On-Shell Effective Theories for Searches and Interpretation of New Physics

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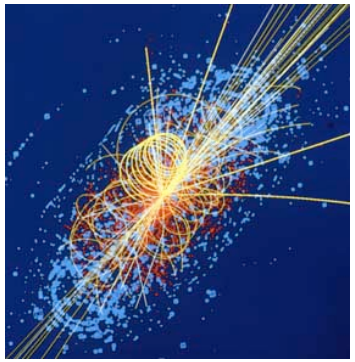
SLAC - Johan Alwall CERN - Michelangelo Mangano

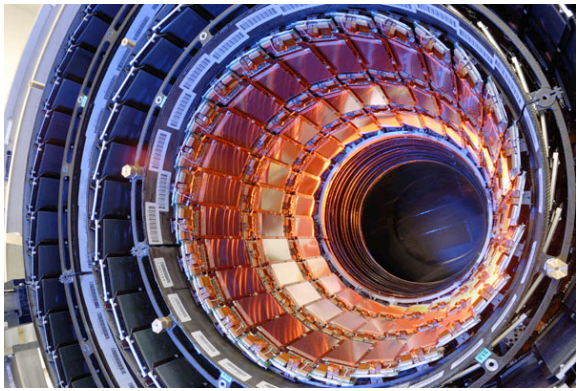
hep-ph/0703088

The challenge for our generation

Nature at 14 TeV



Glorified "Cameras"



$\Rightarrow$

Fundamental Physics:

What new physical principles are being revealed at the TeV scale?

Is nature supersymmetric?

Is the electroweak scale natural?

No conventional wisdom applies...

Collective Hadron Collider Discovery Experience

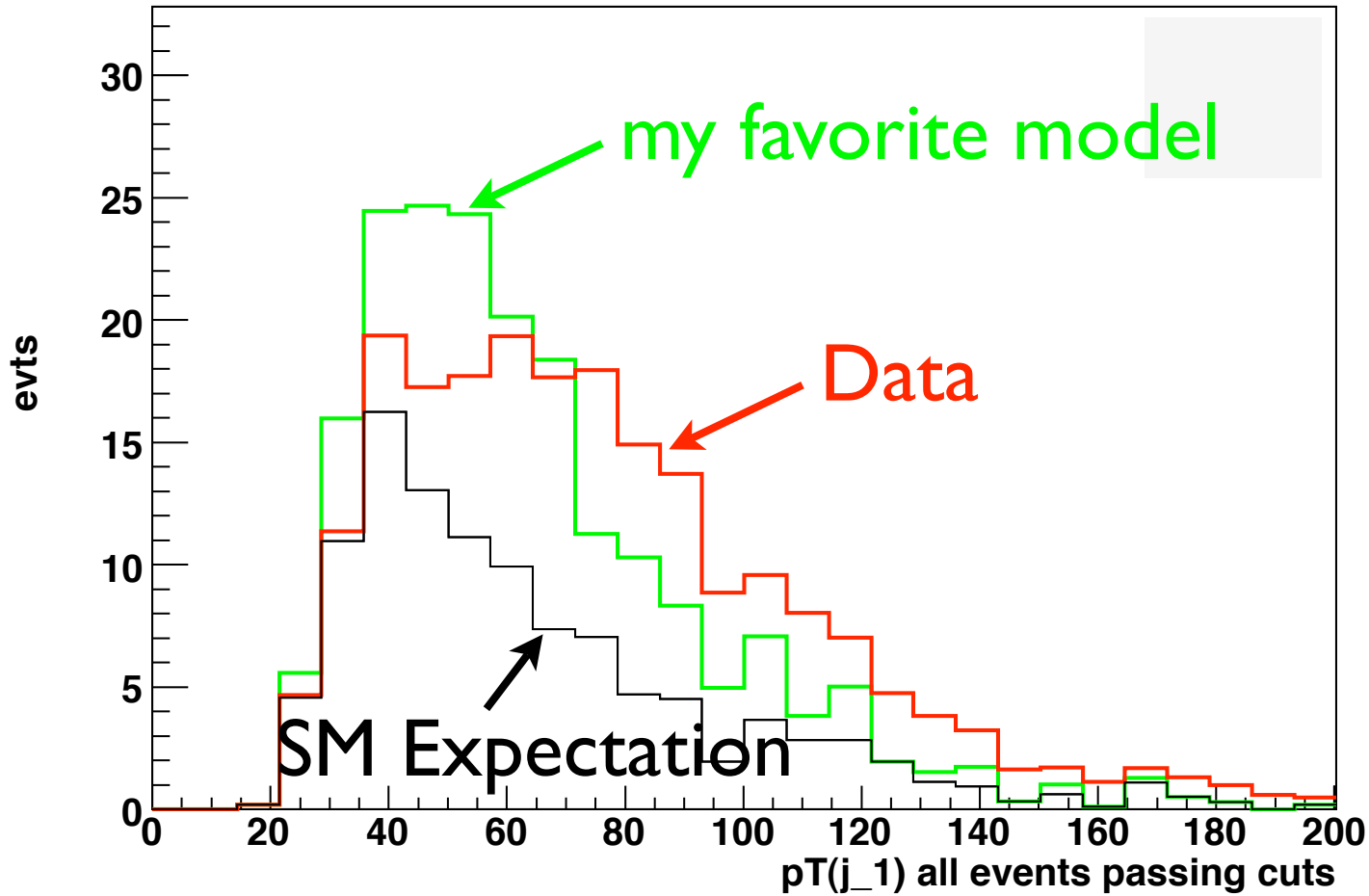
W/Z

No undetermined parameters

t

One unknown parameter (m_t)

In both cases, knew **exactly** what to look for...



What properties of a model are relevant to this comparison?

We may see many such plots at the LHC...

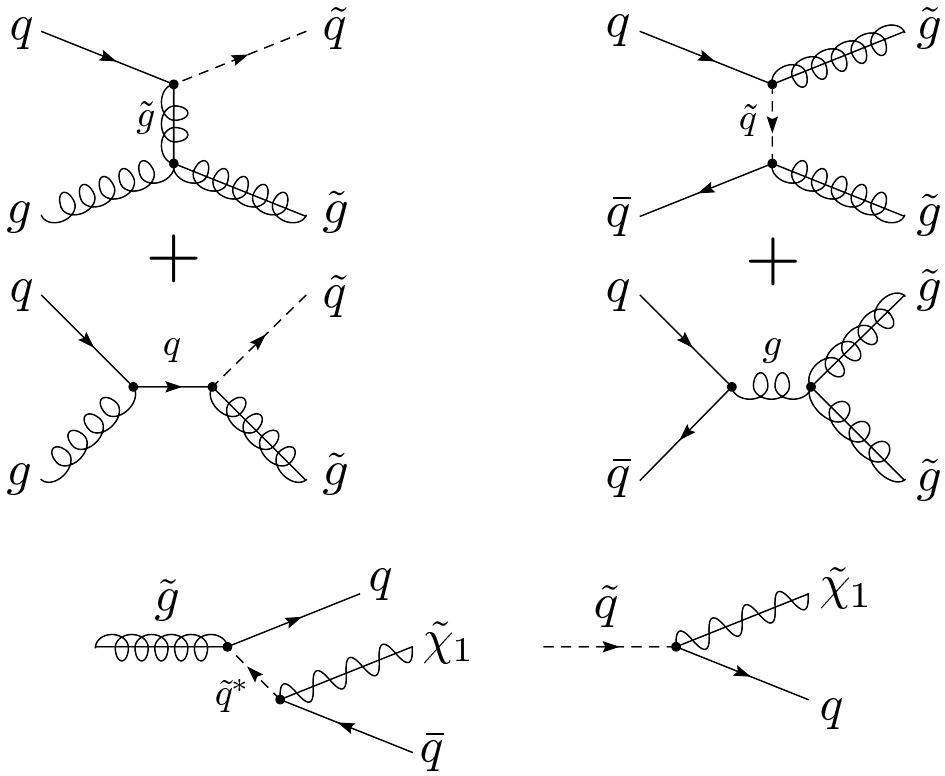
Rule #1:

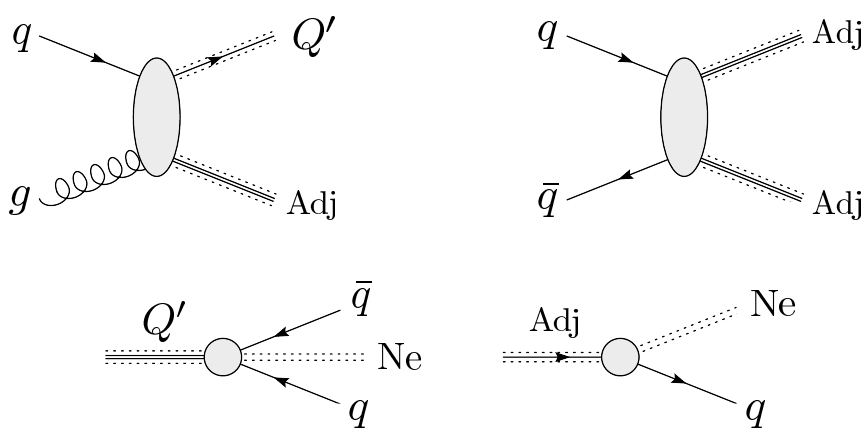
The LHC probes $\sim 10^{-17} cm$

Not $\sim 10^{-30} cm$!

We should be prepared to characterize LHC data using
TeV-scale Effective Field Theories
that are flexible enough to capture possible scenarios

(e.g. MSSM, not mSUGRA)





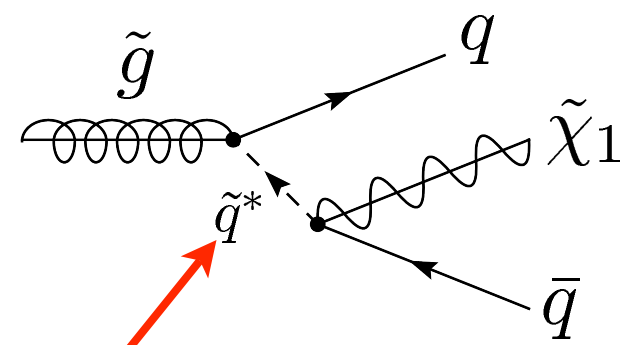
TeV-scale EFTs are still complicated

Can we simplify further?

(an approximate EFT ?)

Rule #2:

Decoupled states don't matter...

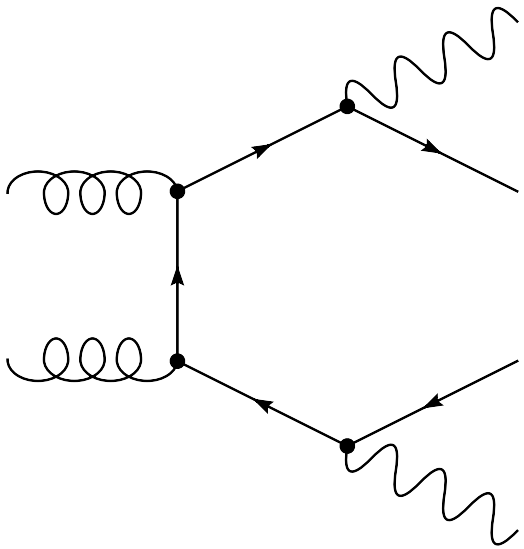


$$\Gamma \propto \left(\frac{g^2}{p^2 - m^2} \right)^2$$

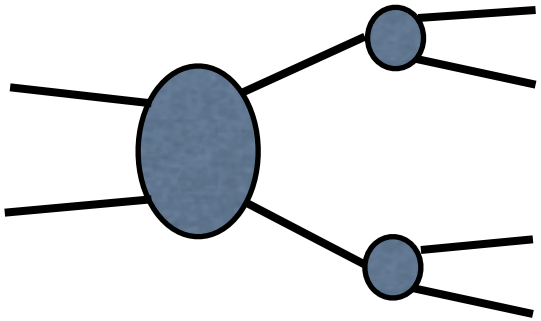
If a state appears off-shell,
not sensitive to mass, spin, couplings
separately, but to **combinations**

Rule #3:

Effect of spin and coupling structure on observables



mimicked by simple parametrization

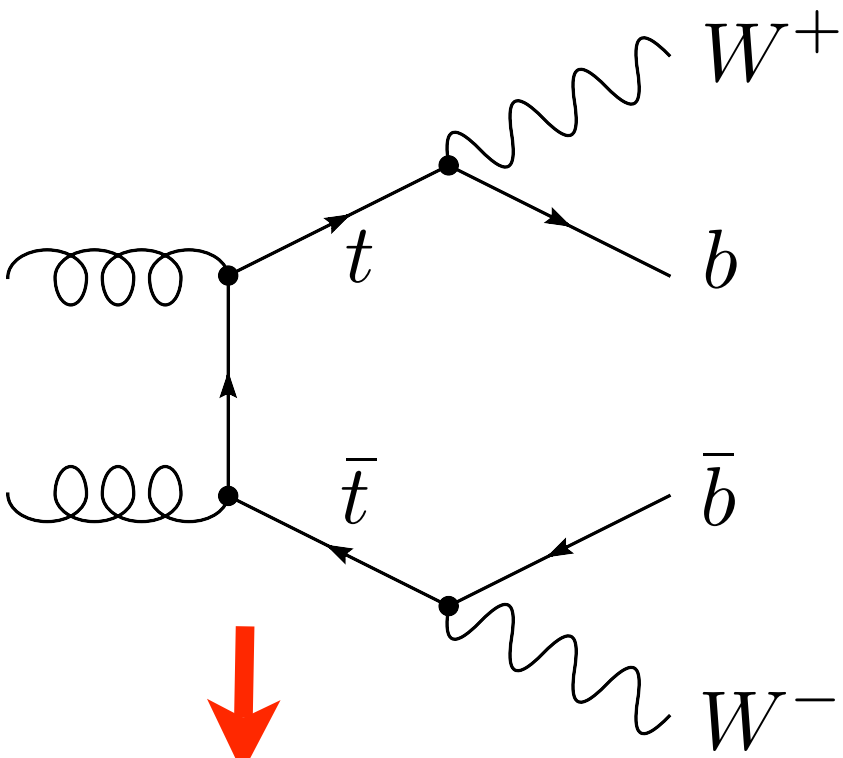


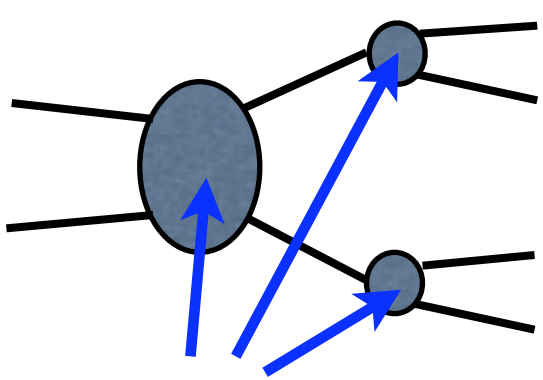
On-Shell Effective Theory:

A description of particle production and decay

(a good and simple approximation to TeV-scale EFTs)

What's an OSET? The Basic Idea:





Simple rules given for these parts

Example: Top Quark

Masses, Rates, and Topology

vs. Amplitudes

Dominant Top Properties:

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

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

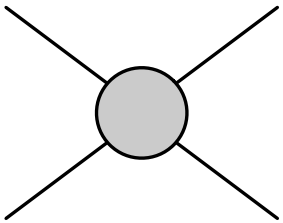
$$m_t, m_W, m_b$$

Detailed Top Properties:

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

t charge

2→2 Folk Theorem

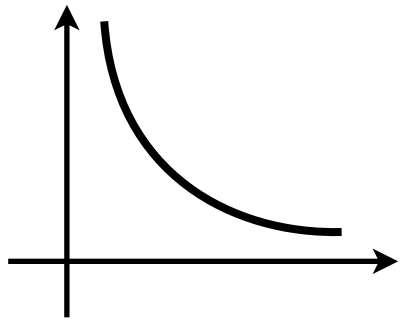


$$|\mathcal{M}|^2 = f(s,\xi) \qquad \xi = \beta_{34}\cos\theta = \frac{\hat{t}-\hat{u}}{\hat{s}} = \frac{p_z}{\sqrt{s}}$$

$$|\mathcal{M}|^2 = \frac{\pi\alpha_s^2}{s^2}\left(\frac{4}{9}\frac{m_{\tilde{g}}^2 - t}{s} + \frac{\left[(m_{\tilde{g}}^2 - t)s + 2m_{\tilde{g}}^2(m_{\tilde{q}}^2 - t)\right]}{(t - m_{\tilde{g}}^2)^2} + u + st + su + tu \quad \text{channels}\right)$$

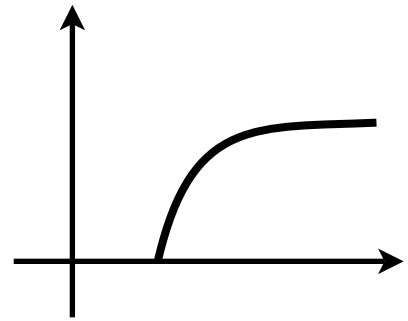
$$\frac{d\sigma}{d\hat{t}} = \int$$

Parton Luminosity



$\times$

Phase Space (Threshold)



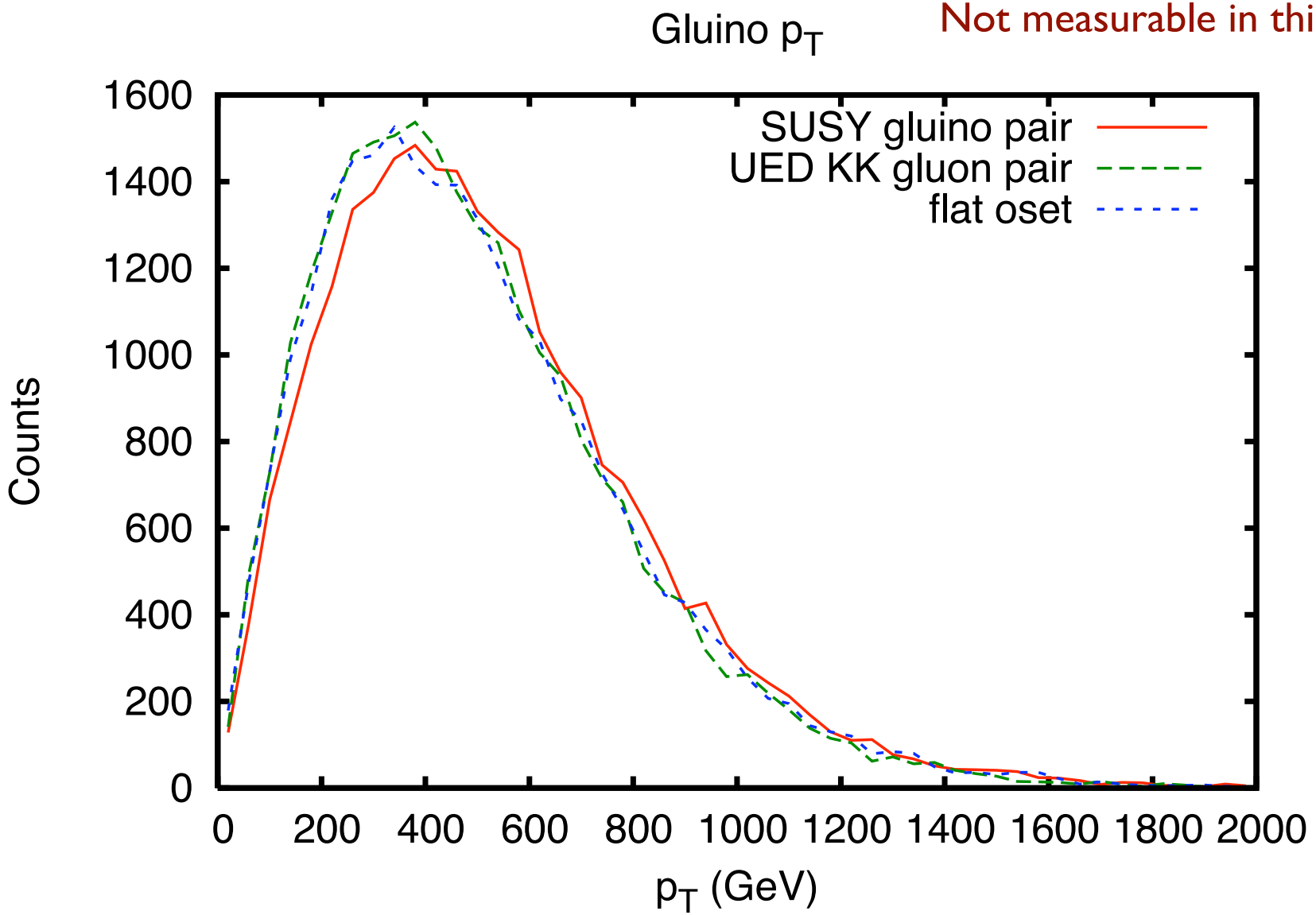
$\times\, |\mathcal{M}|^2$

Well Approximated by Constant!

Cross Sections Dominated by Thresholds!

Modeling Production

Just an example.
Not measurable in this case



Modeling Production

Rapidly falling PDFs

S-wave often dominates

Transverse momentum and rapidity shapes well modeled by constant Matrix Element in most cases!

