Path from the LHC to the New Standard Model via On-Shell Effective Theories

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

$$\begin{matrix}\text{LHC}\\ \text{Data}\end{matrix} \Rightarrow \mathcal{L}\,?$$

Collective Hadron Collider Discovery Experience

$$W/Z \qquad\qquad t$$

No undetermined parameters

One unknown parameter (m_t)

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

Characterizing New Physics

Only a few dynamical variables control the essential phenomenology of new physics at hadron colliders.

Characterizing new physics directly in terms of these variables permits a simple, accurate parametrization of almost **any** model of new physics —

an On-Shell Effective Theory.

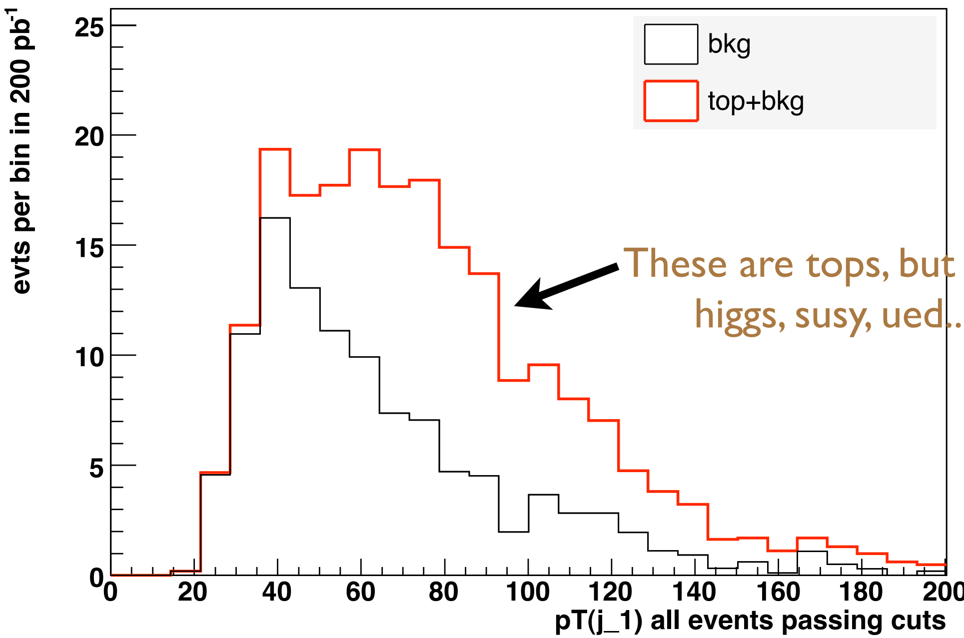
Only with this information can we tackle the fundamental questions:

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

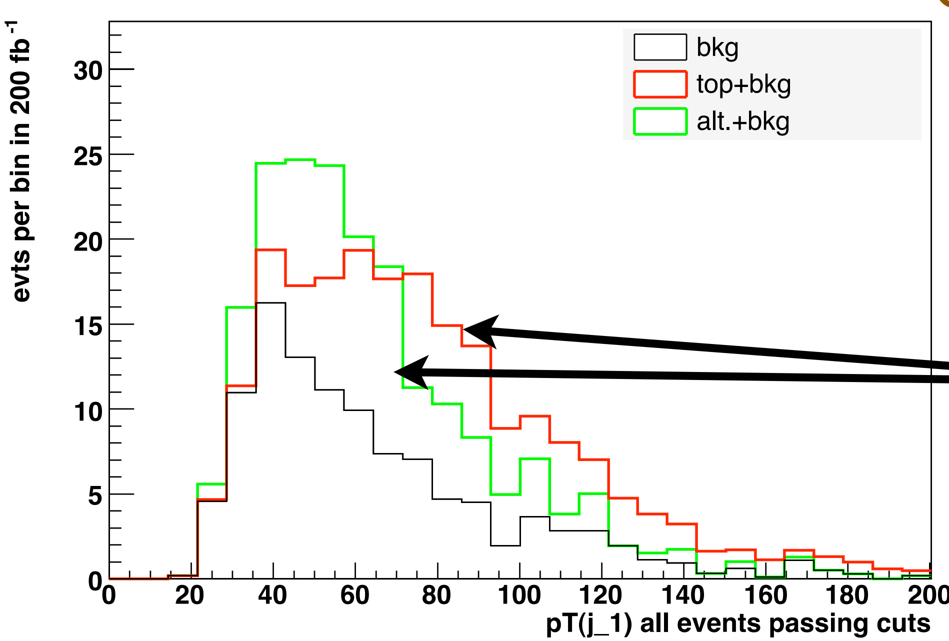
Is nature supersymmetric?

Is the electroweak scale natural?

Suppose we have "interesting" events clearly inconsistent with the SM



These are tops, but imagine higgs, susy, ued...etc



How do we characterize "interesting" events?

The "composite sketch" approach

Exploit an effective description:

Throw out irrelevant info

Characterize topology and kinematics

Close connection to Lagrangian, but far simpler

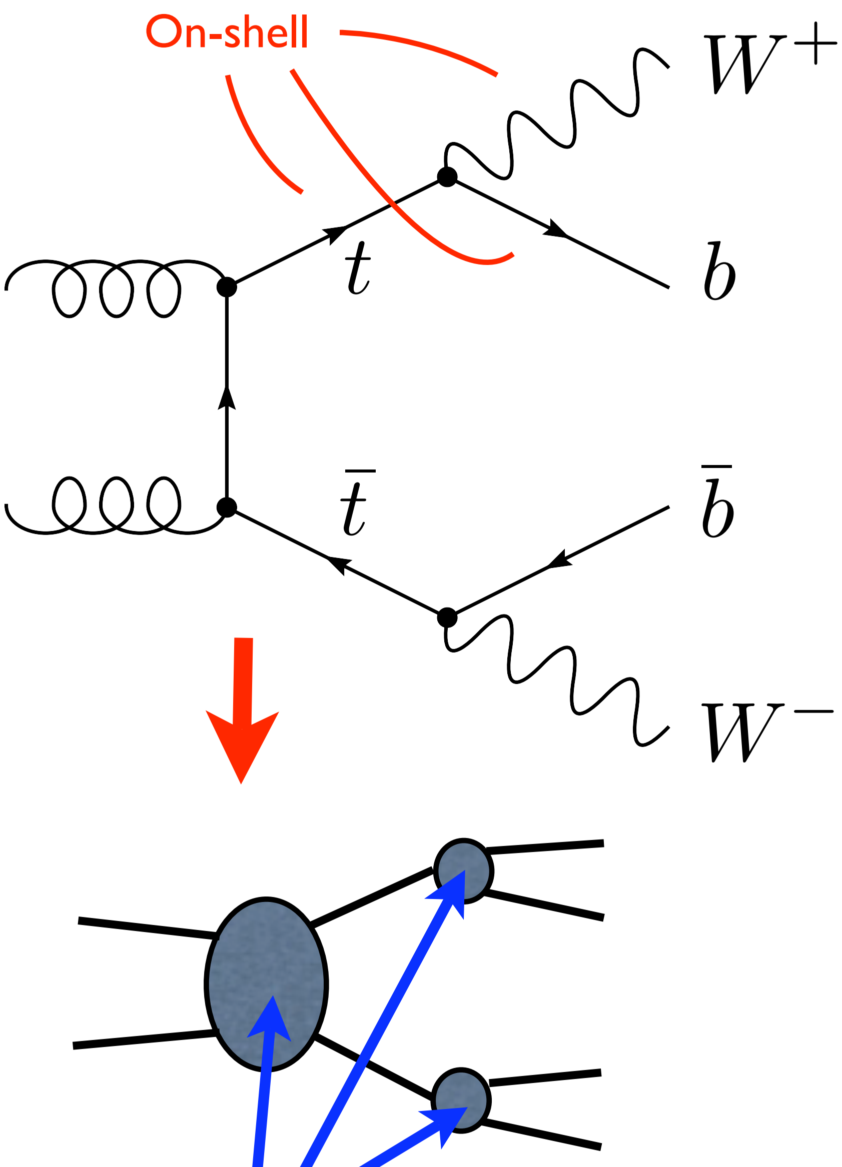
Use On-Shell Effective Theories (OSET)

Fast, accurate, transparent characterization

and discrimination among possibilities

Ask good questions about the data early in the analysis process

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

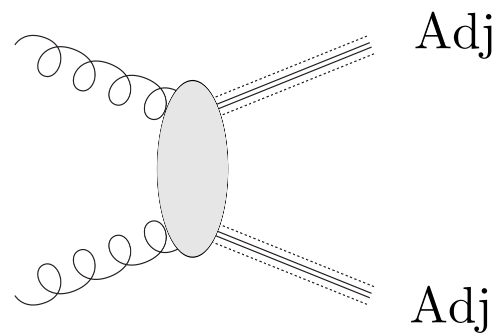
Detailed Top Properties:

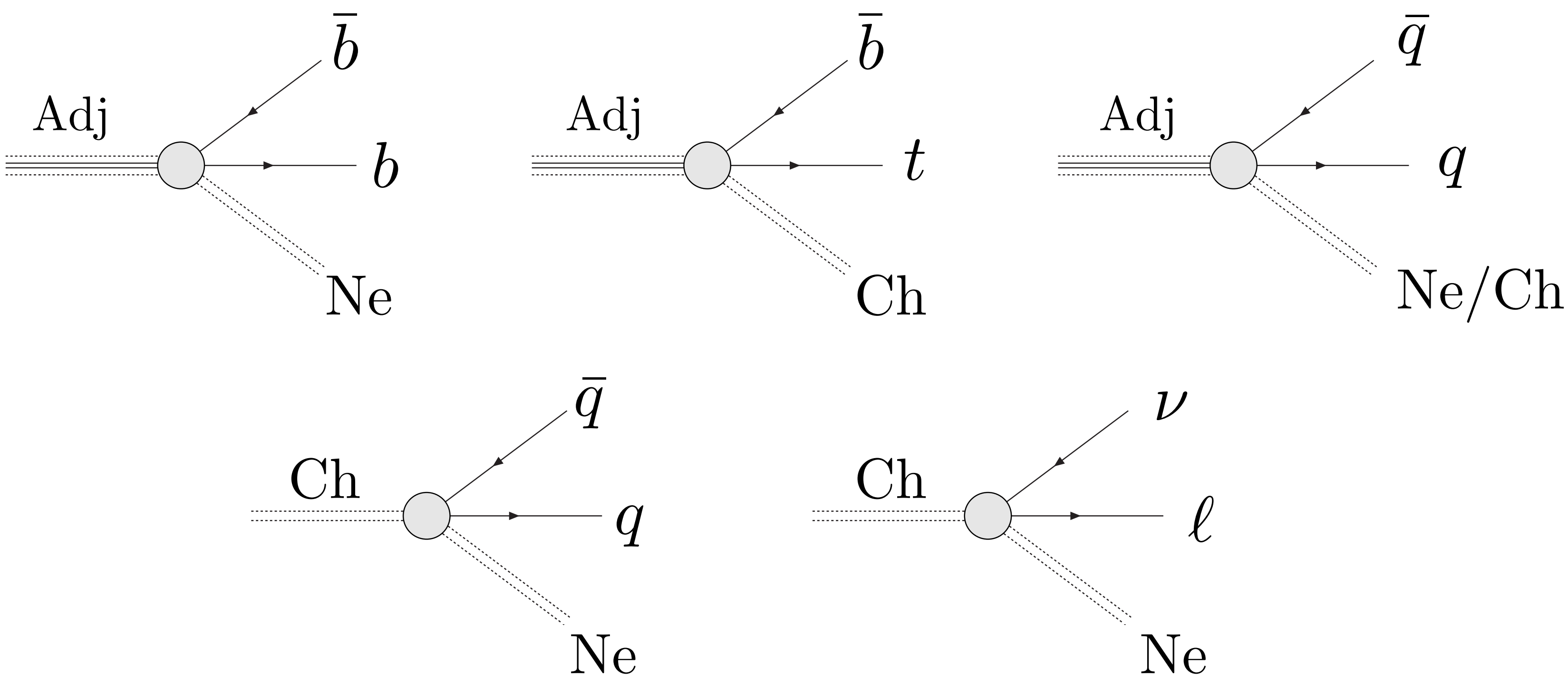
$d\sigma/d\hat{t}$

W helicity

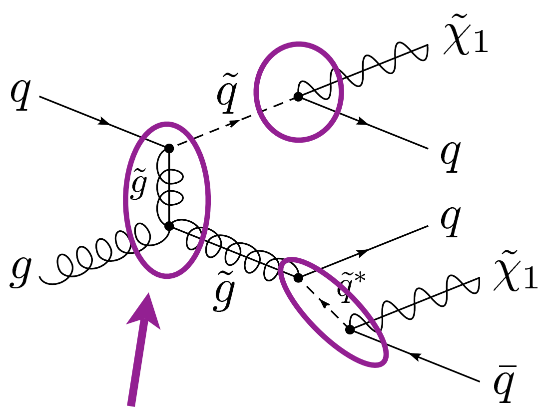
t charge

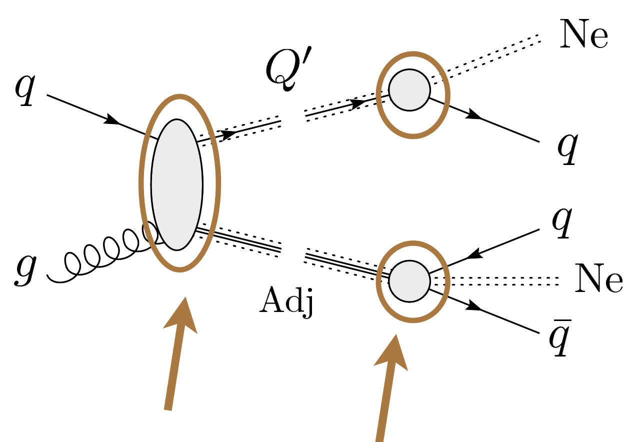
What's an OSET? Complicated Case





OSET Rules: Modeling Production





$$|\mathcal{M}|^2 = \frac{\pi\alpha_s^2}{s^2}\left(\frac{4}{9}\frac{m_{\tilde{g}}^2 - t}{s} + \frac{[(m_{\tilde{g}}^2 - t)s + 2m_{\tilde{g}}^2(m_{\tilde{q}}^2 - t)]}{(t - m_{\tilde{g}}^2)^2}\right.$$

$$\left. + u + st + su + tu \quad \text{channels}\right)$$

try

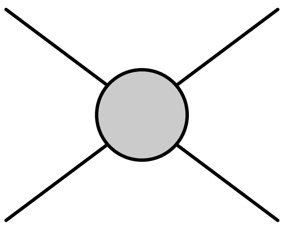
$$|\mathcal{M}|^2 = const.$$

⟶ Monte Carlo

⟶ compare to data

(do kinematics right!)

