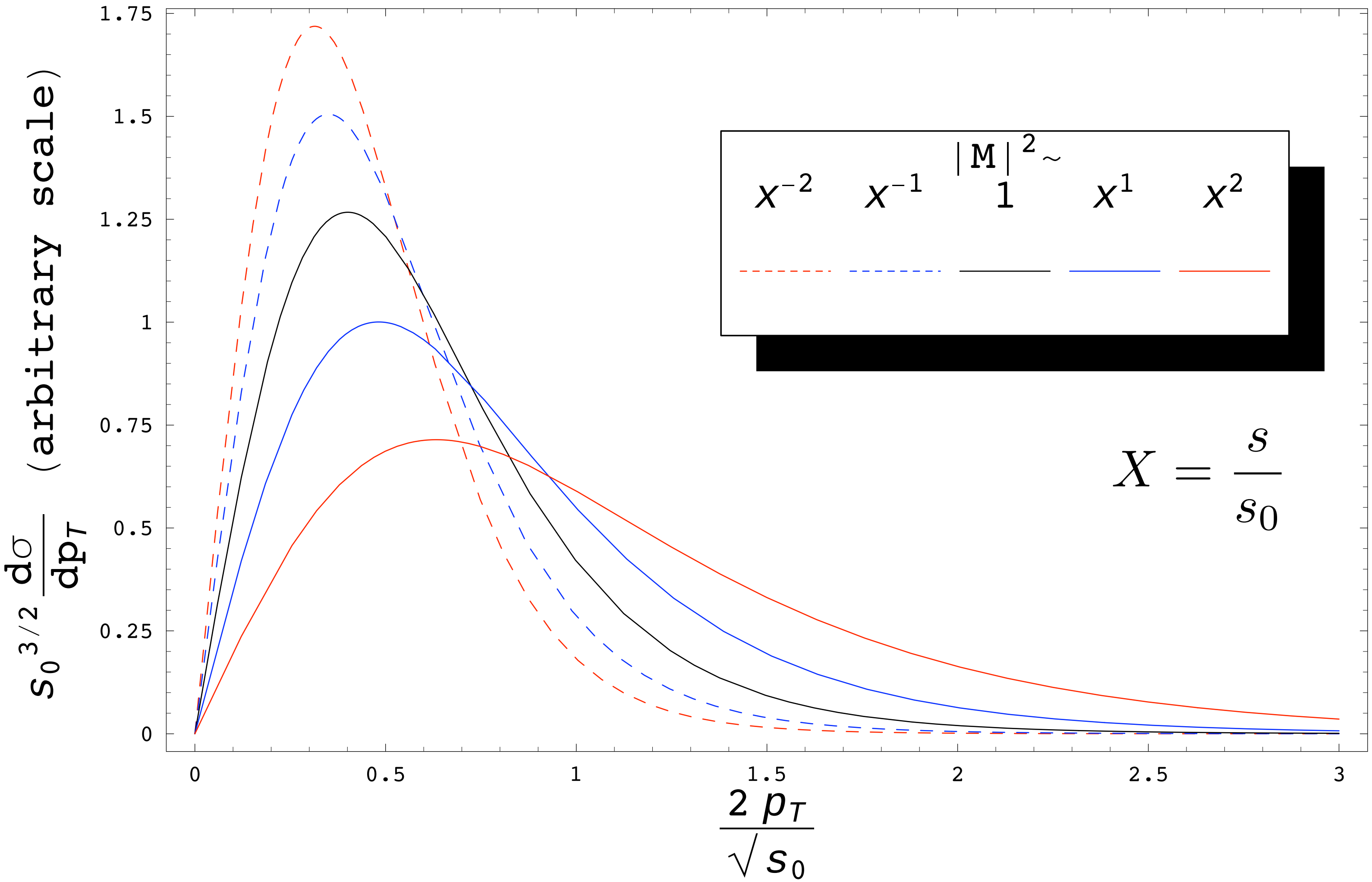
$$\frac{d\sigma}{dx_T} = \sum_n C_n \frac{x_T}{(1+x_T^2)^n} \qquad x_T = \frac{2p_T}{\sqrt{s_0}}$$



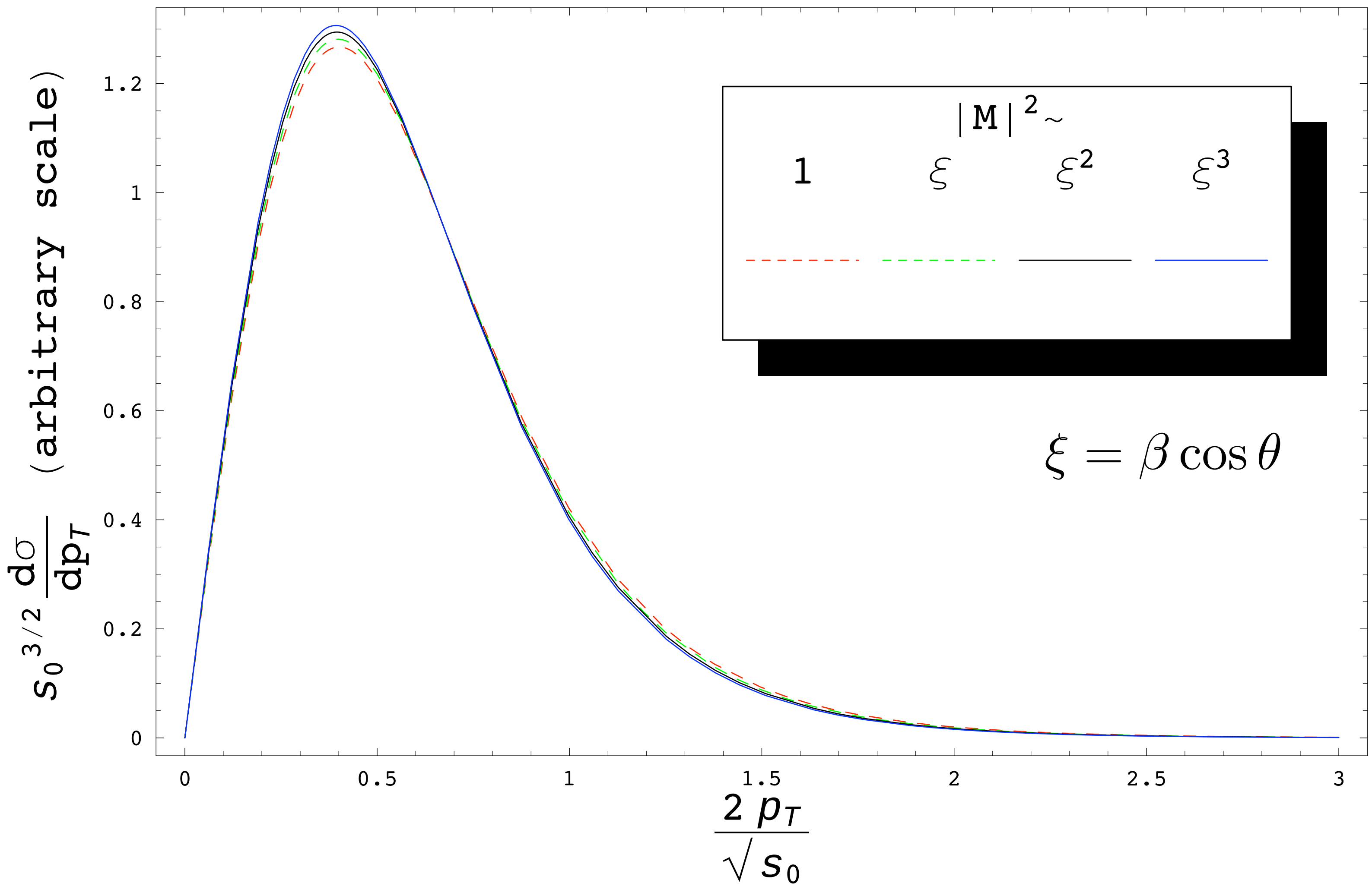
Success of Zeroth-Order scheme related to simple form of First-Order Corrections