This is not very surprising...

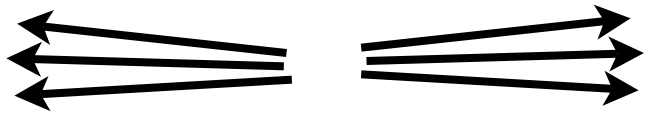
What about extreme kinematics?

What about corrections?

Consider Transverse Momentum

Adding powers of $\cos(\theta)$ to ME

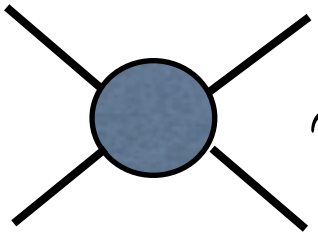
Amplitude peaked near beam-line low p_T



This clearly changes inclusive p_T shapes?

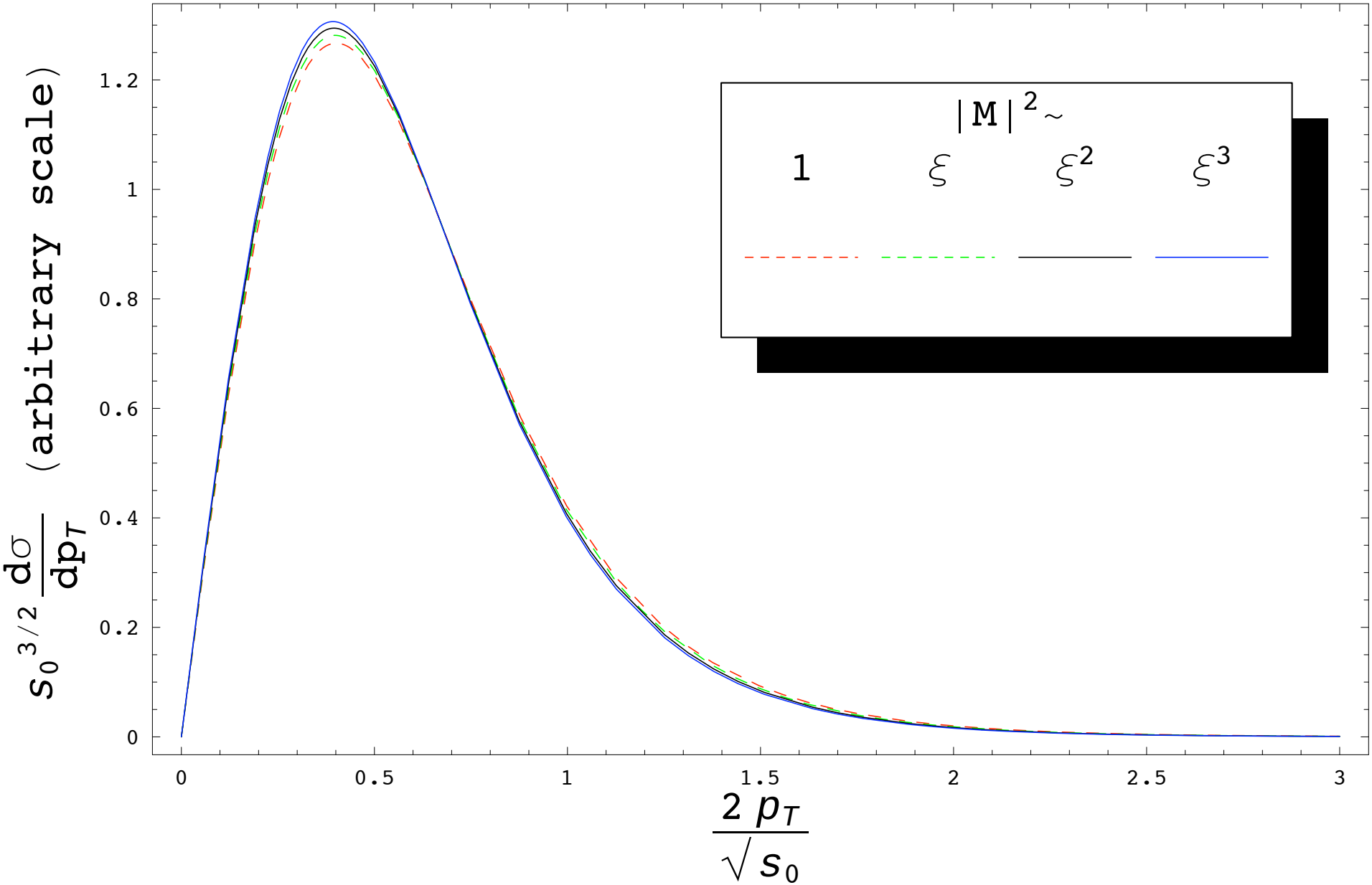
...but in relativistic amplitude, $\cos(\theta)$ always comes with β

How do powers of $\beta\cos(\theta)$ in ME alter p_T shapes?



$$\sim |M|^2 \sim X^q \xi^p$$

ξ-Independence of Transverse Shape!