2→2 Folk Theorem

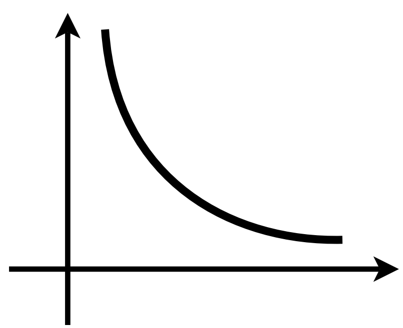


$$|\mathcal{M}|^2 = f(s, \xi) \qquad \xi = \beta_{34} \cos\theta = \frac{\hat{t} - \hat{u}}{\hat{s}} = \frac{p_z}{\sqrt{s}}$$

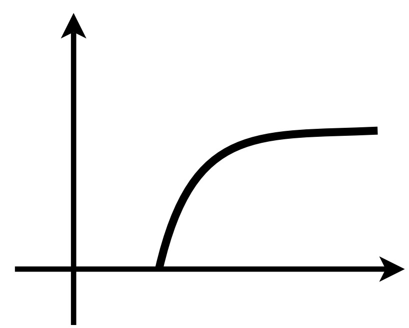
Parton Luminosity

Phase Space (Threshold)

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



$\times$



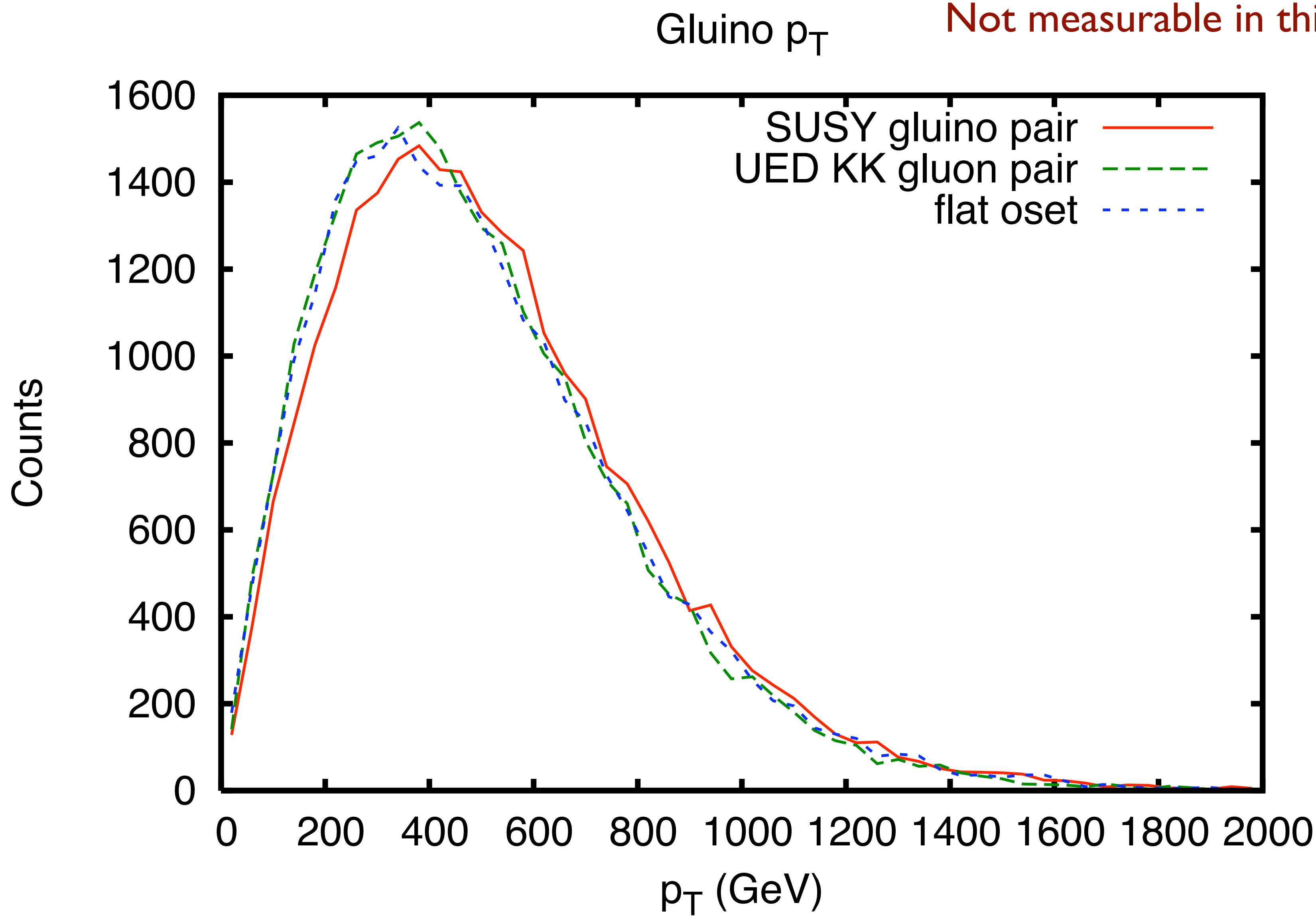
$\times |\mathcal{M}|^2$

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

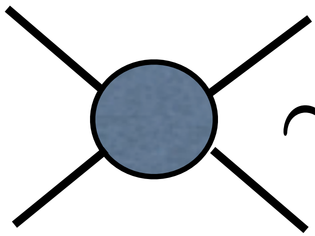
Transverse momentum and rapidity shapes well modeled by constant Matrix Element in most cases!

This is not very surprising...

What about extreme kinematics?

What about corrections?

Adding Corrections:



Full ME

$$\sim |M|^2 = \sum_{p,q} C_{pq} X^p \xi^q$$

Contains CM threshold behavior

Contains CM angular and threshold structure

General Expansion

$$X \equiv \frac{s}{s_{th}}$$

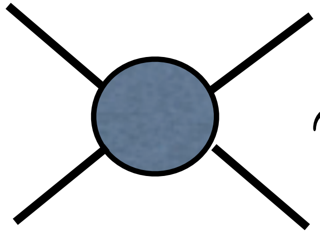
$$\xi \equiv \beta_{34} \cos(\theta)$$

Parton Luminosty

CM rapidity integrated

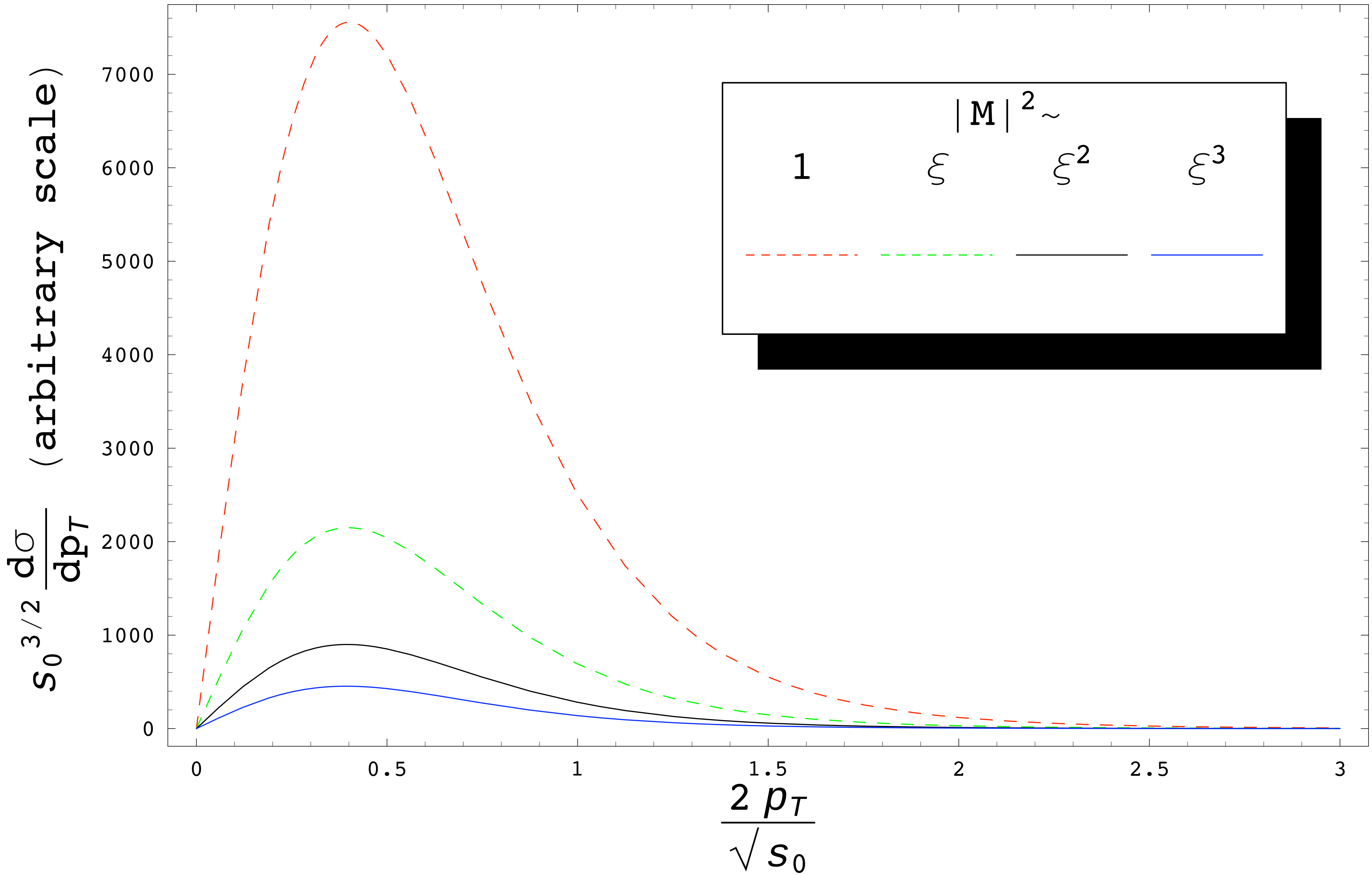
$$\rho_{PDF} \sim \tau^a \log(\tfrac{1}{\tau})$$

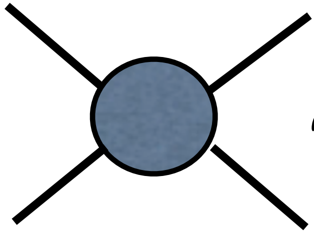
How much matrix element structure survives PDF convolution?