$$|\mathcal{M}|^2 \propto 1 \quad \Rightarrow \quad n \approx 3$$

Transverse Structures

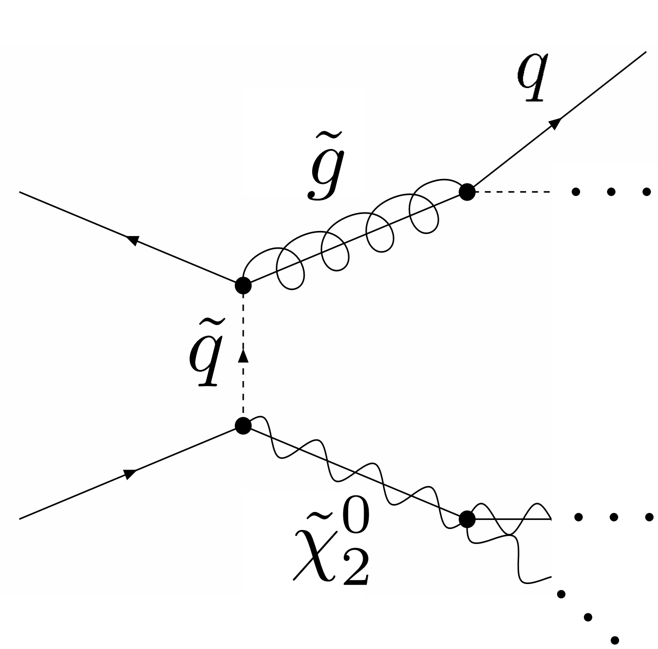


Shape Invariance

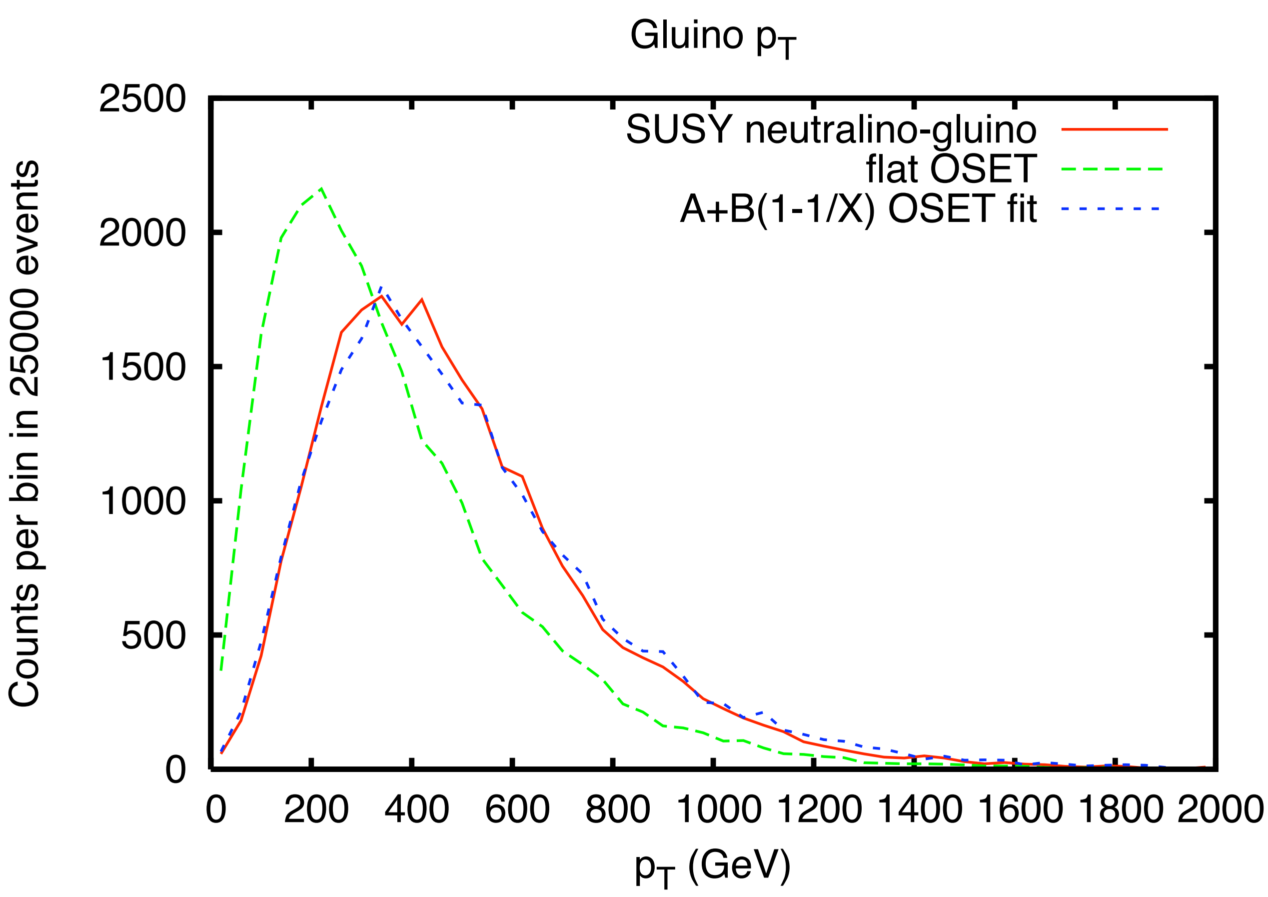


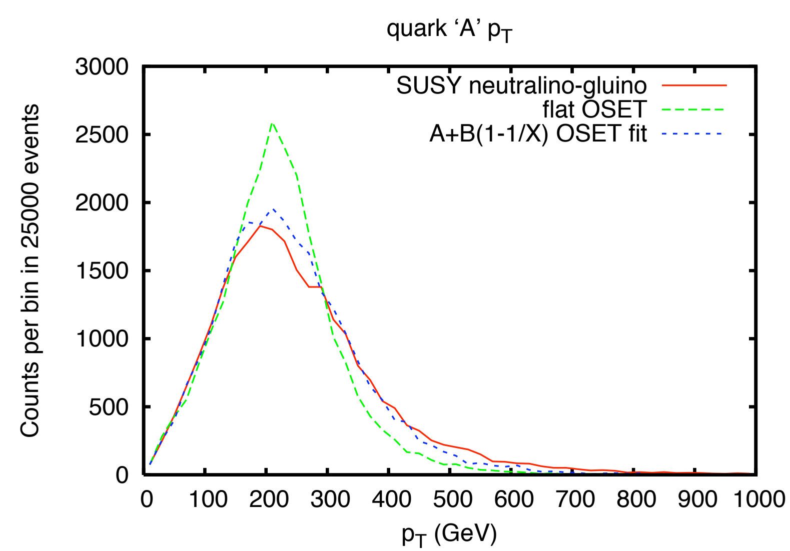
Two Parameter Fits

$$|\mathcal{M}_{\text{approx}}|^2 = A + B\frac{s_0}{s}$$



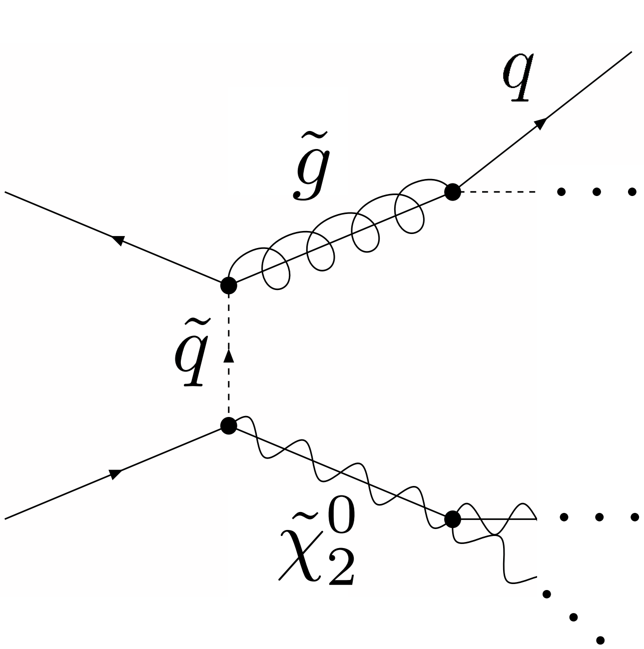
$$m(\tilde{q}) < m(\tilde{g})$$