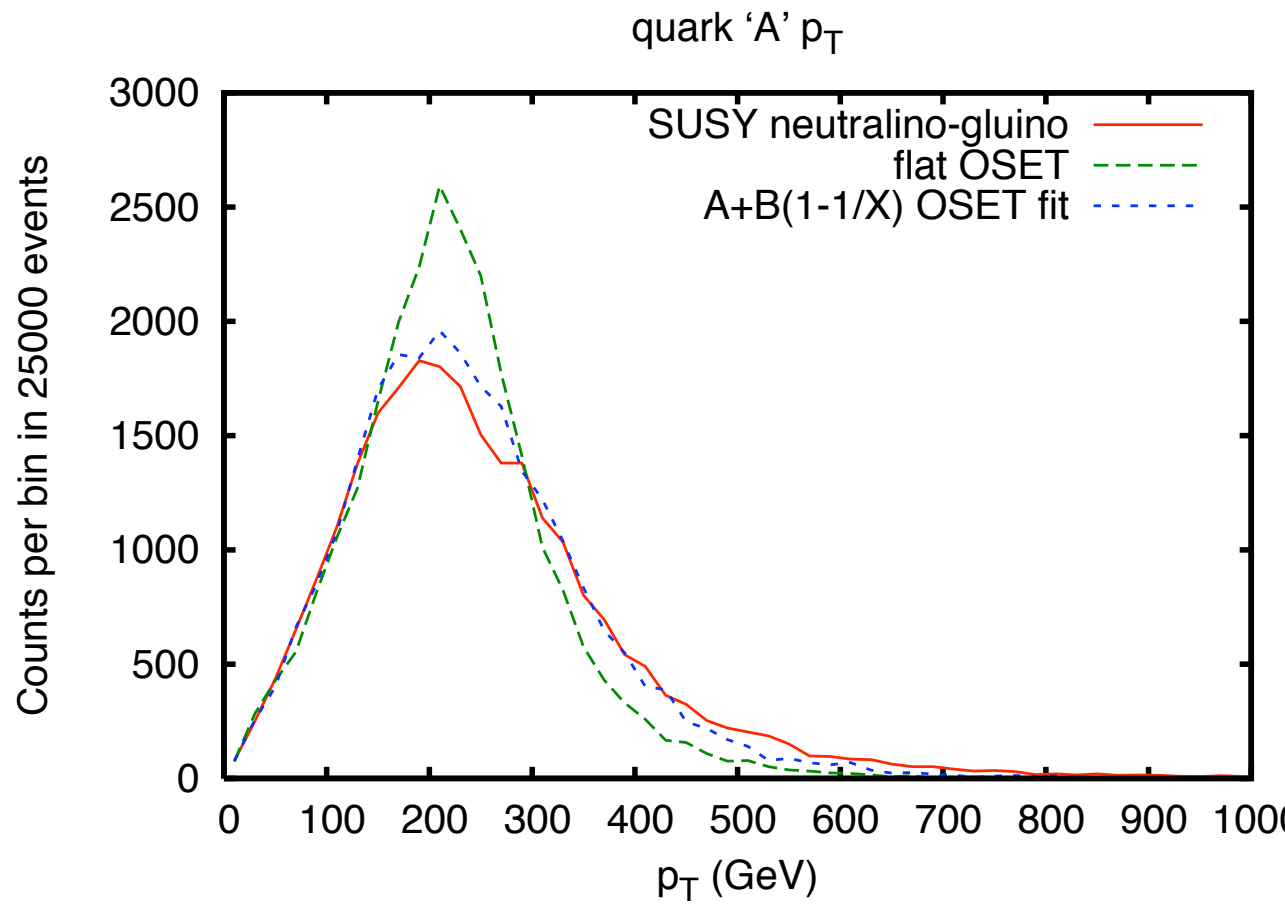


"Normal" Behavior

$$m_{t\text{-chan}} \sim m_{\tilde{g}}$$

p-wave $\rightarrow$ suppressed near threshold.

$$\propto \beta^2$$



$$|\mathcal{M}|^2 = A + B\left(1 - \frac{s_{\text{thresh}}}{s}\right)$$

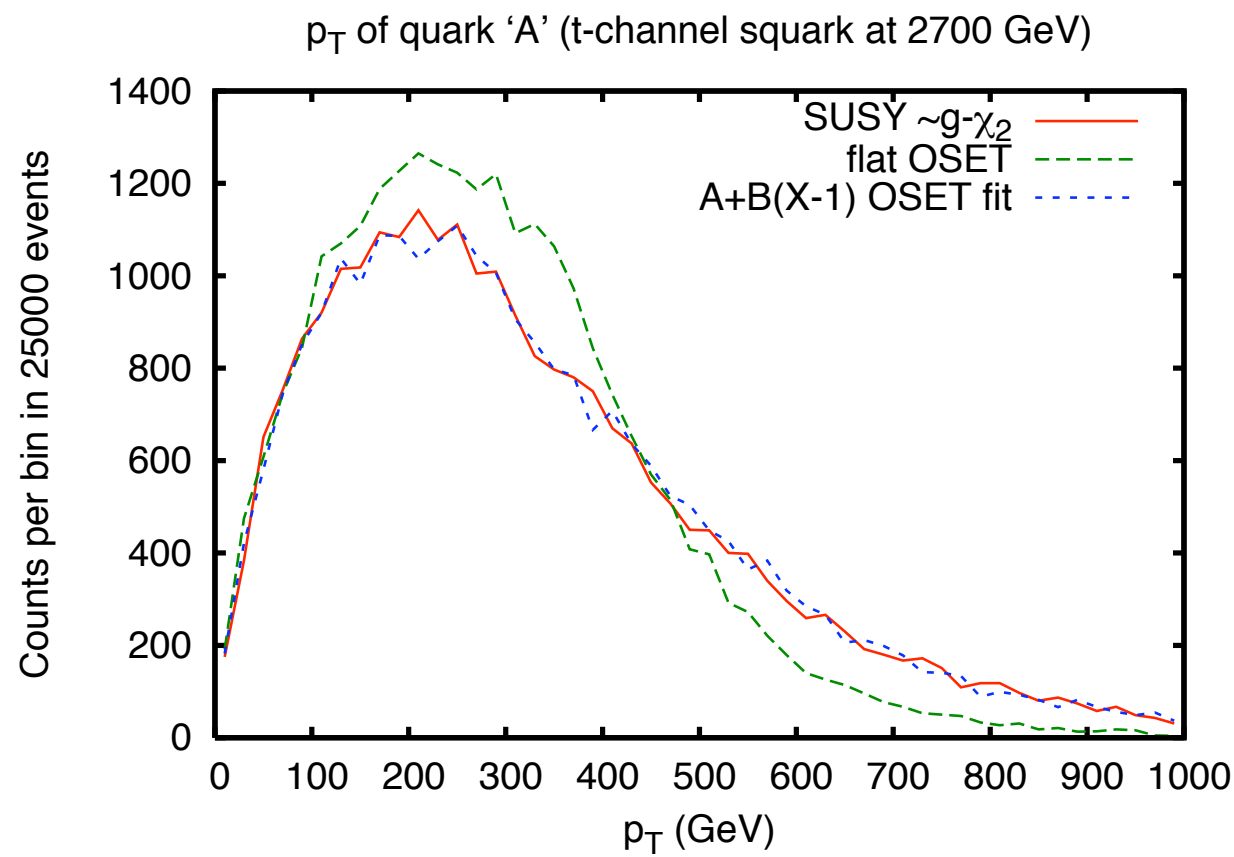
"Contact" Operator Behavior

$$m_{t\text{-chan}} \gg m_{\tilde{g}}$$

contact interaction

$$|\mathcal{M}|^2 \propto s^2$$

up to $\sqrt{s} \sim m_{t\text{-chan}}$



$$|\mathcal{M}|^2 = A + B\left(\frac{s}{s_{\text{thresh}}} - 1\right)$$

Defining an OSET

Production:

$2 \to 1$ Use Breit Wigner

$2 \to 2$

Usually dominates

"Normal" Behavior

$$|\mathcal{M}|^2 = A + B\left(1 - \frac{s_{\rm thresh}}{s}\right)$$

"Contact" Operator Behavior

or

$$|\mathcal{M}|^2 = A + B\left(\frac{s}{s_{\rm thresh}} - 1\right)$$

Dominant ξ correction can be included (not usually necessary)

$2 \to 3$ Use "standard" modes with OSET decay scheme

Decay:

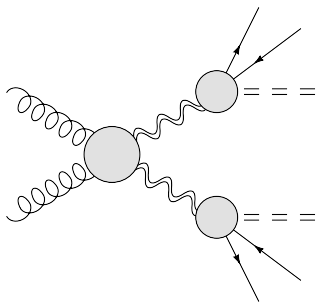
- Polynomial in $\cos\theta$: rank determined by spins, coefficients by masses. Spin correlations can be included.
- Single-object lab-frame distributions well approximated by phase space decays.

See: hep-ph/0703088 for detail...

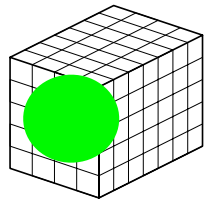
Using OSETs for Interpretation at the LHC

OSET Modeling of Data

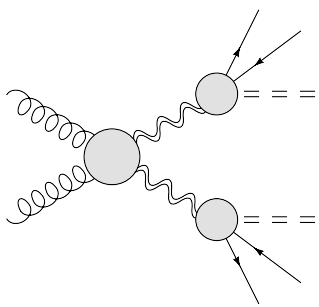
(MARMOSET, MC generation with Pythia, output in LH format.)