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

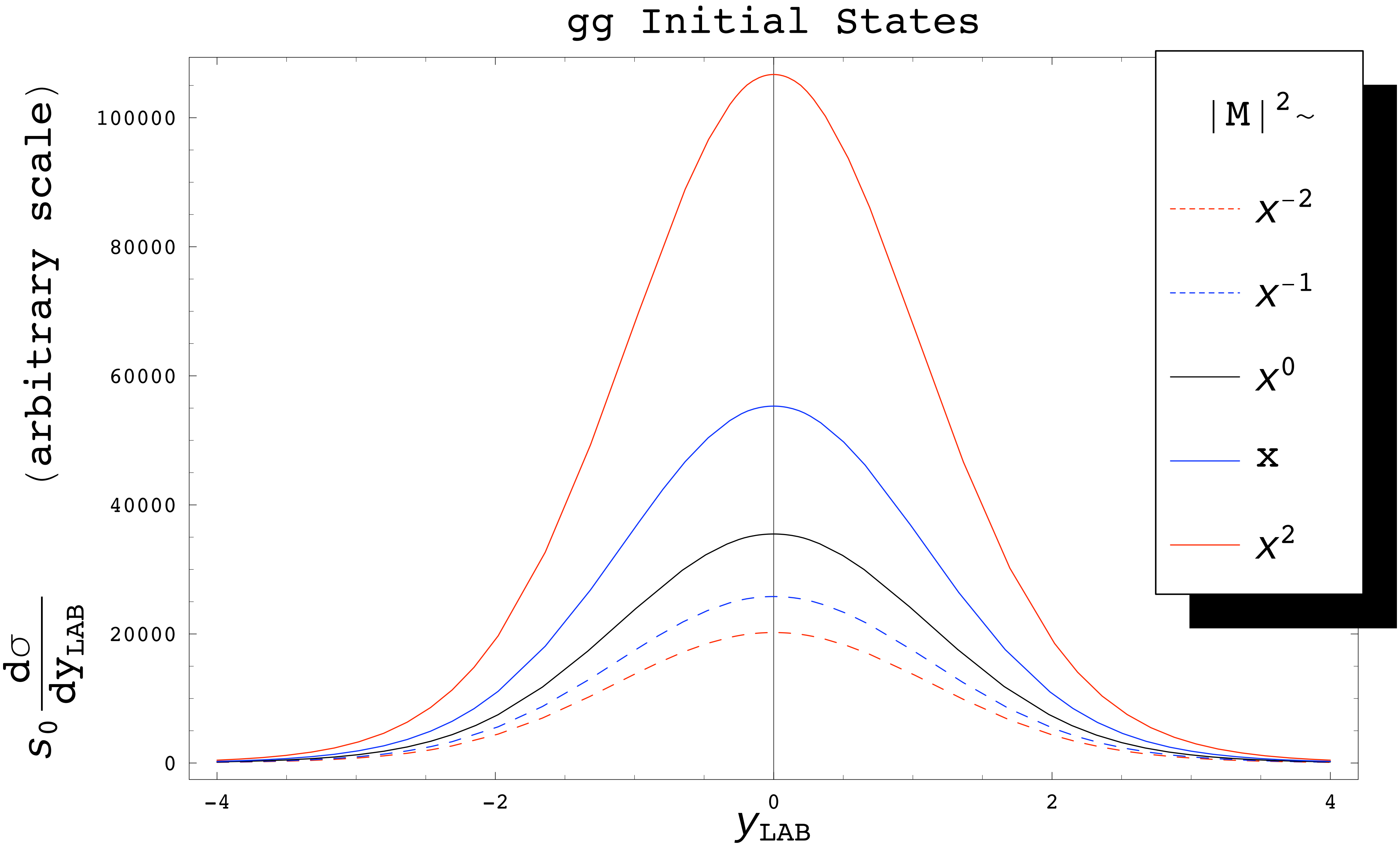
Threshold Suppression

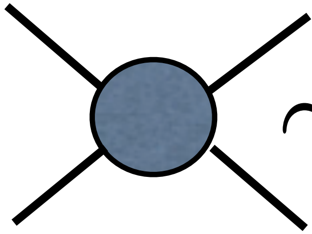




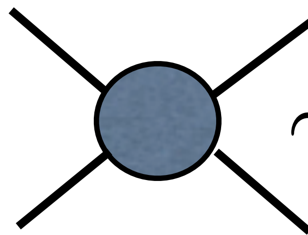
$\sim |M|^2 \sim X^q \xi^p$

Threshold Suppression



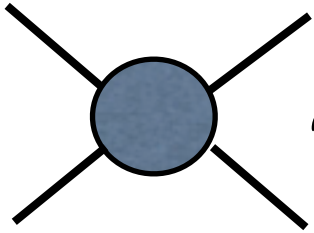


$$\sim |M|^2 = \sum_{p,q} C_{pq} X^p \xi^q$$



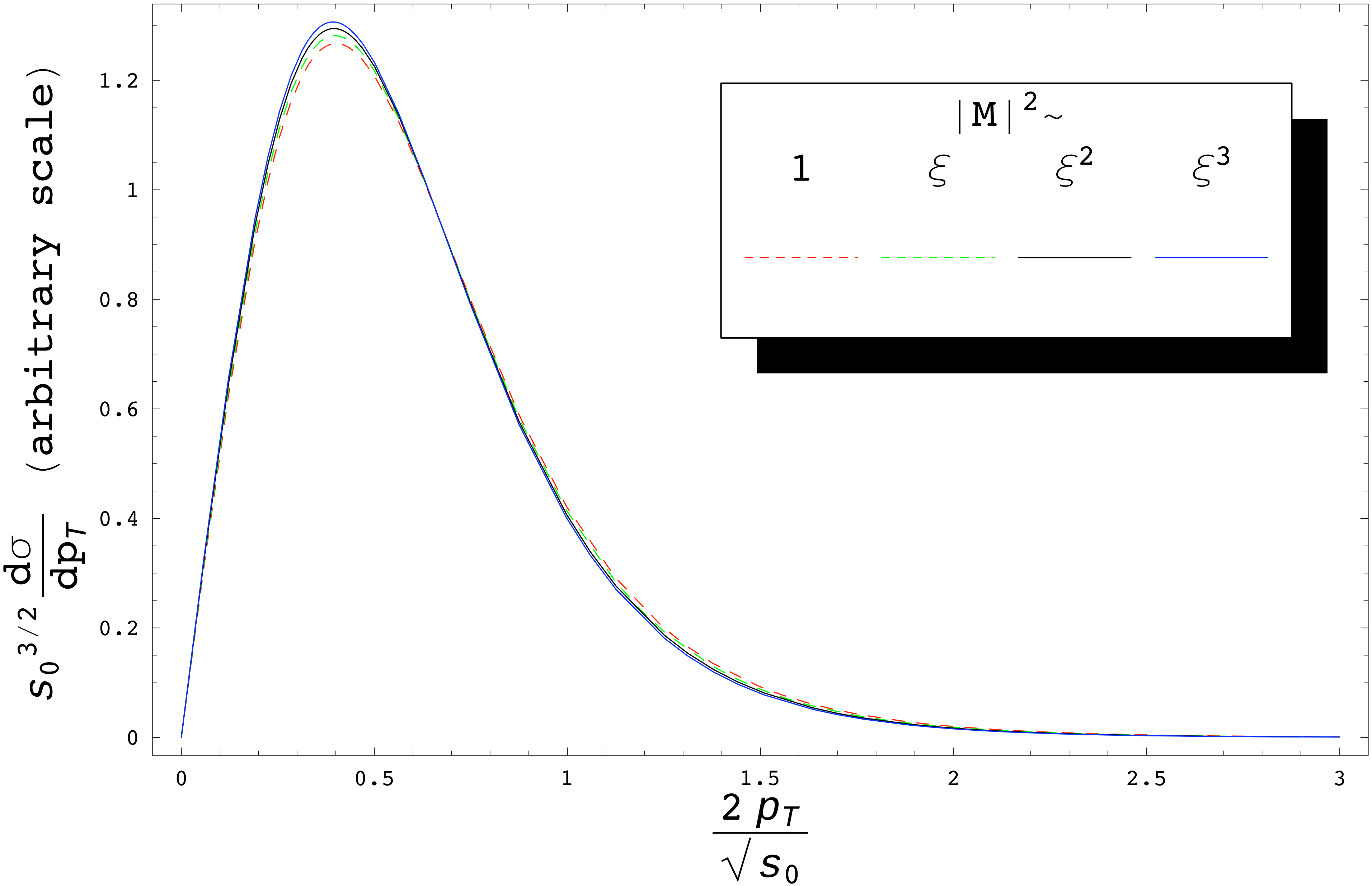
$$\rightarrow \quad \sim |M|^2 \sim X^q \xi^p$$

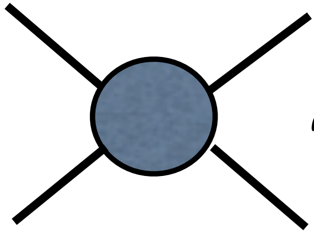
Only near-threshold behavior survives



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

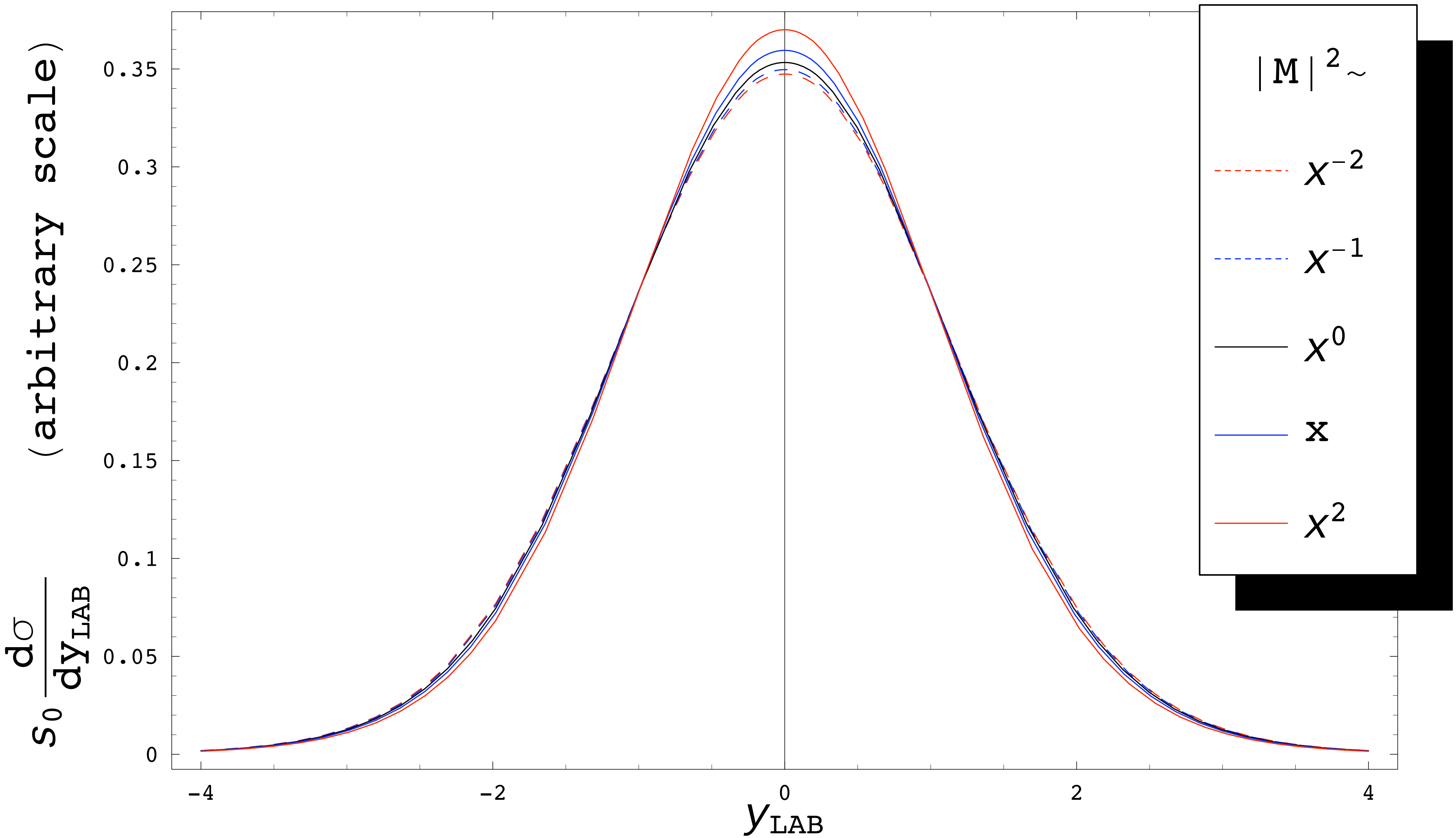
ξ-Independence of Transverse Shape!



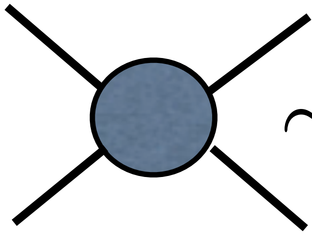


$$\sim |M|^2 \sim X^q \xi^p$$

X-Independence of rapidity Shape!



Shape Invariance



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

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

Inclusive p_T shape invariant under:

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

Inclusive y_{lab} shape invariant under:

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

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

Defining an OSET

Production:

$2 \rightarrow 1$ Use Breit Wigner

$2 \rightarrow 2$

Usually dominates

"Normal" Behavior

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

or

"Contact" Operator Behavior

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

Dominant ξ correction can be included (not usually necessary)

$2 \rightarrow 3$ 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.