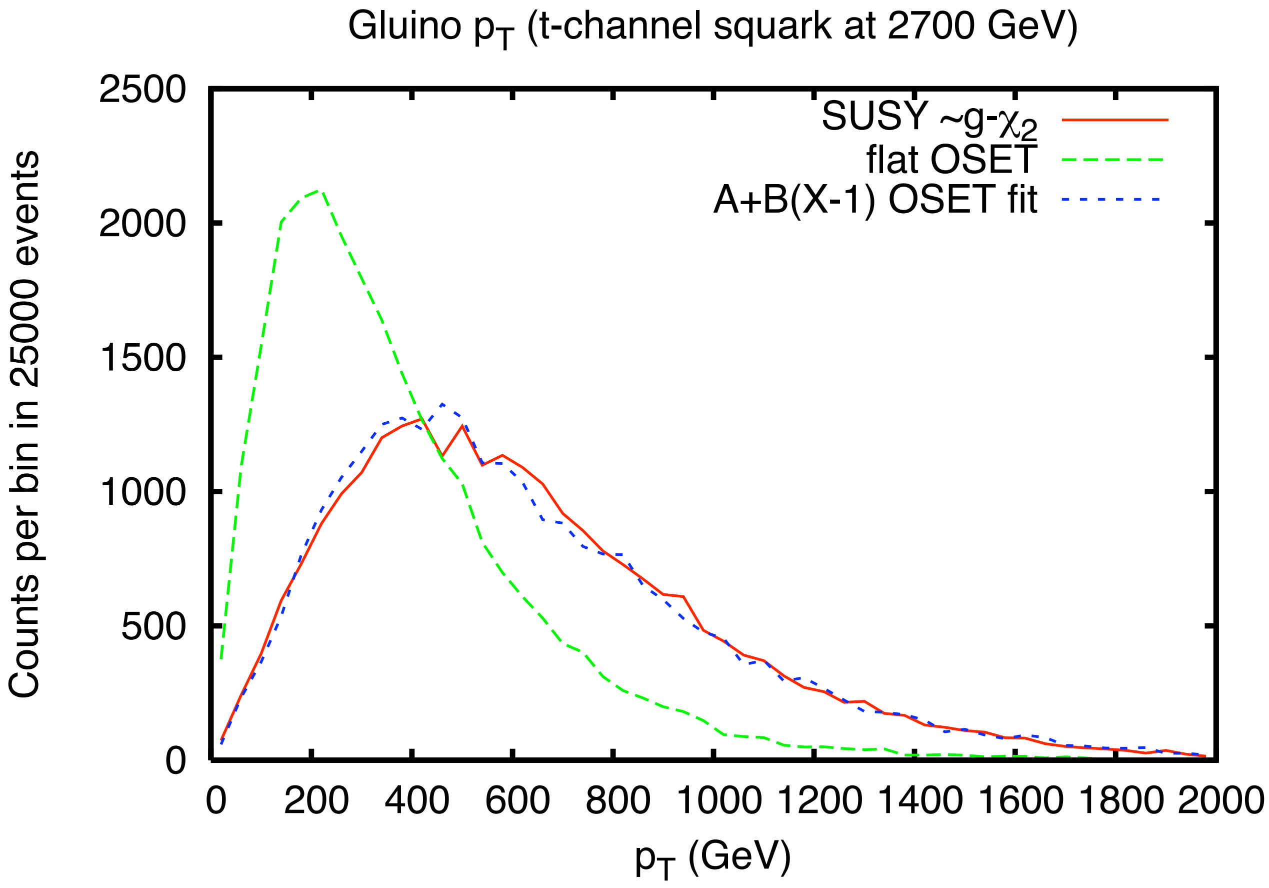


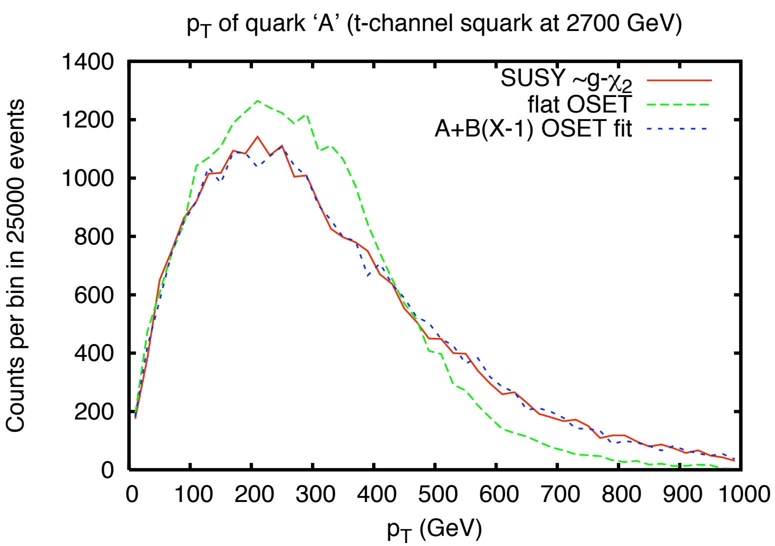
Two Parameter Fits

$$|\mathcal{M}_{\text{approx}}|^2 = A + C\frac{s}{s_0}$$



$$m(\tilde{q}) \gg m(\tilde{g})$$





Analytic Justification

Final State Masses Affect Available Beam Rapidity

$$s_0 \frac{d\sigma}{dx_T} = \int dX \left(\frac{x_T}{2X\xi} \right) \rho_{ab}(X, s_0) \left(s^2 \frac{d\sigma_{ab}}{dt} \right)$$