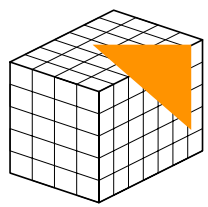
$= \times \sigma_1 \times \mathrm{Br}_{1a} \times \mathrm{Br}_{1b}$



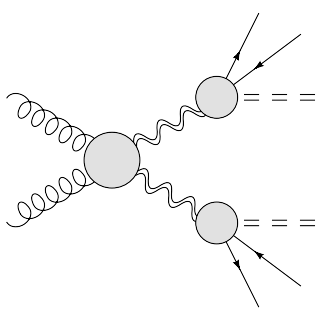
mc1



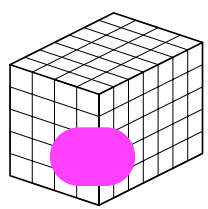
$= \times \sigma_2 \times \mathrm{Br}_{2a} \times \mathrm{Br}_{2b}$



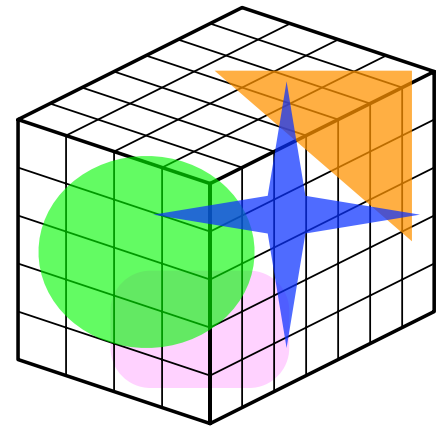
mc2



$= \times \sigma_3 \times \mathrm{Br}_{3a} \times \mathrm{Br}_{3b}$



mc3



Data

OSETs consistently include correlations among final states

↓

OSETs have predictive power!

OSET parameter space scanned through event re-weighting → FAST !!!

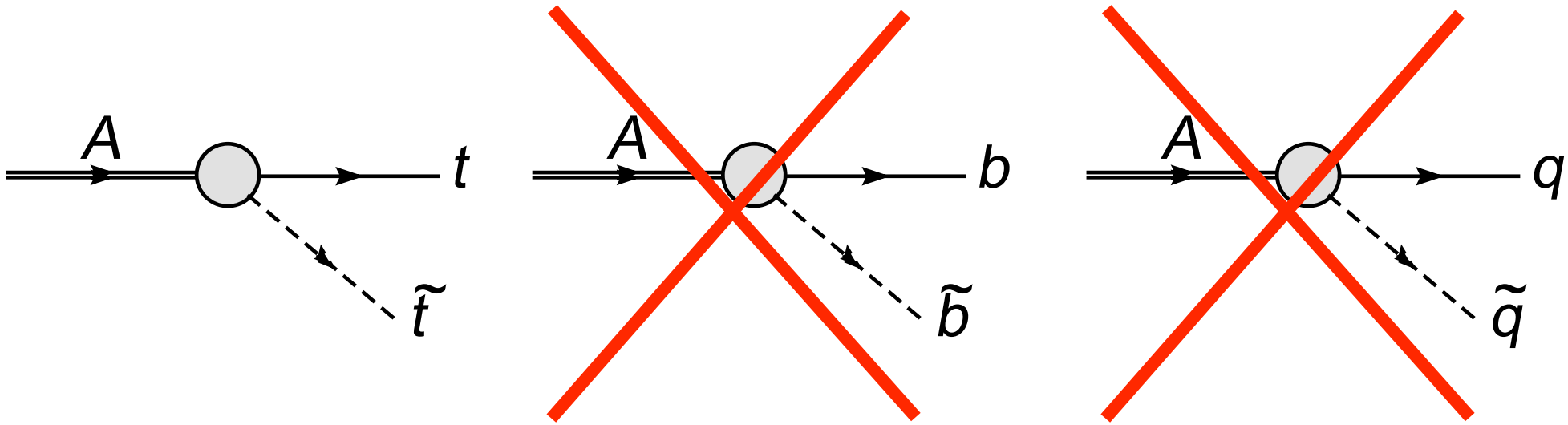
Example using OSETs
(data challenge)

- SUSY Orbifold model with very heavy gauginos (> 5 TeV)
- Light scalars
- **<u>also</u>** light colored adjoint Φ decaying through

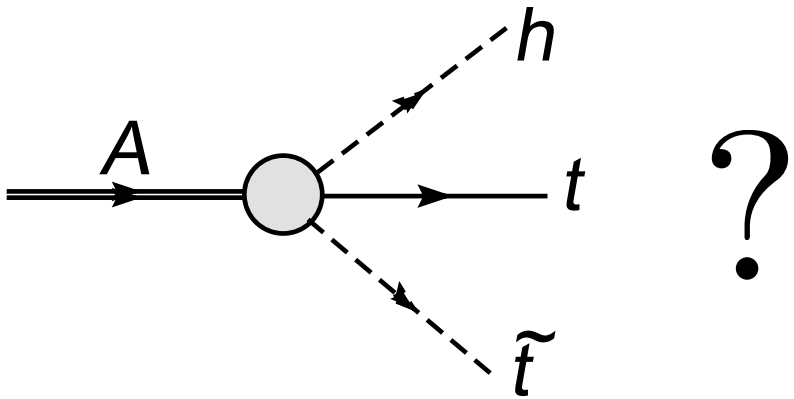
$$W \supset \frac{\Phi}{M} Q_3 H_u U_3^c$$

- looks like gluino with wrong decay modes!

"Gluino" Decays?

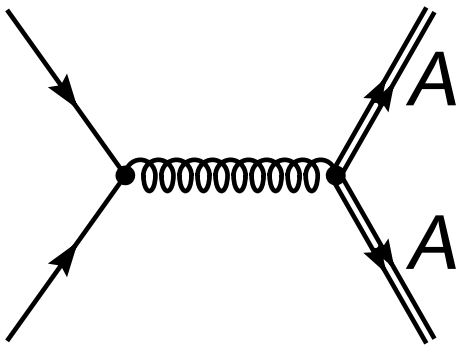


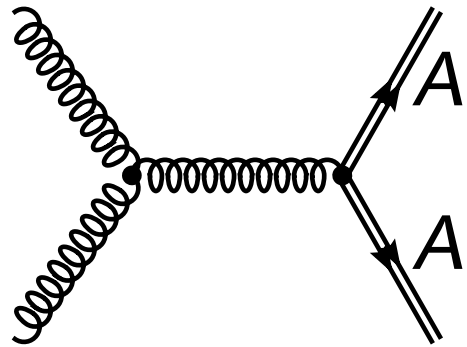
Hints of a rare decay? (some many-b events, two jets+$\gamma\gamma$ with $m_{\gamma\gamma} = 114$ GeV

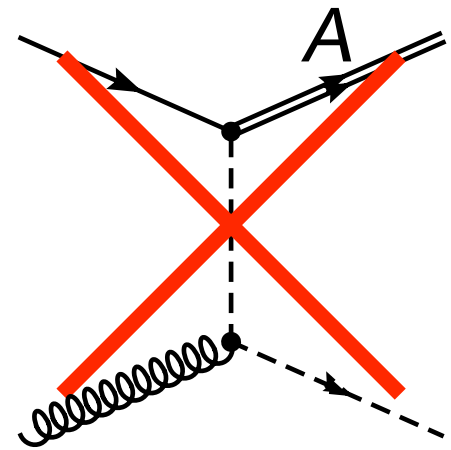


“Gluino” Production

rate consistent with QCD production through fermion only...