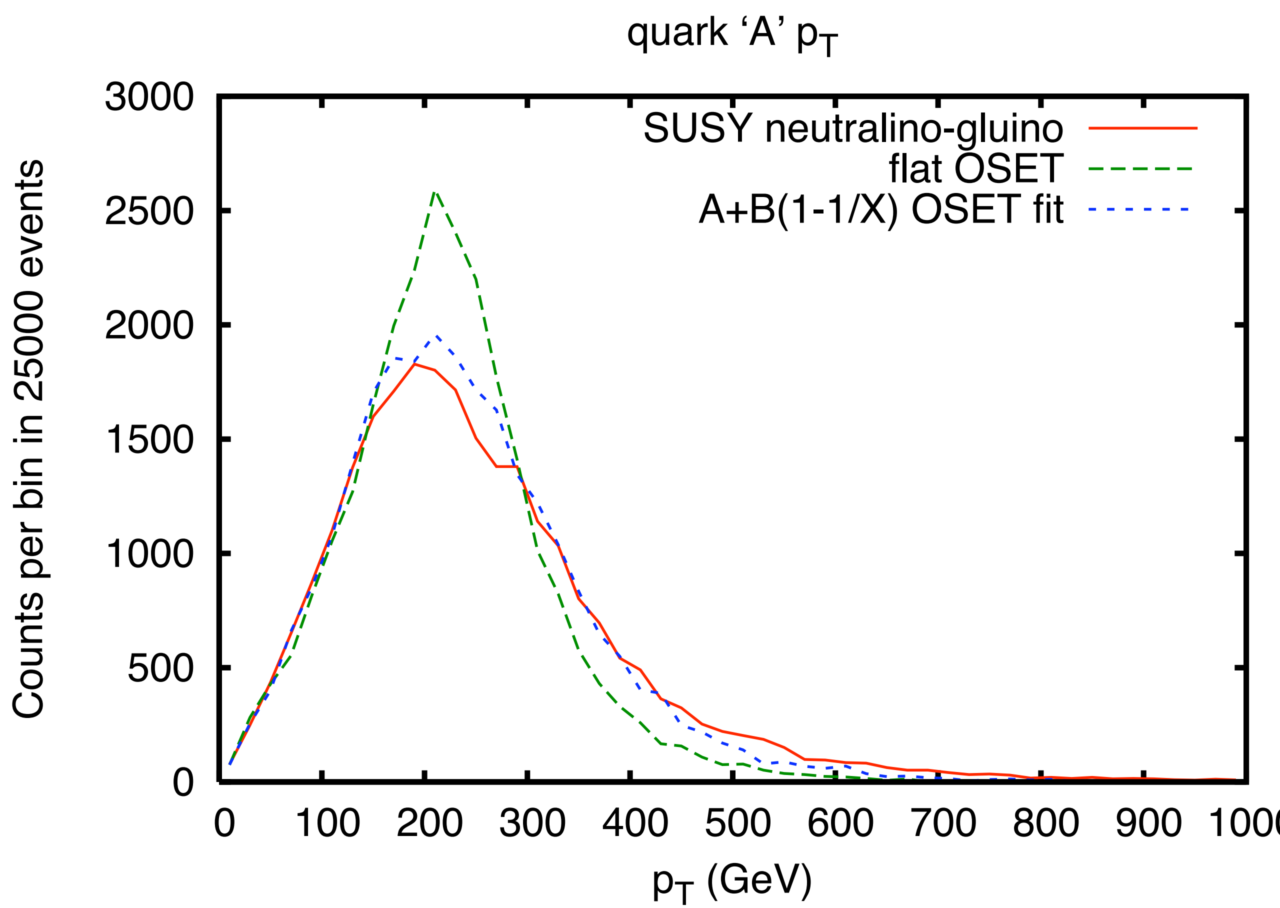
See: hep-ph/0703088 for detail...

“Normal” Behavior

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

p-wave $\rightarrow$
suppressed
near threshold.

$$\propto \beta^2$$



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

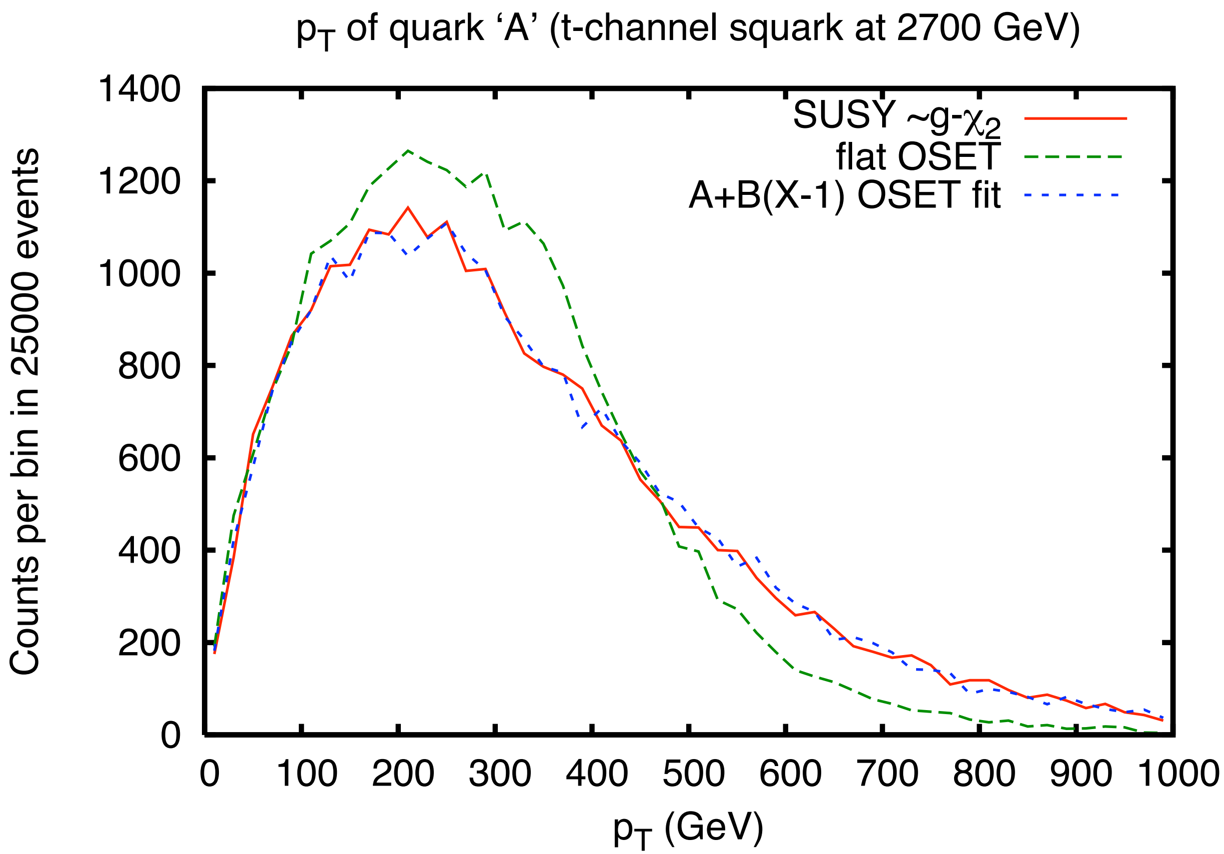
"Contact" Operator Behavior

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

contact interaction

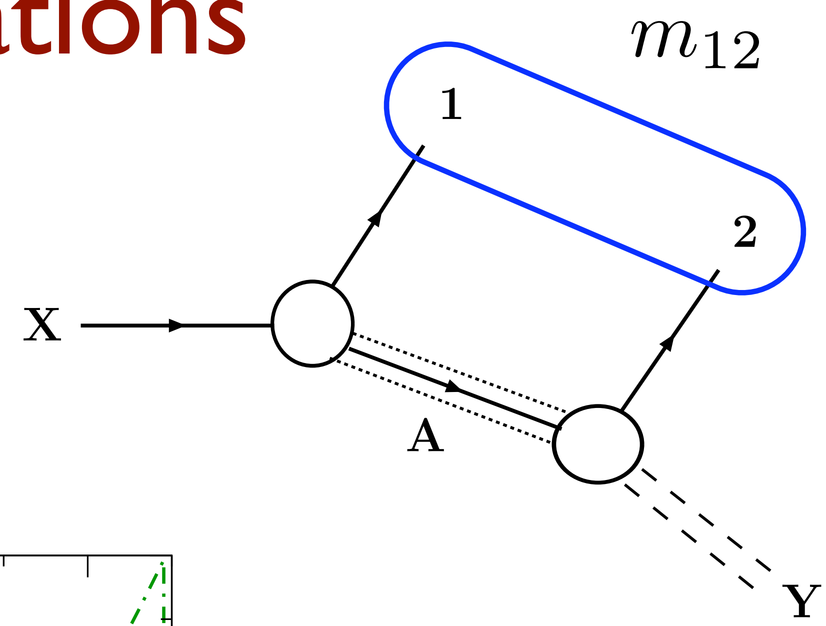
$$|\mathcal{M}|^2 \propto s^2$$

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

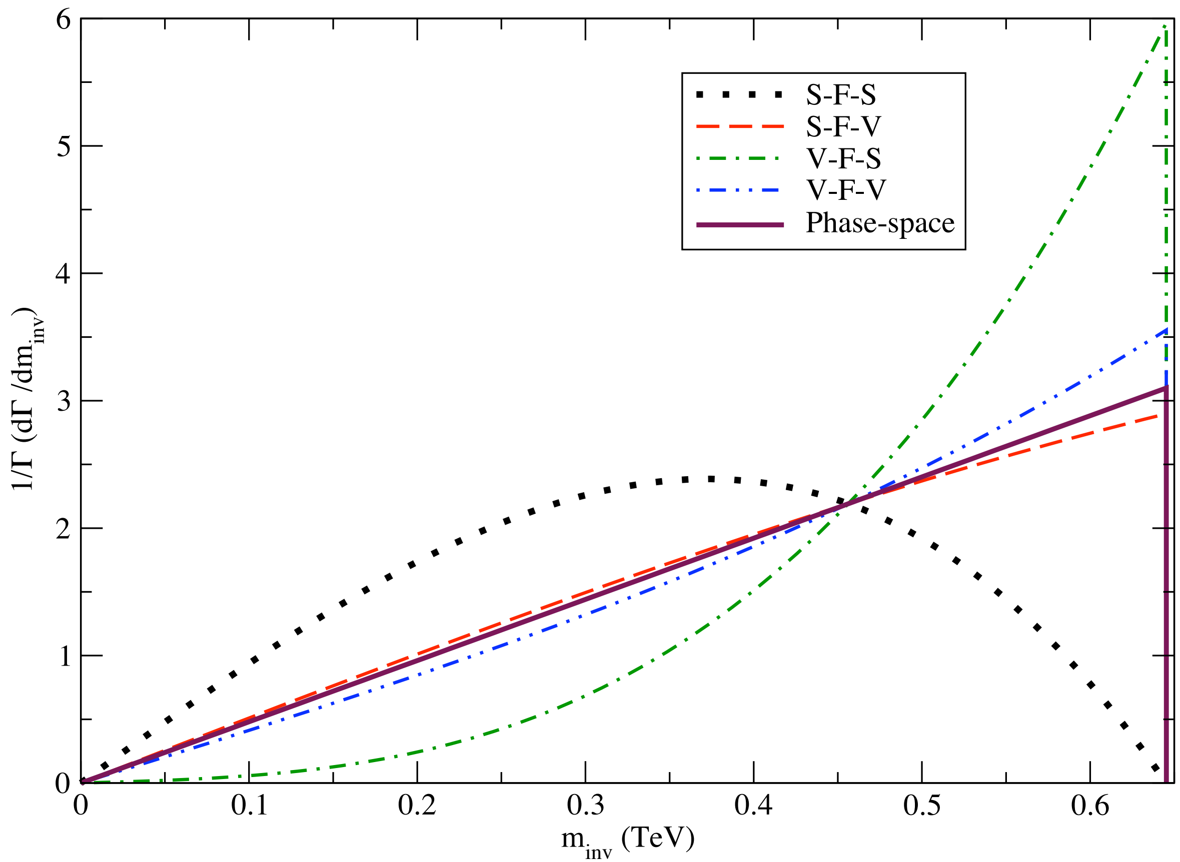


$$|\mathcal{M}|^2 = A + B\left(\frac{s}{s_{\text{thresh}}} - 1\right)$$

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

Why Monte-Carlo an OSET?

- MODEL: Fast, sufficiently accurate event generation for your favorite model

- DATA: Check consistency of partial interpretations of candidate new-physics signals

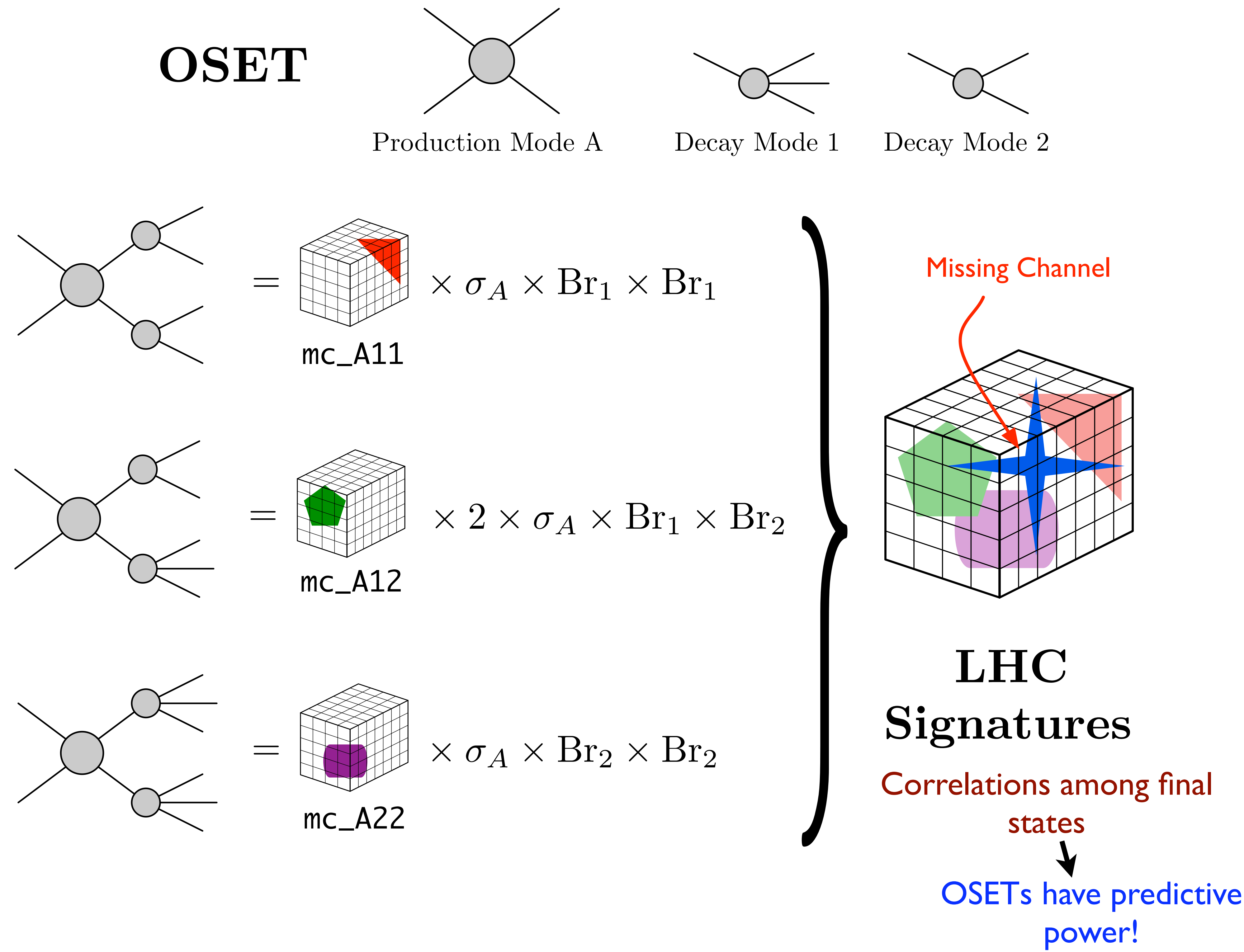
MARMOSET

Mass and Rate Modeling in On-Shell Effective Theories

- Masses and SU(3) and U(1) quantum numbers of new particles, their production and decay modes **fully specify model**
- An OSET implies many topologies, and Monte Carlo is generated separately for each
- Topologies can be combined by weighting according to hadronic cross-sections and decay branching fractions