Differential Cross Section — Phase Space — Rapidity Integrated Parton Luminosity — Amplitude

$$X = \frac{s}{s_0} \qquad x_T = \frac{2p_T}{\sqrt{s_0}} \qquad \xi = 1 - \frac{1 + x_T^2}{X} + \mathcal{O}(\Delta)$$

$$1 + x_T^2 + \mathcal{O}(\Delta) < X < \frac{s_{\text{beam}}}{s_0} \qquad \Delta = \left(\frac{m_A - m_B}{m_A + m_B} \right)^2$$

Equal Mass Approximation

Taking maximum beam energy to infinity and equal final state masses:

$$\gamma = \frac{1 + x_T^2}{X}$$

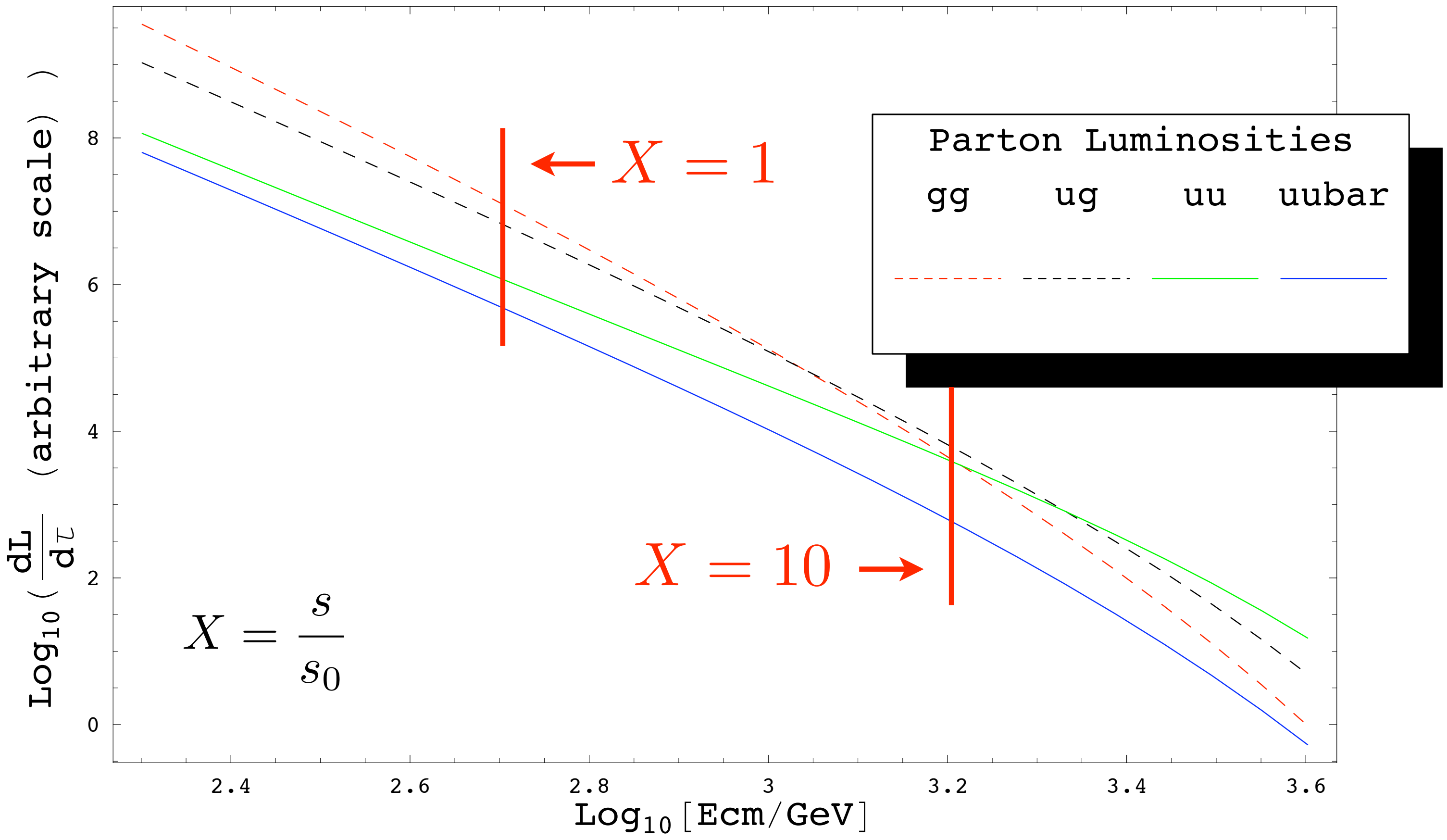
$$s_0 \frac{d\sigma}{dx_T} = x_T \int_0^1 d\gamma \; g(\gamma) \; \rho_{ab}(X, s_0) \; C_{pq} X^p \xi^q$$

- $s_0 \frac{d\sigma}{dx_T}$: Differential Cross Section
- $x_T \int_0^1 d\gamma \; g(\gamma)$: Phase Space
- $\rho_{ab}(X, s_0)$: Rapidity Integrated Parton Luminosity
- $C_{pq} X^p \xi^q$: Amplitude

$$X = \frac{1 + x_T^2}{\gamma} \qquad \xi = 1 - \gamma$$

If only the parton luminosity were a simple power of X...