...and no associated production with squark.

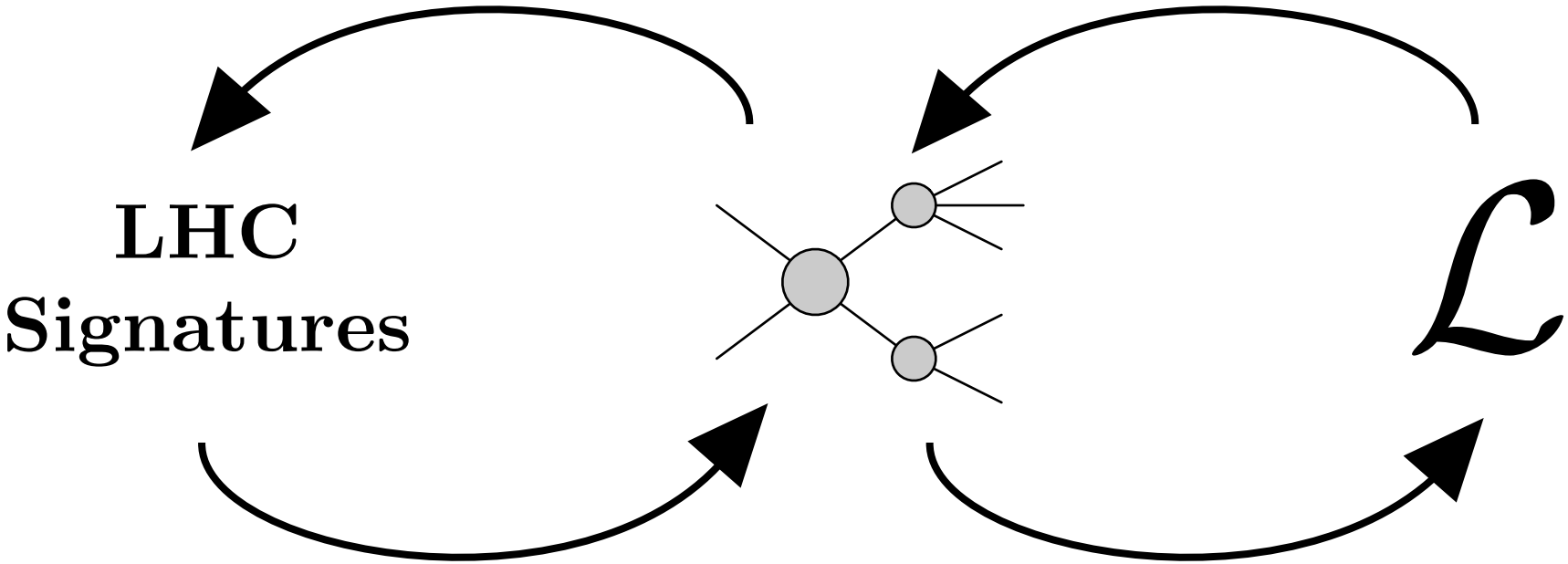
It’s not a gluino!

$$\text{Only couples to tops} \rightarrow W \supset \frac{\Phi}{M} Q_3 H_u U_3^c$$

On-Shell Effective Theories: THE BIG PICTURE

OSET concisely describes many topologies with correlated rates

Lagrangian consistency constrains OSET



Simple observables and correlations between them constrain OSET

OSET constrains and motivates new physics Lagrangian

Conclusions

OSETs → Efficient New Physics Monte Carlo Analysis

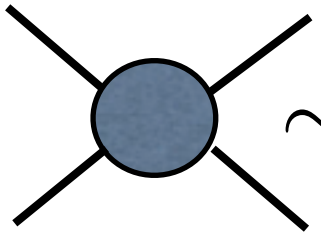
OSETs → Model-Independent Characterization of Data

OSETs → Starting Point for Theory Investigation

- A bridge between data and a fundamental theory
- Accurately reproduce coarse-grained features of data (analysis techniques under development...)
- Supports casting a wide net in case of surprises

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

Shape Invariance



$$\sim |M|^2 \sim X^q \xi^p$$

PDF E_{cm} and y_{cm} homogeneity properties

Inclusive p_T shape invariant under:

$$|M|^2 \rightarrow |M|^2 \xi^m$$

Inclusive y_{lab} shape invariant under:

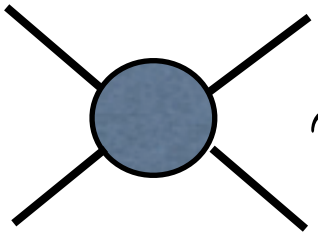
$$|M|^2 \rightarrow |M|^2 X^n$$

Simple "Universal" corrections to constant ME!

Messy collider environment turned to our advantage

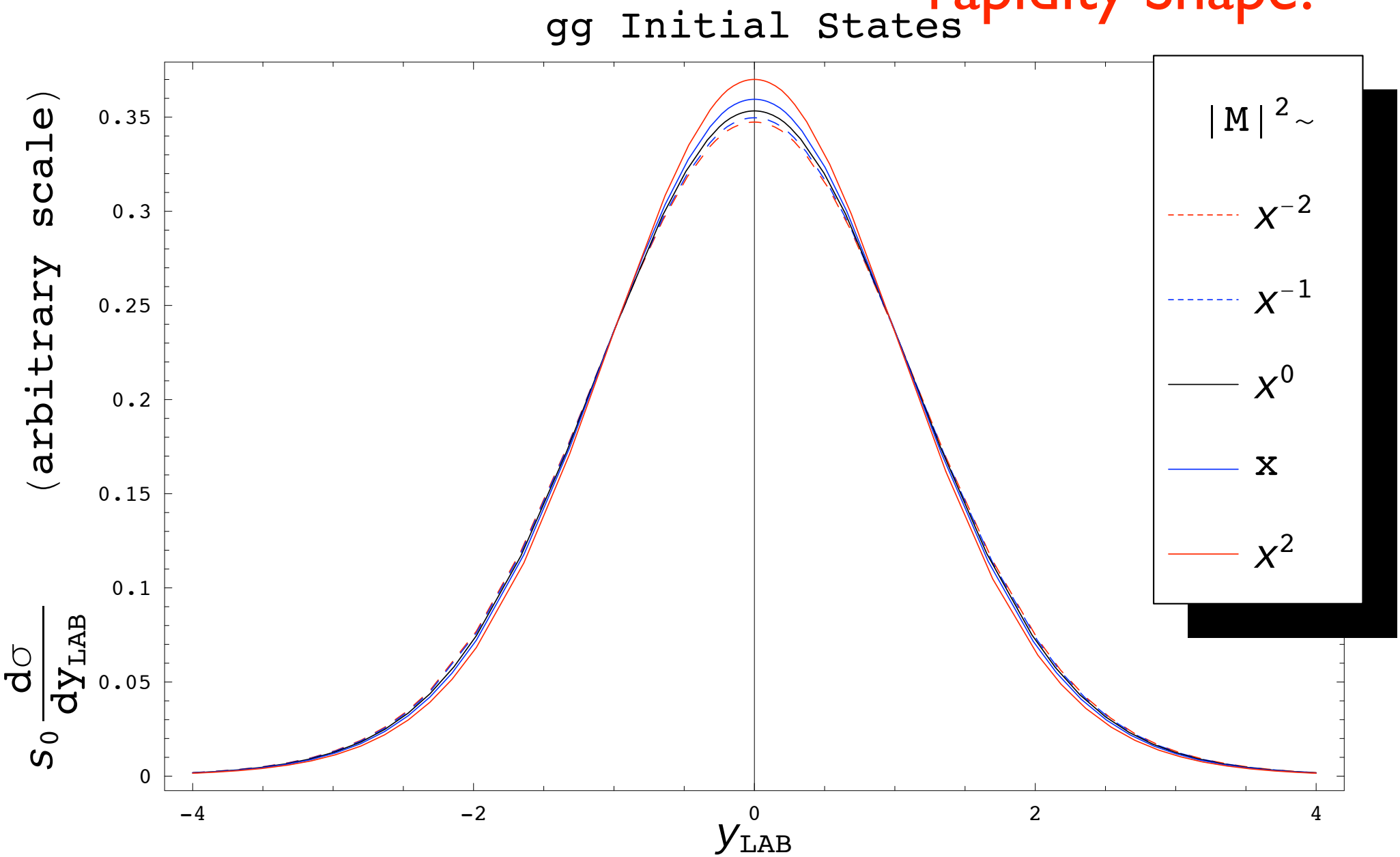
Caveats:
- Correct PDFs necessary
- Large final state mass asymmetry requires care
- Transverse momentum-rapidity correlations not included beyond phase space