"offline" reweighting of MC $\longrightarrow$ **fast**!

scan models by simulating coarsely spaced mass points


OSET
Production Mode A
Decay Mode 1
Decay Mode 2
$= \times \sigma_A \times \mathrm{Br}_1 \times \mathrm{Br}_1$
mc_A11
$= \times 2 \times \sigma_A \times \mathrm{Br}_1 \times \mathrm{Br}_2$
mc_A12
$= \times \sigma_A \times \mathrm{Br}_2 \times \mathrm{Br}_2$
mc_A22
Missing Channel
LHC Signatures
Correlations among final states
OSETs have predictive power!

MARMOSET: Simple Monte Carlo for Any Model

Coarse Mass Scanning

Rate Scanning by Reweighting Existing Monte Carlo

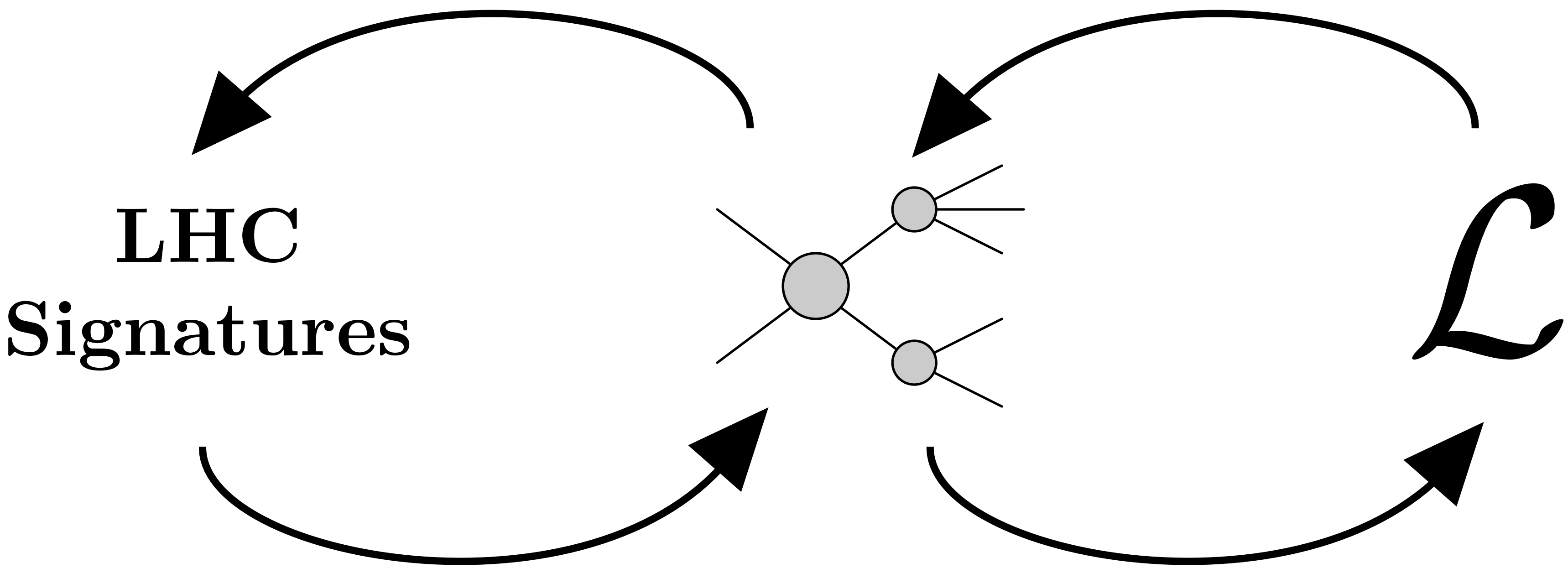
vs.

Lagrangian Simulation

Intricate dependence of σ,Br on many Lagrangian parameters demands fine scanning of all of them.

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

Use OSET MC like a “think-pad”

The Michigan Black Box

1st and 2nd LHC Olympics

$\tilde{q}_{1,2}$	1.8–2.1 TeV
$\tilde{b}_R$	2.0 TeV
$\tilde{t}_R, \tilde{q}_{3L}$	1.4 TeV
$\widetilde{W}$	1.0 TeV
$\widetilde{B}$	480 GeV
$\tilde{g}$	450 GeV
$\tilde{h}$	125 GeV

$(\tan\beta = 19)$

A SUSY model

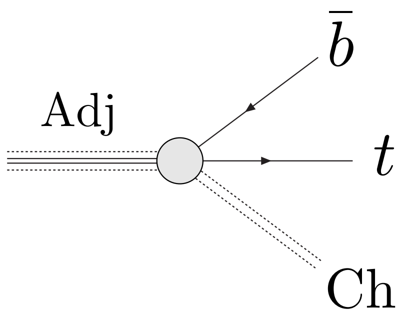
(nothing like CMSSM)

Signatures are quite simple...

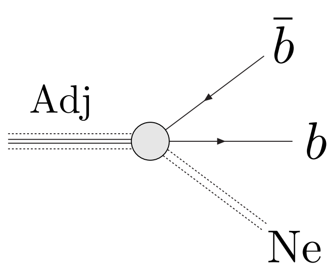
visible in many searches

how do you combine results?
what params reproduce them?

Where do you see it?



First discovery in 1lepton+jets+MET search?
2l+jets+MET?

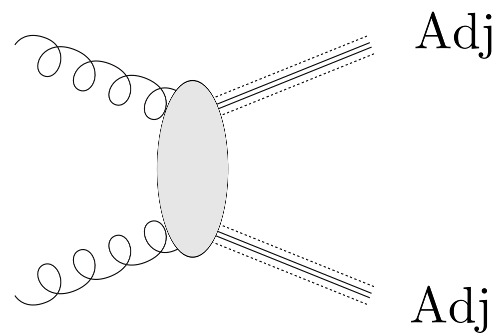


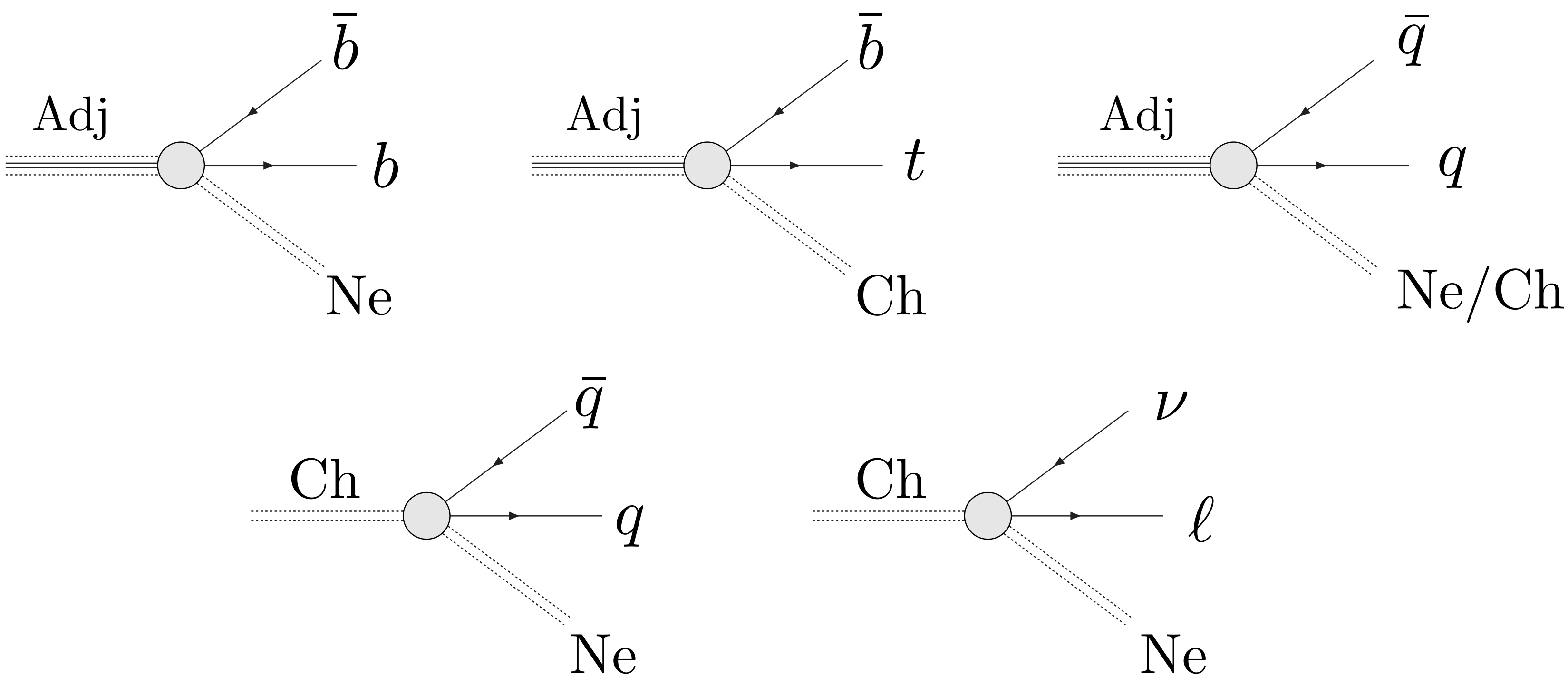
Signal in $b\bar{b}$+jets+MET,
jets+MET

(with unrealistic detector, we've seen it after TDR low-mass SUSY analysis cuts in inclusive jets+MET — lots to see after $1fb^{-1}$)

The Michigan Black Box

Process/Kinematic Characterization





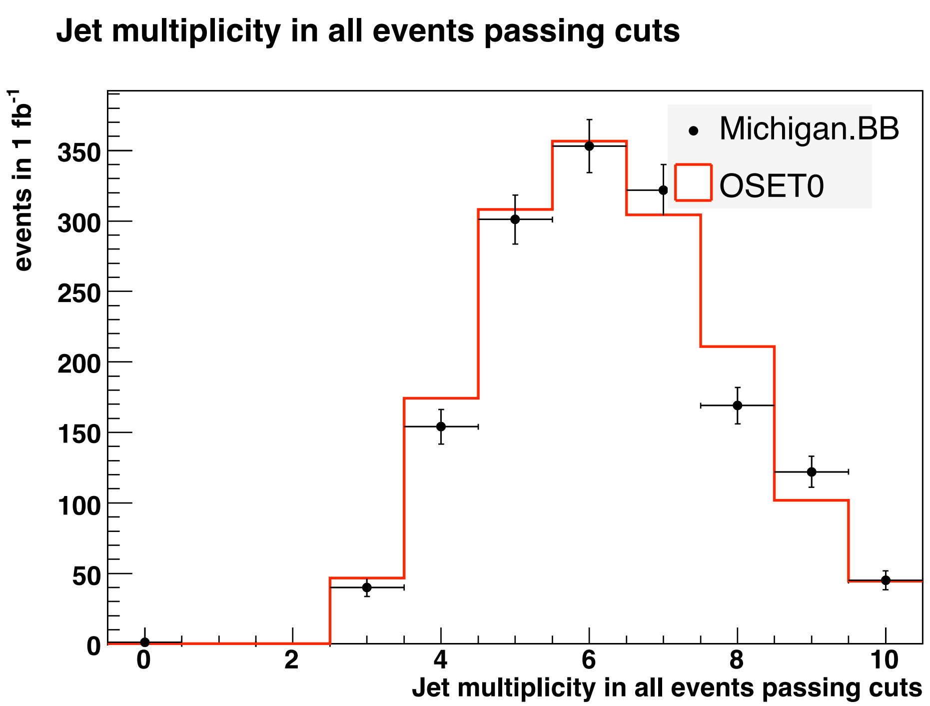
Parameterizing Rates in MARMOSET

Process	**fit rate**	**Actual rate** $(1fb^{-1})$
$N(gg \to Adj\,Adj)$	30600 ± 1300	27950
$Br(Adj \to t\bar{b}Ch^{-}$ or $c.c.)$	0.77 ± 0.01	0.77
$Br(Adj \to b\bar{b}Ne)$	0.21 ± 0.01	0.22
$Br(Adj \to q\bar{q}Ne)$	0.02 ± 0.01	0.01
$Br(Ch \to q\bar{q}'Ne)$	0.44 ± 0.11	0.6
$Br(Ch \to e/\mu\bar{\nu}Ne)$	0.55 ± 0.11	0.4