Parton Luminosities



$$\rho_{ab}(X, s_0) \propto \frac{1}{X^r} \qquad r \sim 3$$

Transverse Shape Invariance

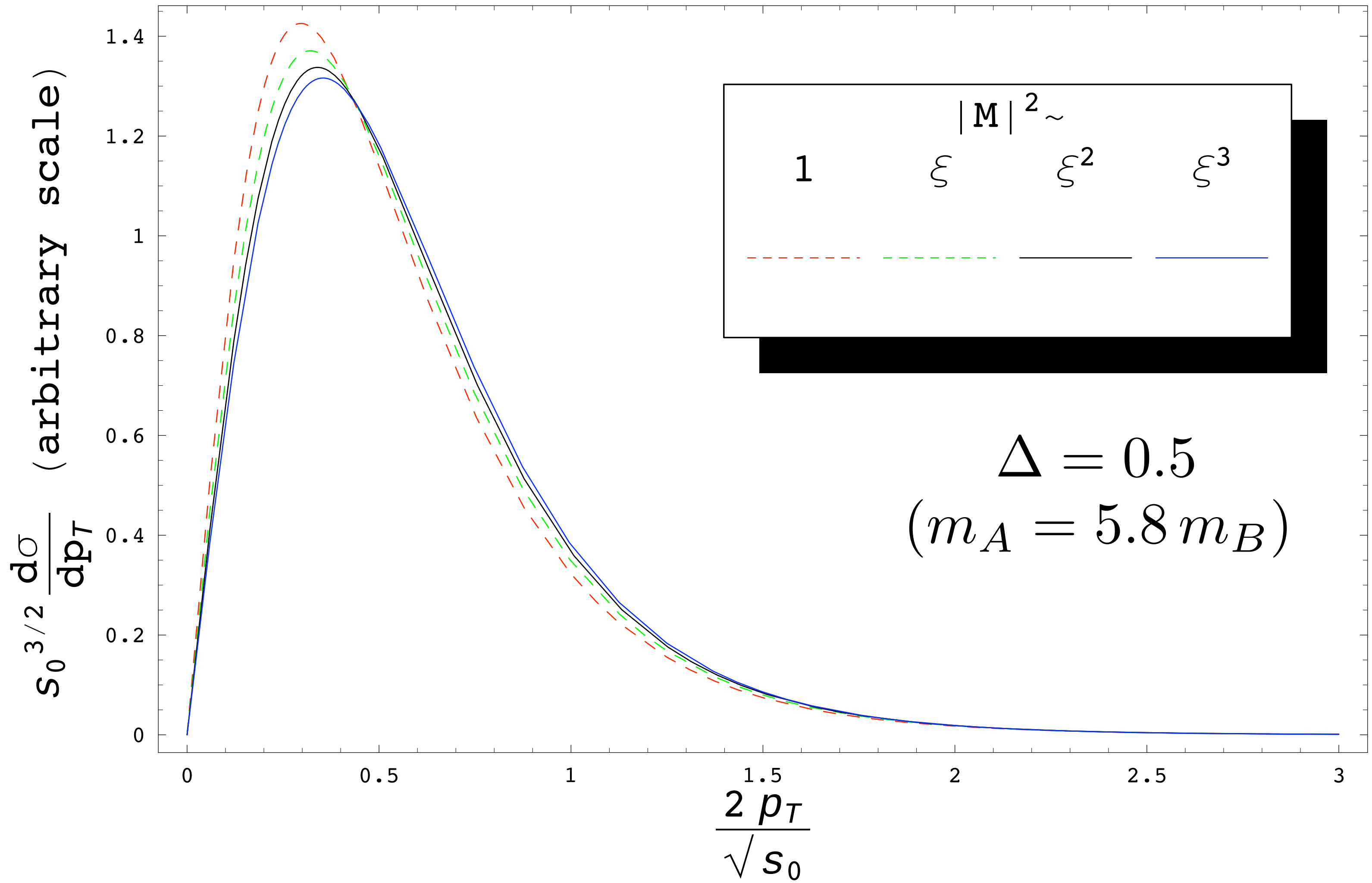
Independent of q!

$$\frac{d\sigma}{dx_T} = C'_{pq} \frac{x_T}{(1 + x_T^2)^{r-p}}$$

$$|\mathcal{M}|^2 \propto s^p (\beta \cos\theta)^q \qquad \rho_{ab} \propto \frac{1}{s^r} \qquad x_T = \frac{2p_T}{\sqrt{s_0}}$$

Transverse Structure Dominantly Determined by Center-of-Mass Energy Dependence of PDFs and Amplitudes

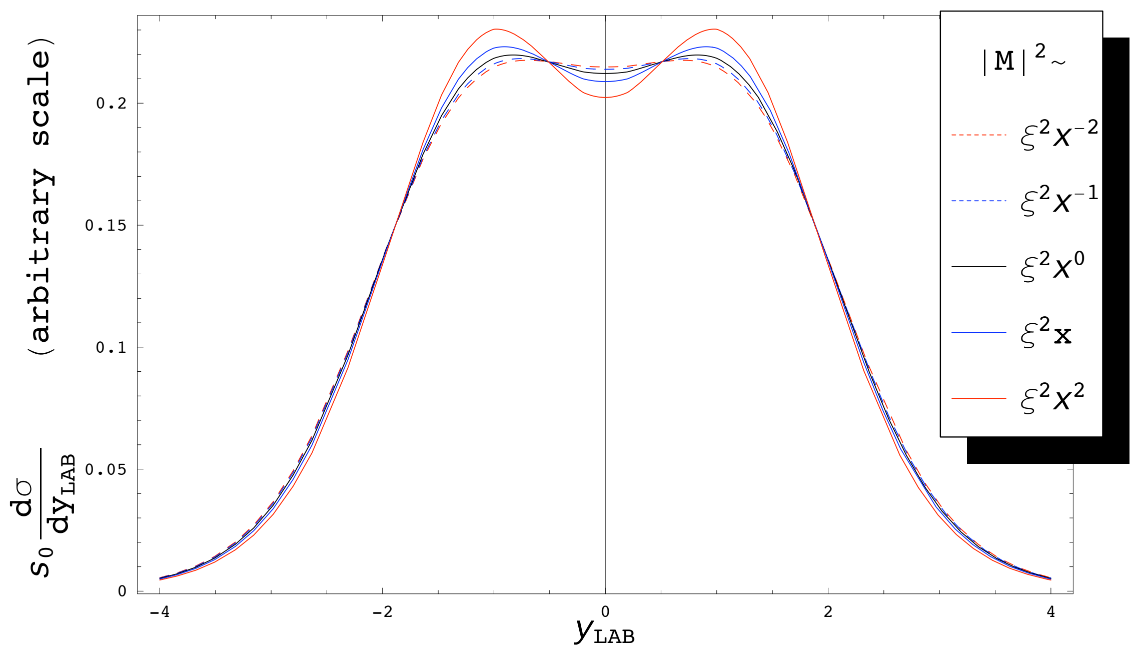
Finite Mass Corrections



Rapidity Structure

If boundaries of phase space are irrelevant...

$$\frac{d\sigma}{d\eta} \text{ invariant under } |\mathcal{M}|^2 = \xi^q \to \xi^q s^p \ !$$

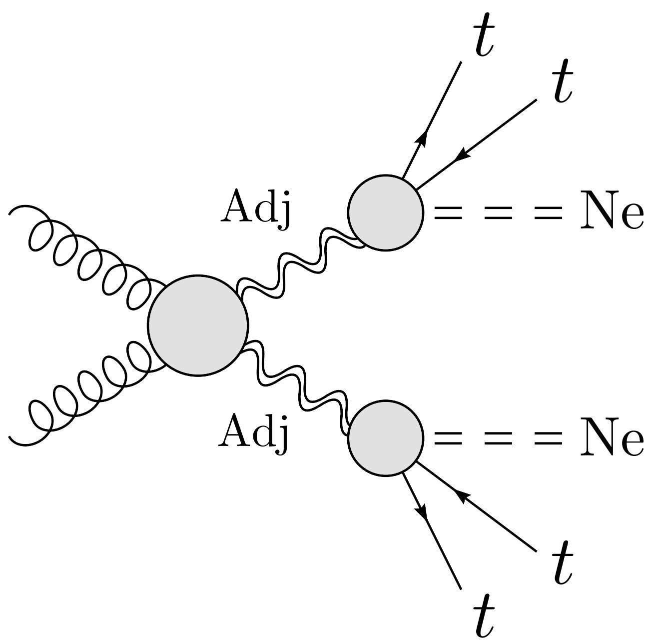


Transverse and rapidity structures roughly factorize at Hadron Colliders.

Rapidity distributions very sensitive to PDFs.

OSET scheme will not give correct transverse/rapidity correlations.