See: hep-ph/0703088 for detail...

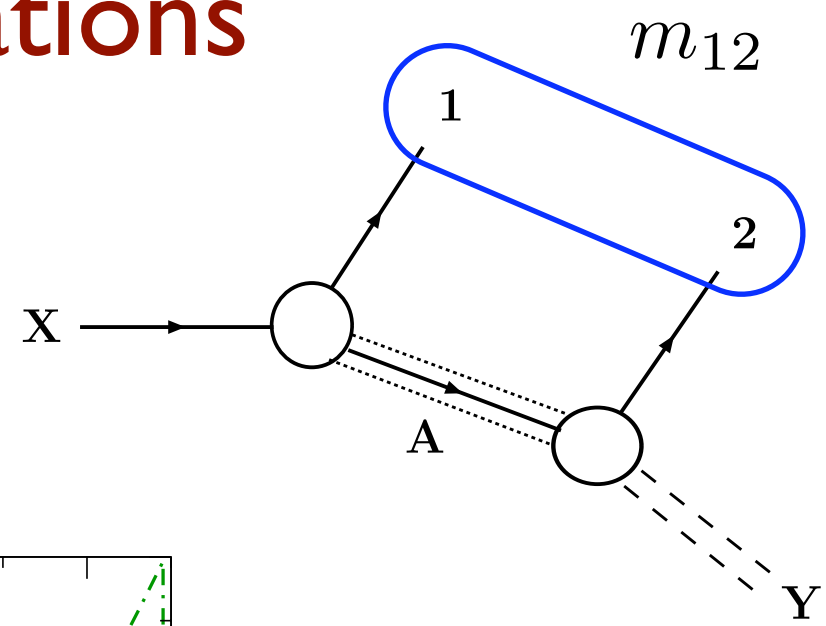


$$\sim |M|^2 \sim X^q \xi^p$$

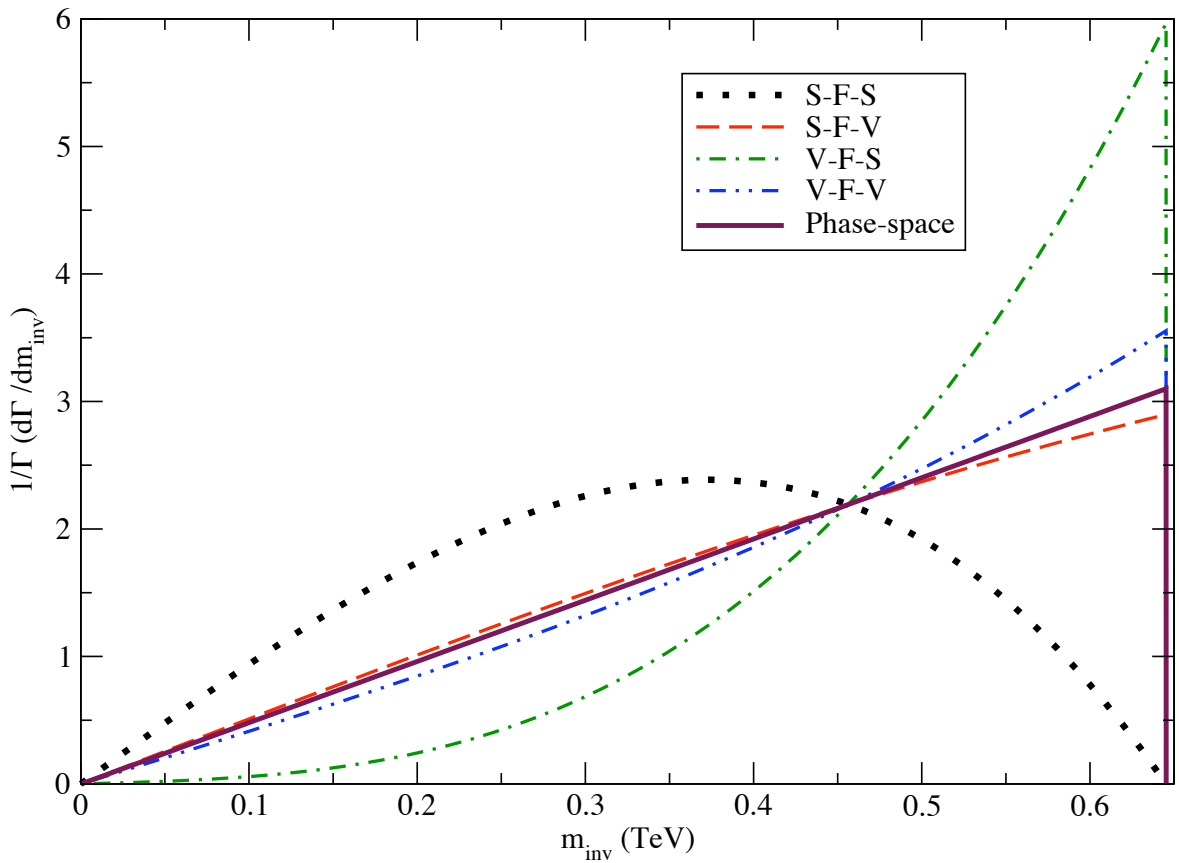
X-Independence of rapidity Shape!



Spin/Helicity Correlations in Decay?



Di-object Distributions



Angular correlations in cascade decays are known to be important!

See J. Alwall's talk about MadGraph/OSETs at Princeton MC4BSM