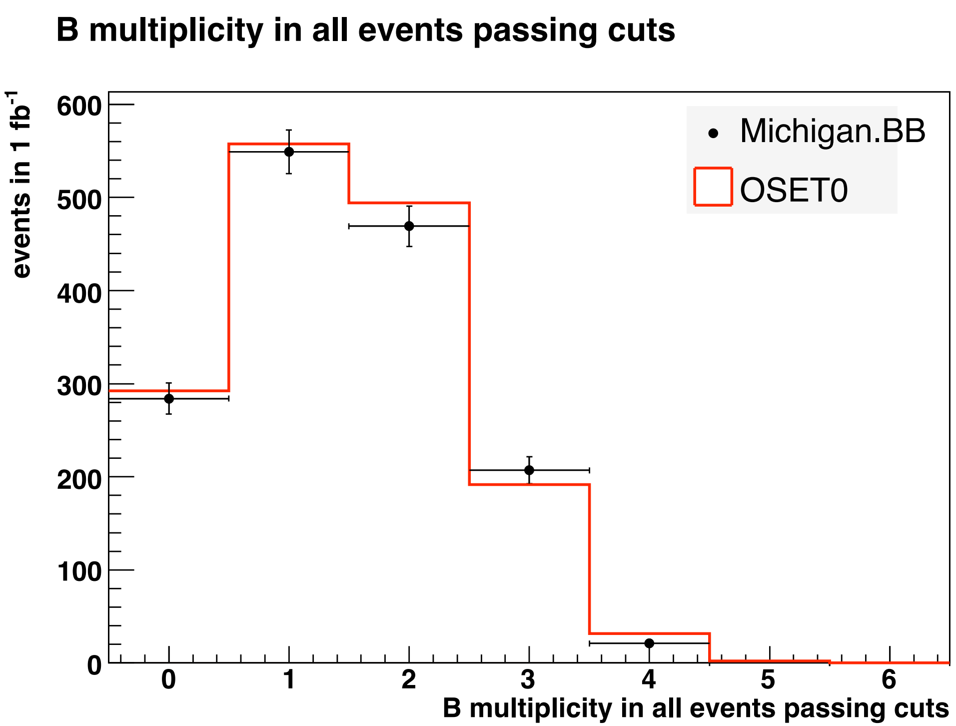
Example Distributions

$$(1\ \text{fb}^{-1})$$

jet multiplicity



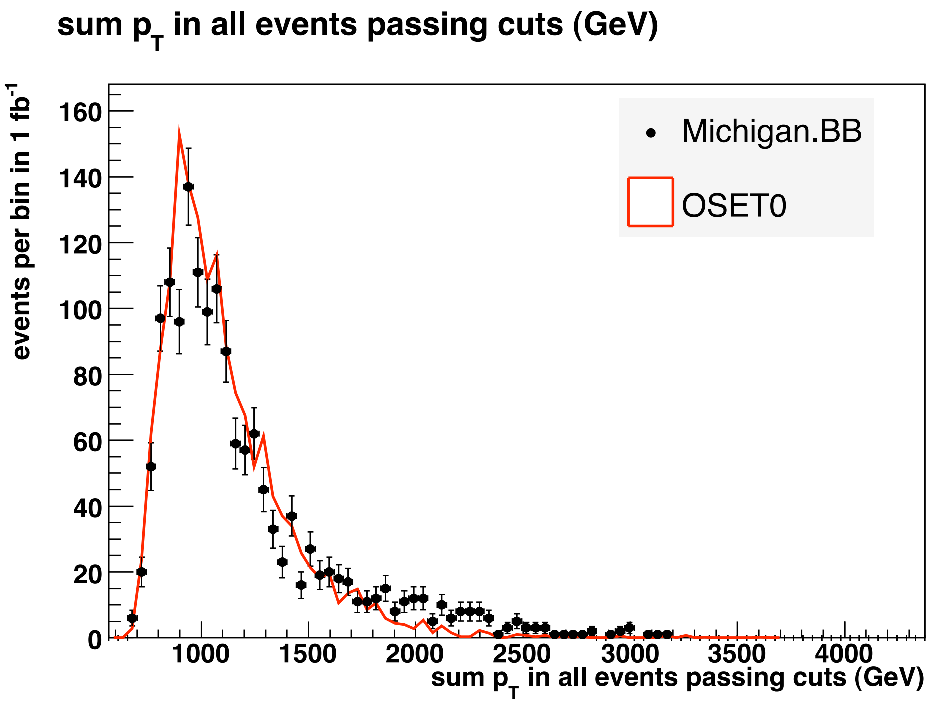
b-tag multiplicity

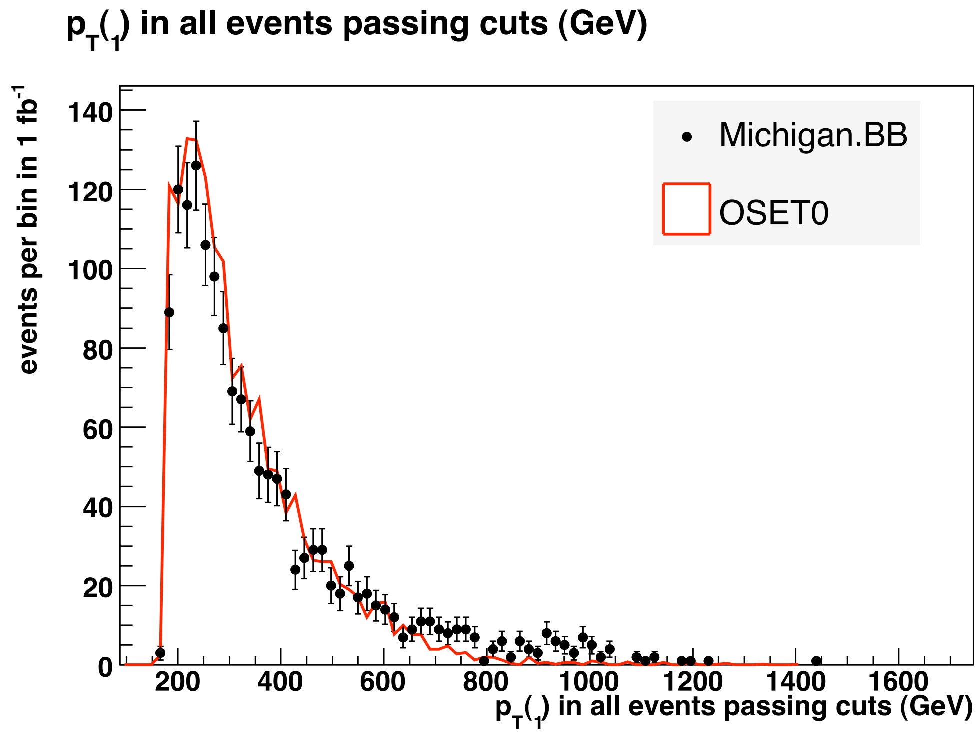


Example Distributions

$$(1\ \mathrm{fb}^{-1})$$

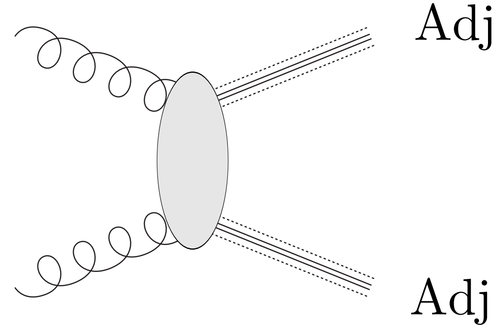
$$m_{\mathrm{eff}} = \sum_i p_T^i \qquad\qquad p_T(j_1)$$

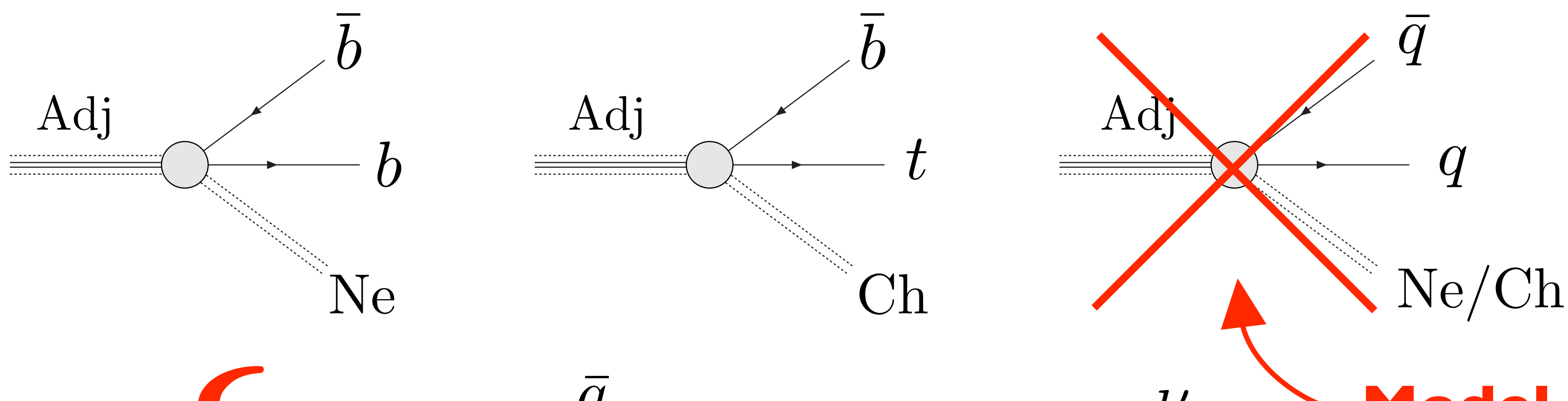




The Michigan Black Box

Striking features **lead to model predictions**



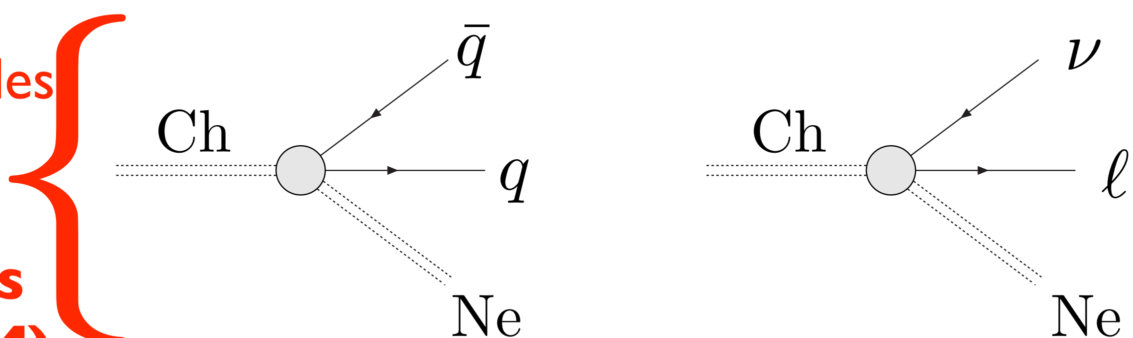


Model must explain its absence!