On-Shell Effective Theories (v2)



New Physics Properties:

$m_{\rm Adj}$ $m_{\rm Ne}$

$\sigma(gg \to \text{Adj Adj})$ "$\frac{d\sigma}{dp_T}$" "$\frac{d\sigma}{d\eta}$"

$\text{Br}(\text{Adj} \to t\ t\ \text{Ne})$ "$\frac{d\Gamma}{dm_{12}}$"

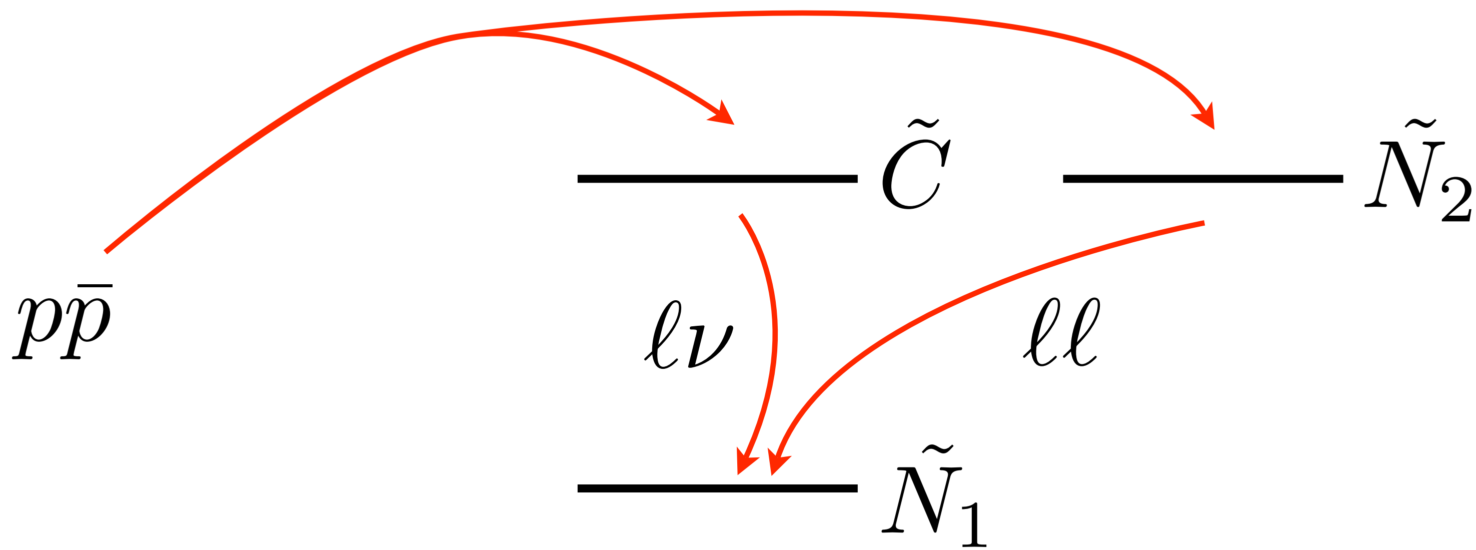
Characterize New Physics In Term of Production/Decay Topologies, Rates, Masses, and a Small Number of Shape Parameters

MC: σ Br m $|\mathcal{M}_{\rm approx}|^2$

MARMOSET in the Pre-LHC Era

Using MARMOSET to Study Trileptons at the TeVatron

Trileptons at the TeVatron



mSUGRA (4.1 parameters)

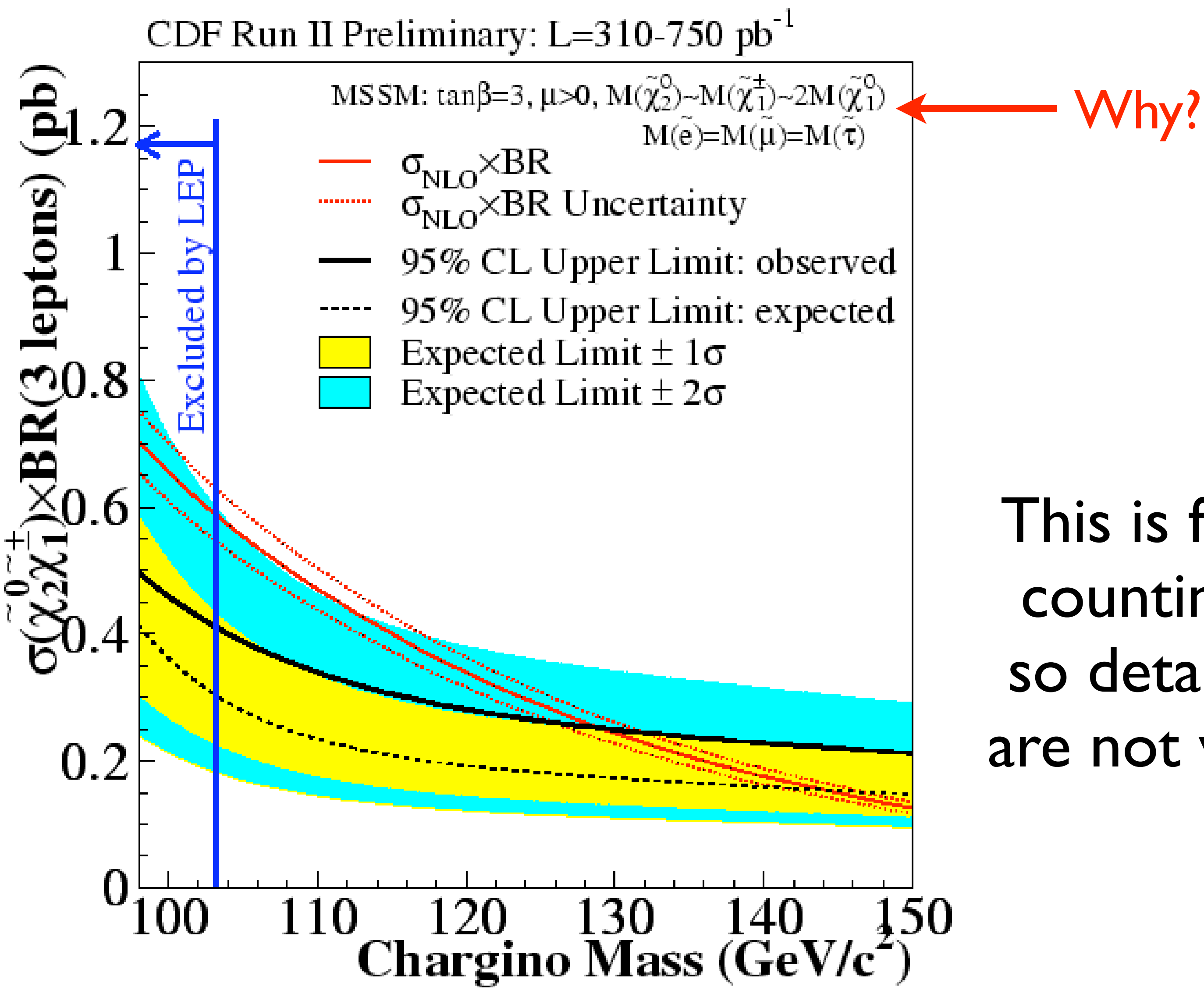
$$m_0,\ m_{1/2},\ A_0,$$

$$\text{sign}\ \mu,\ \tan\beta$$

Small number of parameters at the expense of complicated correlations among rates, cross sections, and masses.