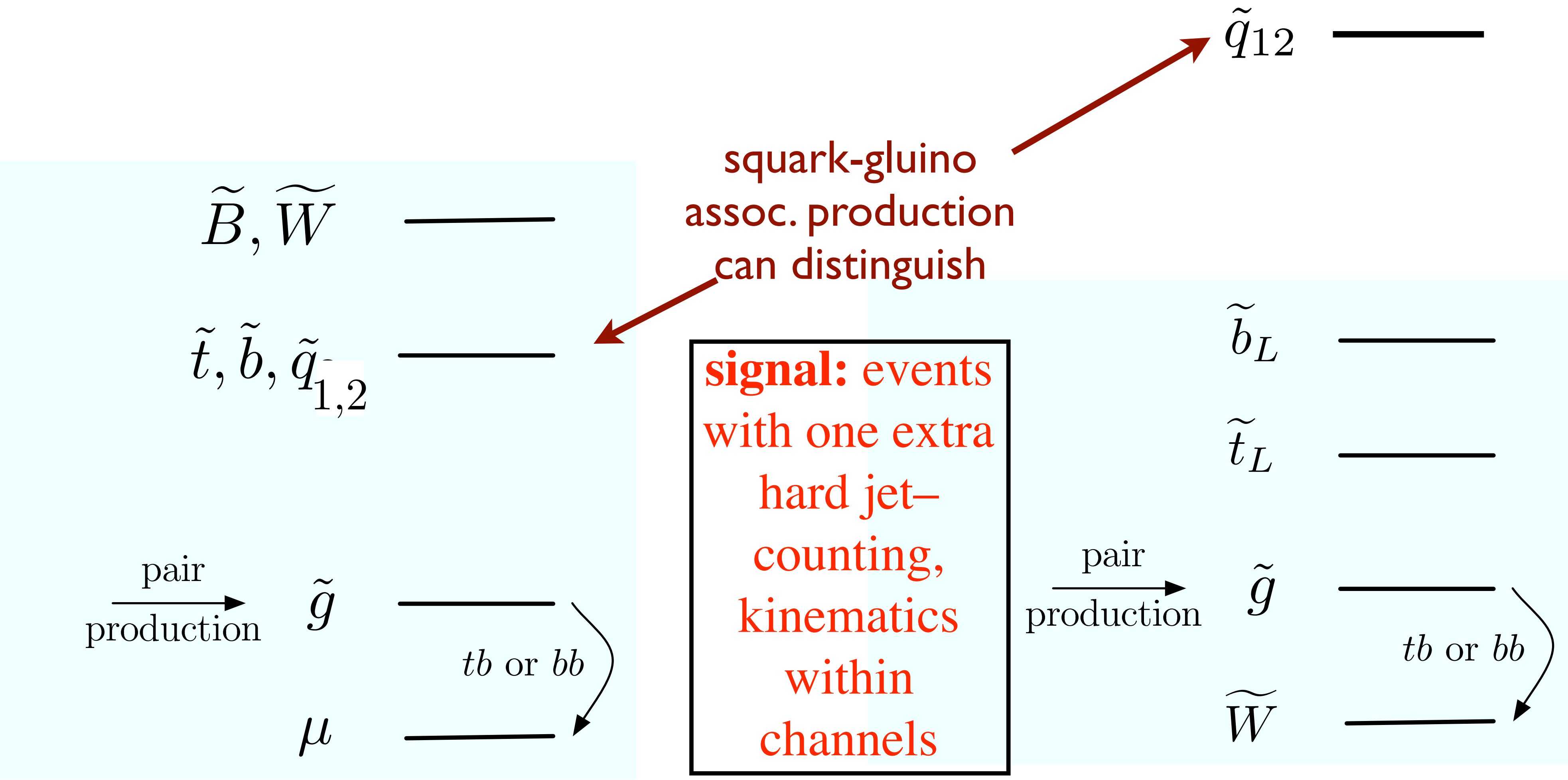
no long cascades

⇓

few light neutralinos (not CMSSM)



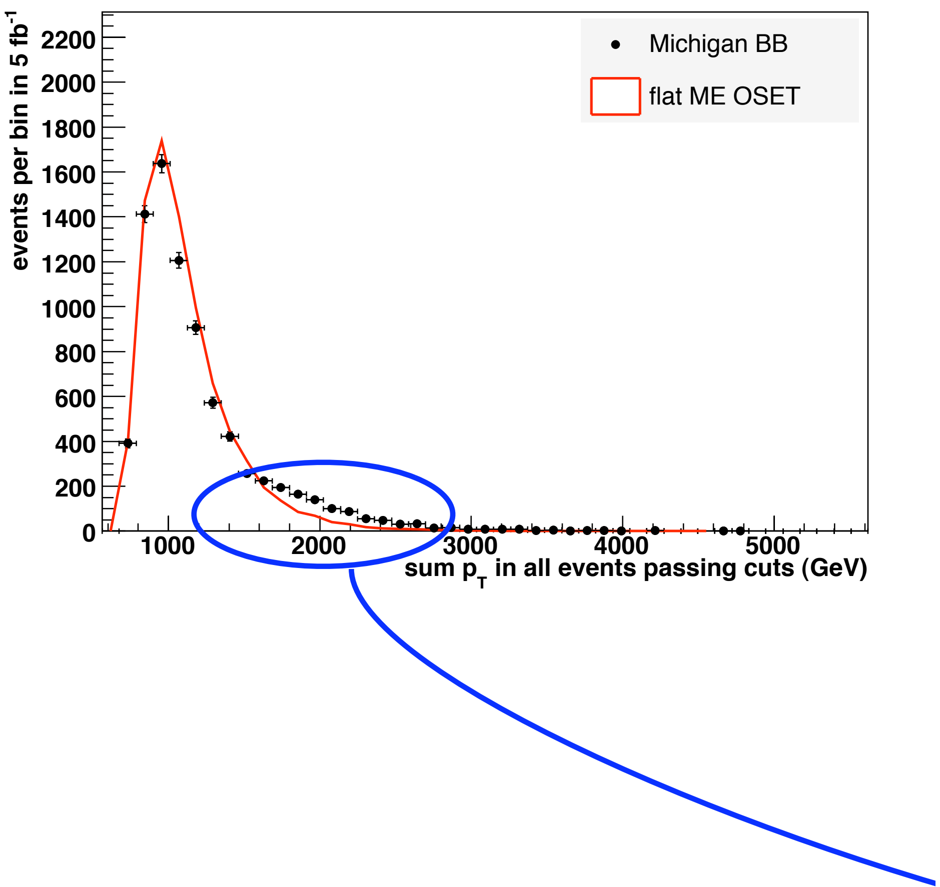
Two SUSY Scenarios



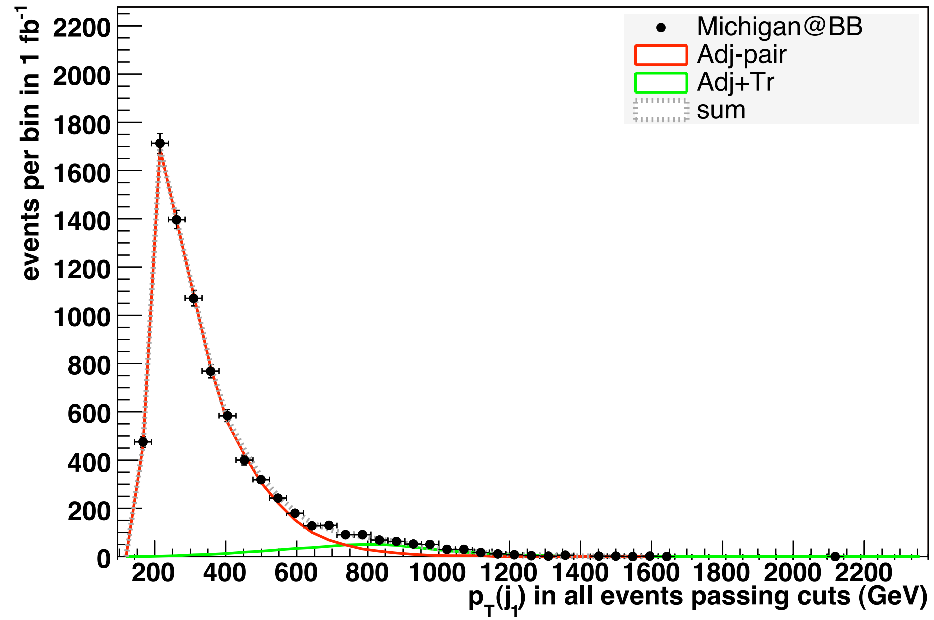
2j channel suppressed
by small couplings to Higgsino

or

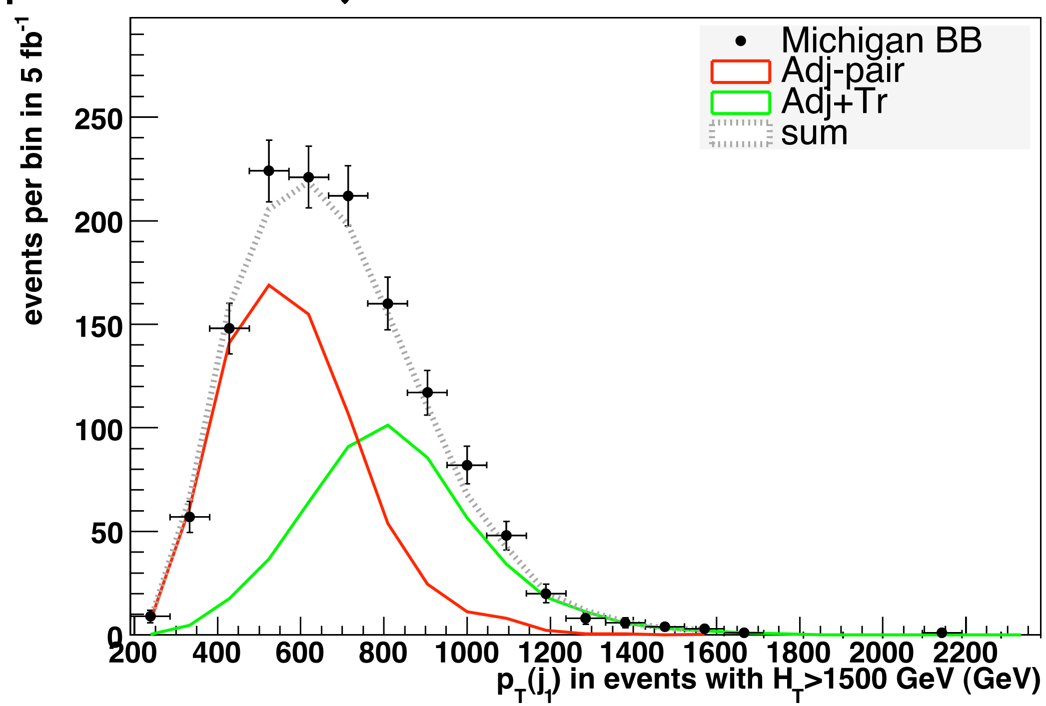
2j channel suppressed
by high squark mass