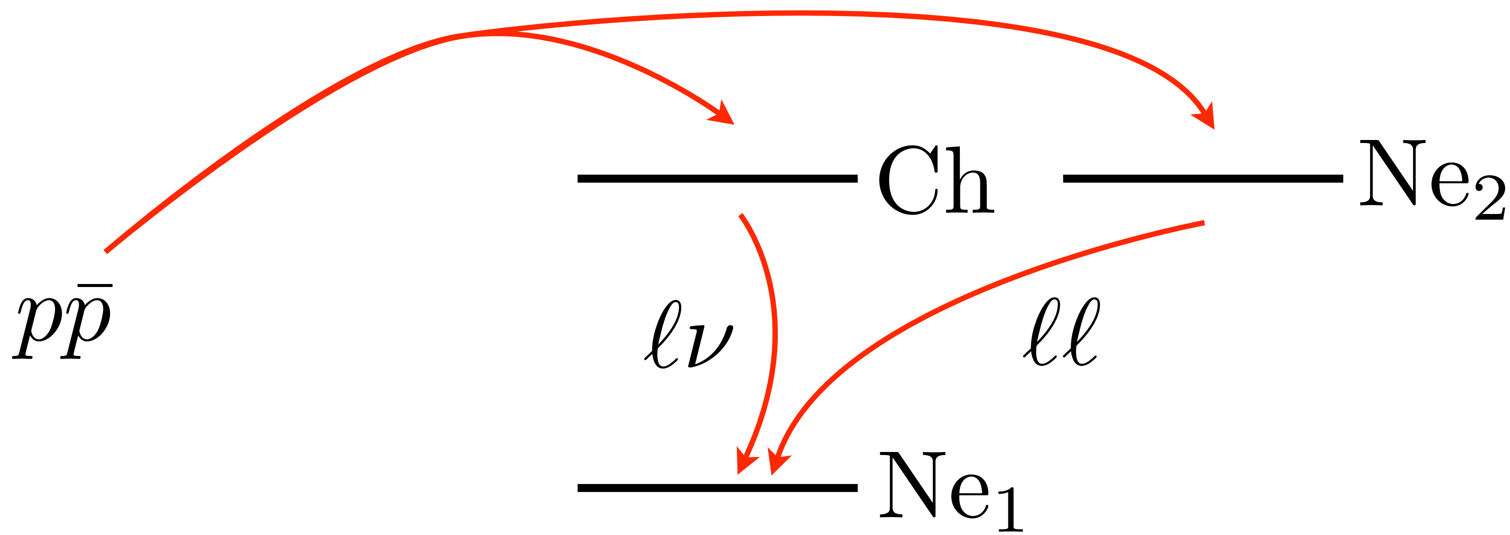
$$m_0 \to m_{\tilde{\tau}} \to \text{Br}(\tilde{C} \to \tilde{N}_1 \ell\nu) \qquad m_0 \to m_{H_u} \to \mu \to \tilde{C}, \tilde{N}\ \text{mixing}$$

Trileptons at the TeVatron



This is fundamentally a counting experiment, so detailed kinematics are not very important.

Trileptons at the TeVatron



OSET (8 parameters)

$$\sigma(q\bar{q} \to \text{Ch Ne}_2)$$

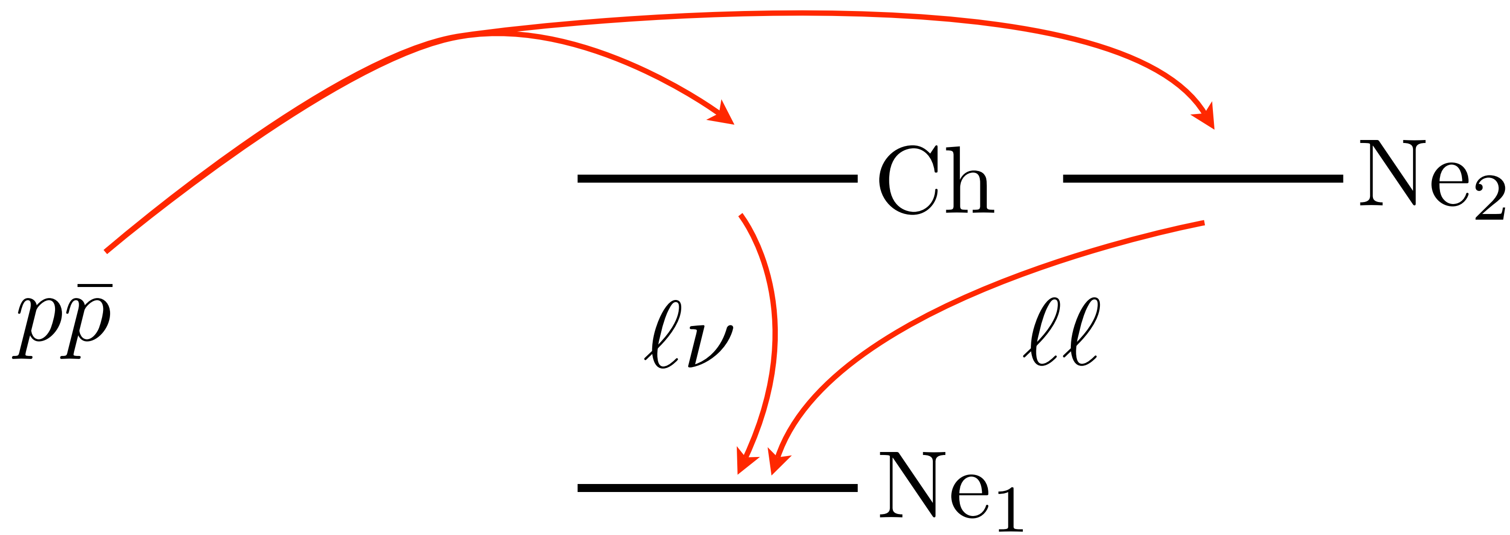
$$\left.\begin{array}{l} \text{Br}(\text{Ch} \to \text{Ne}_1 \ell\nu) \\ \text{Br}(\text{Ne}_2 \to \text{Ne}_1 \ell\ell) \end{array}\right\} \quad \ell = e, \mu, \tau$$

$$m_{\text{Ch}}, m_{\text{Ne}_1}, m_{\text{Ne}_2}$$

More information from same data!

E.g. : How does exclusion depend on heavy-light splitting?

Trileptons at the TeVatron



Search Optimized OSET (3 parameters)

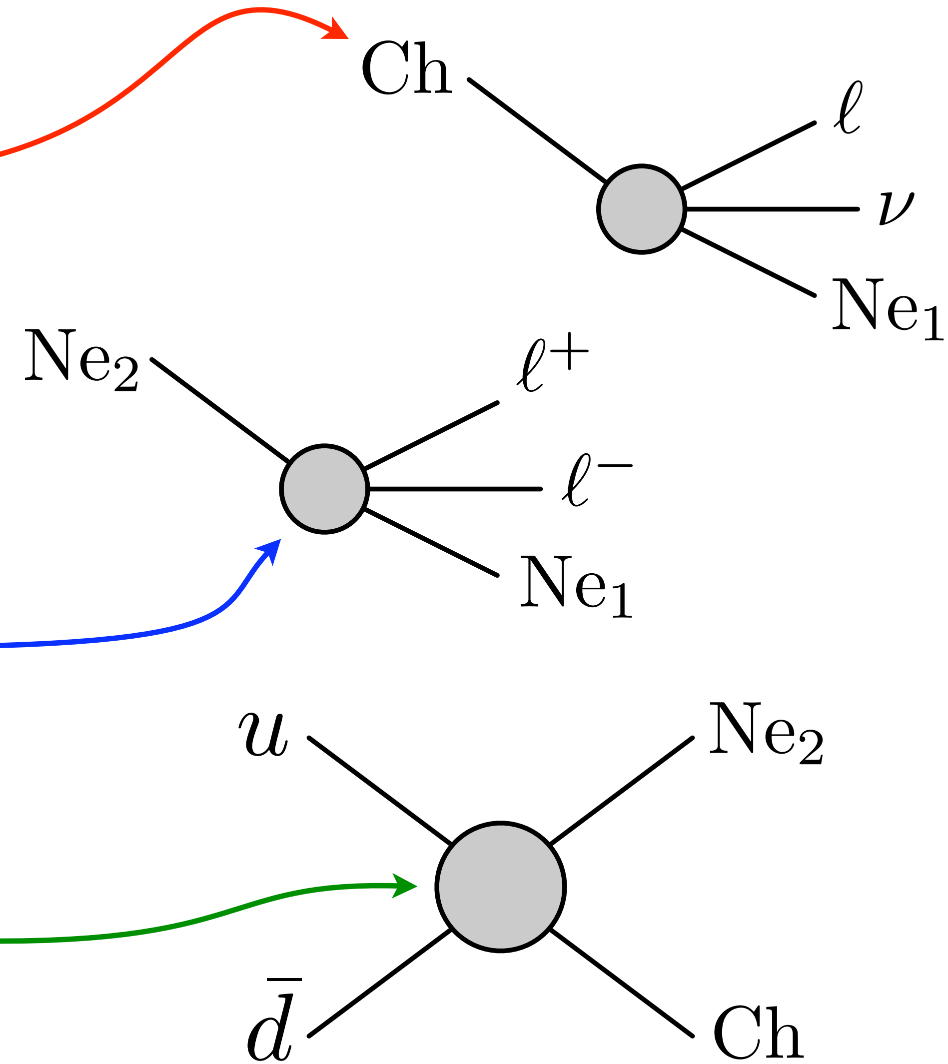
$$\sigma(q\bar{q} \to \mathrm{Ch\ Ne_2}) \times \mathrm{Br}(\mathrm{Ch} \to \mathrm{Ne_1}\ell\nu) \times \mathrm{Br}(\mathrm{Ne_2} \to \mathrm{Ne_1}\ell\ell)$$

$$\ell = e/\mu \text{ universal, ignore } \tau$$

$$m_{\mathrm{Ch}} = m_{\mathrm{Ne_1}}, m_{\mathrm{Ne_2}}$$

Trileptons Input File

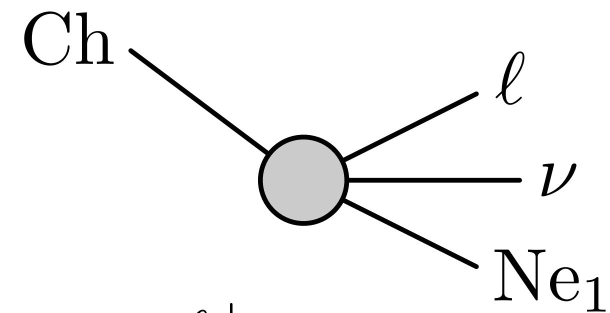
```
Ne2     : m=125 EM=0 SU3=0
Ch Ch~  : m=125 EM=3 SU3=0
Ne1     : m=100 EM=0 SU3=0

Ch > e+   nu_e   Ne1 $ Br_Ch
Ch > mu+  nu_mu  Ne1 $ Br_Ch
Ch > tau+ nu_tau Ne1 $ Br_Ch

Ne2 > e+   e-   Ne1 $ Br_Ne
Ne2 > mu+  mu-  Ne1 $ Br_Ne
Ne2 > tau+ tau- Ne1 $ Br_Ne

u dbar > Ch Ne2 : matrix=1
u dbar > Ch Ne2 : matrix=2
u dbar > Ch Ne2 : matrix=3
u dbar > Ch Ne2 : matrix=4
u dbar > Ch Ne2 : matrix=5
```

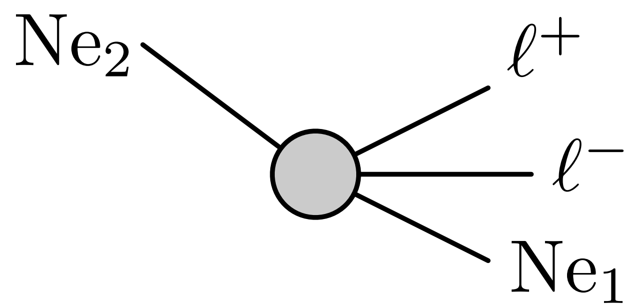


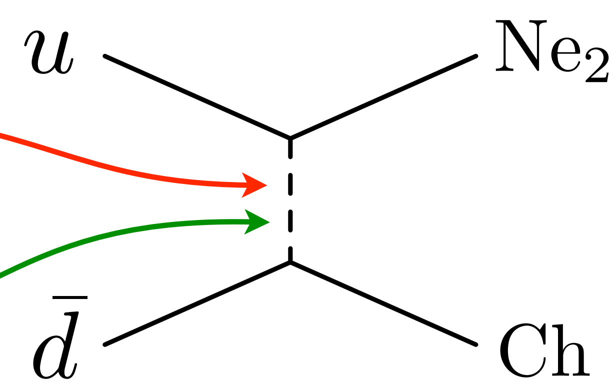
Study Transverse Systematics!

MadGraph 2→2 Trileptons

```
Ne2     : m=125 EM=0 SU3=0 spin=F
Ch Ch~  : m=125 EM=3 SU3=0 spin=F
Ne1     : m=100 EM=0 SU3=0 spin=F

Ch > e+   nu_e   Ne1 $ Br_Ch
Ch > mu+  nu_mu  Ne1 $ Br_Ch
Ch > tau+ nu_tau Ne1 $ Br_Ch

Ne2 > e+   e-   Ne1 $ Br_Ne
Ne2 > mu+  mu-  Ne1 $ Br_Ne
Ne2 > tau+ tau- Ne1 $ Br_Ne

U' U'~  : m=500 EM=2  SU3=3 spin=S
D' D'~  : m=500 EM=-1 SU3=3 spin=S

u dbar > Ch Ne2 : s-channel=W+
u dbar > Ch Ne2 : t-channel=U'
u dbar > Ch Ne2 : t-channel=D'
```







Real SUSY Matrix Elements!

MARMOSET

hep-ph/0703088 www.marmoset-mc.net

MC: m σ Br $|\mathcal{M}_{\mathrm{approx}}|^2$

- Factorizes Interpretation Problem
  $\mathrm{LHC} \longleftrightarrow \mathrm{OSET} \longleftrightarrow \mathcal{L}$

- Confronts Challenge of Hadron Colliders
  Shape invariance reduces what is measurable but allows for a simplified description of BTSM physics.

- Invariant Characterization of LHC Data with Real Physics Meaning
  OSET language is accessible to theorists outside of the experimental collaborations.