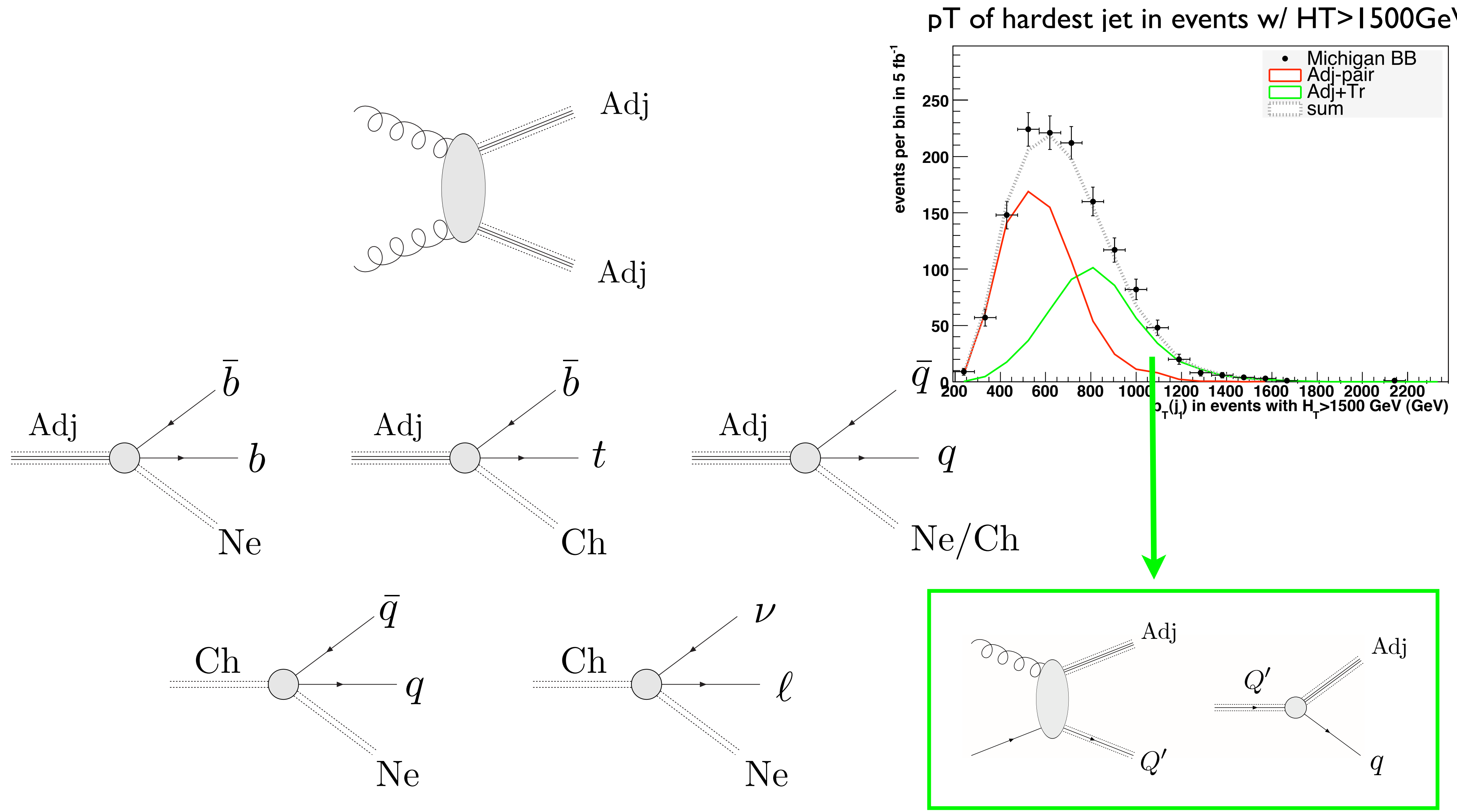
pT of hardest jet in all events



pT of hardest jet in events w/ HT>1500GeV

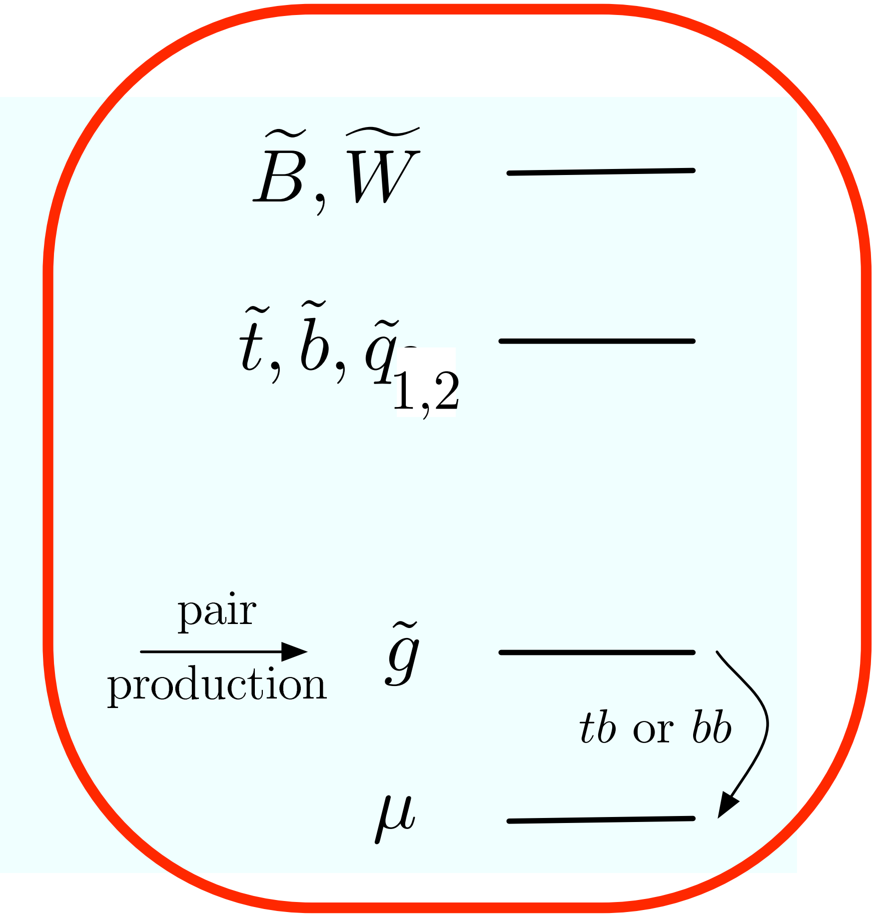


The Michigan Black Box



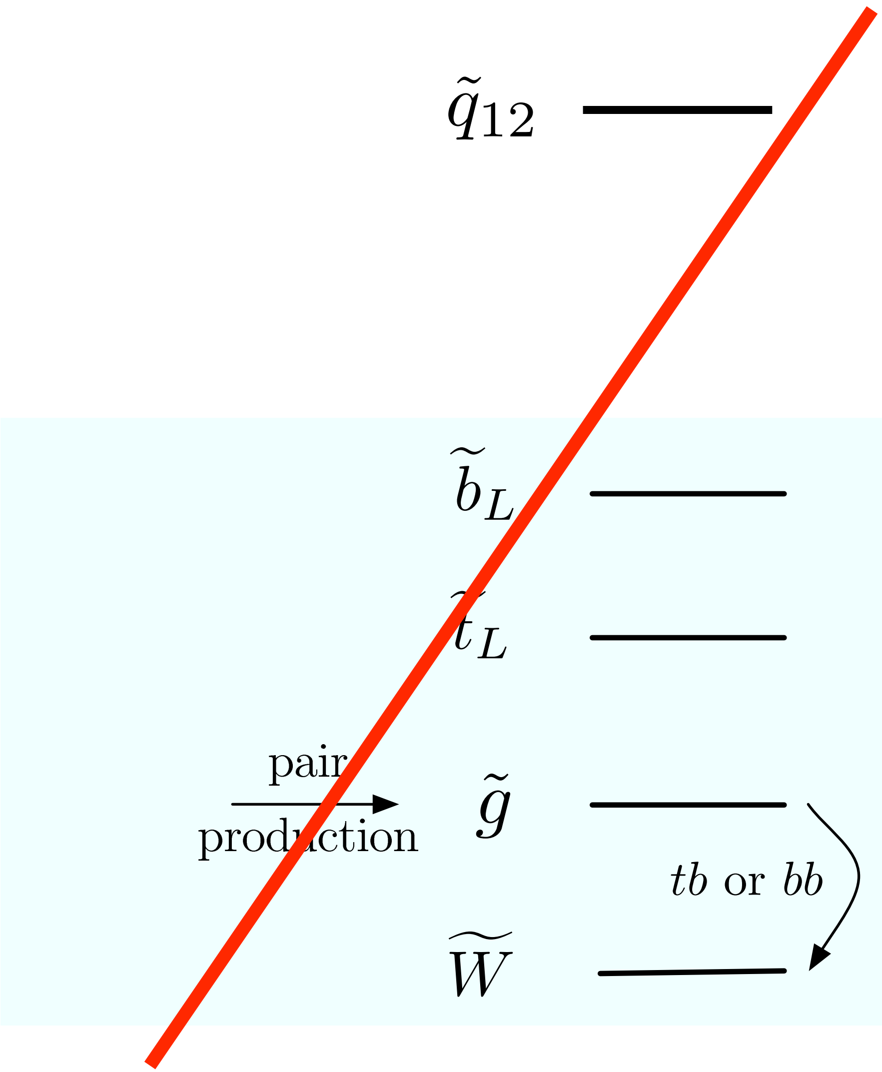
Two SUSY Scenarios

only this model reproduces associated production!



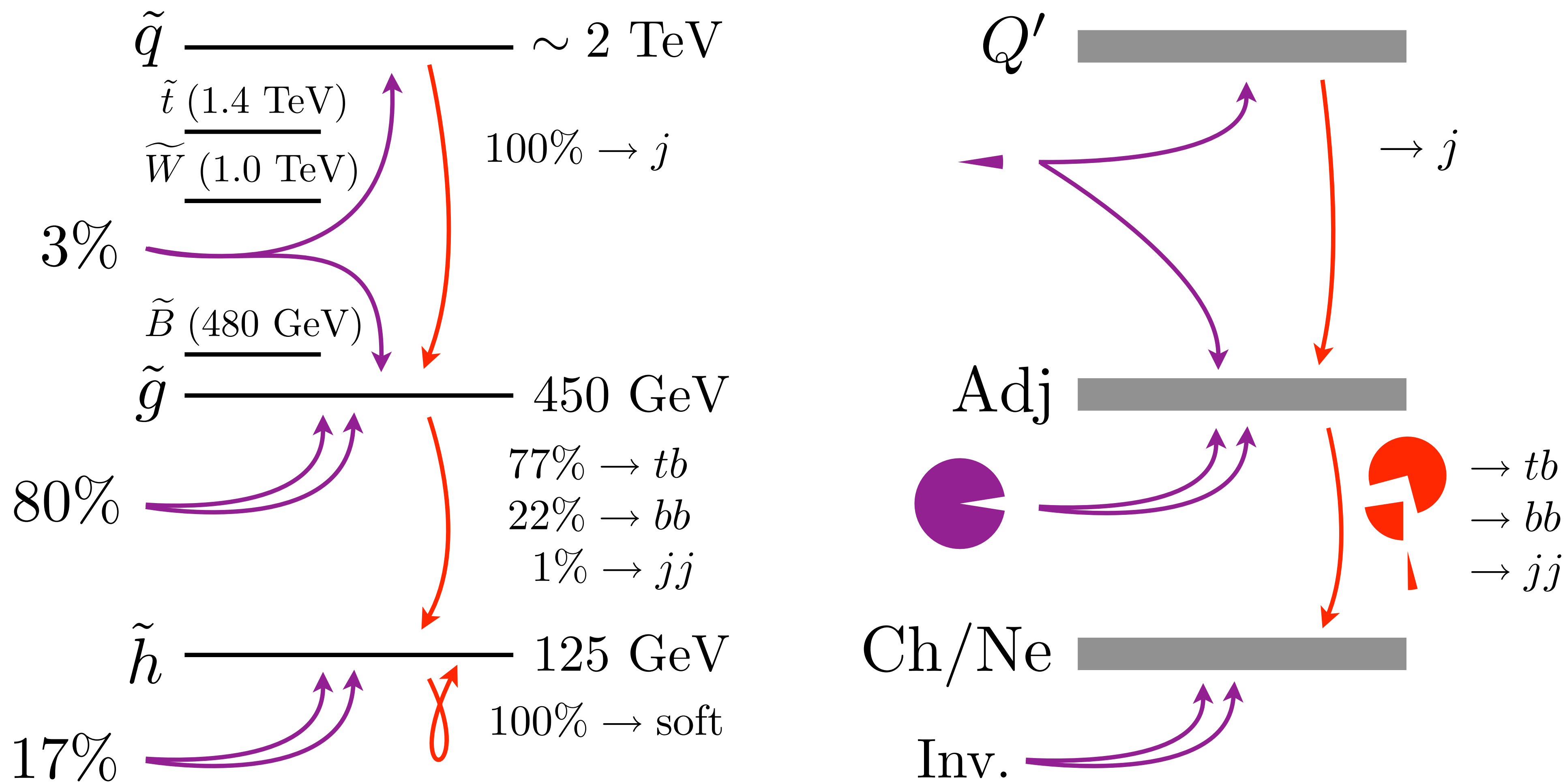
2j channel suppressed
by small couplings to Higgsino

or



2j channel suppressed
by high squark mass

Michigan Box (MSSM)



DBox

Nima & Natalia vs. Jesse & Philip
(Marmoset Smackdown)

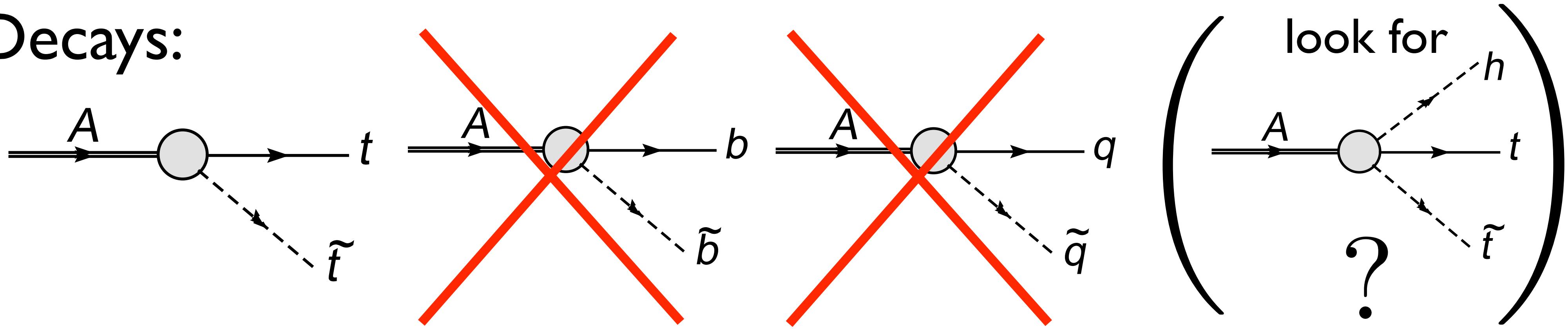
- SUSY with very heavy gauginos (> 5 TeV)
- Light scalars
- **also** light colored adjoint Φ decaying through

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

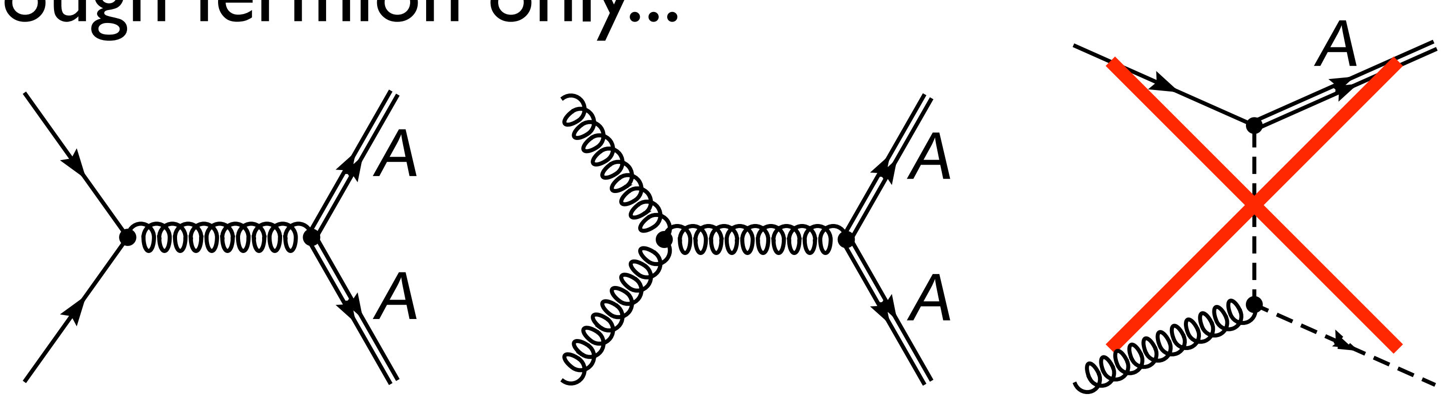
- looks like gluino with wrong decay modes!

DBox "Gluino"?

Decays:

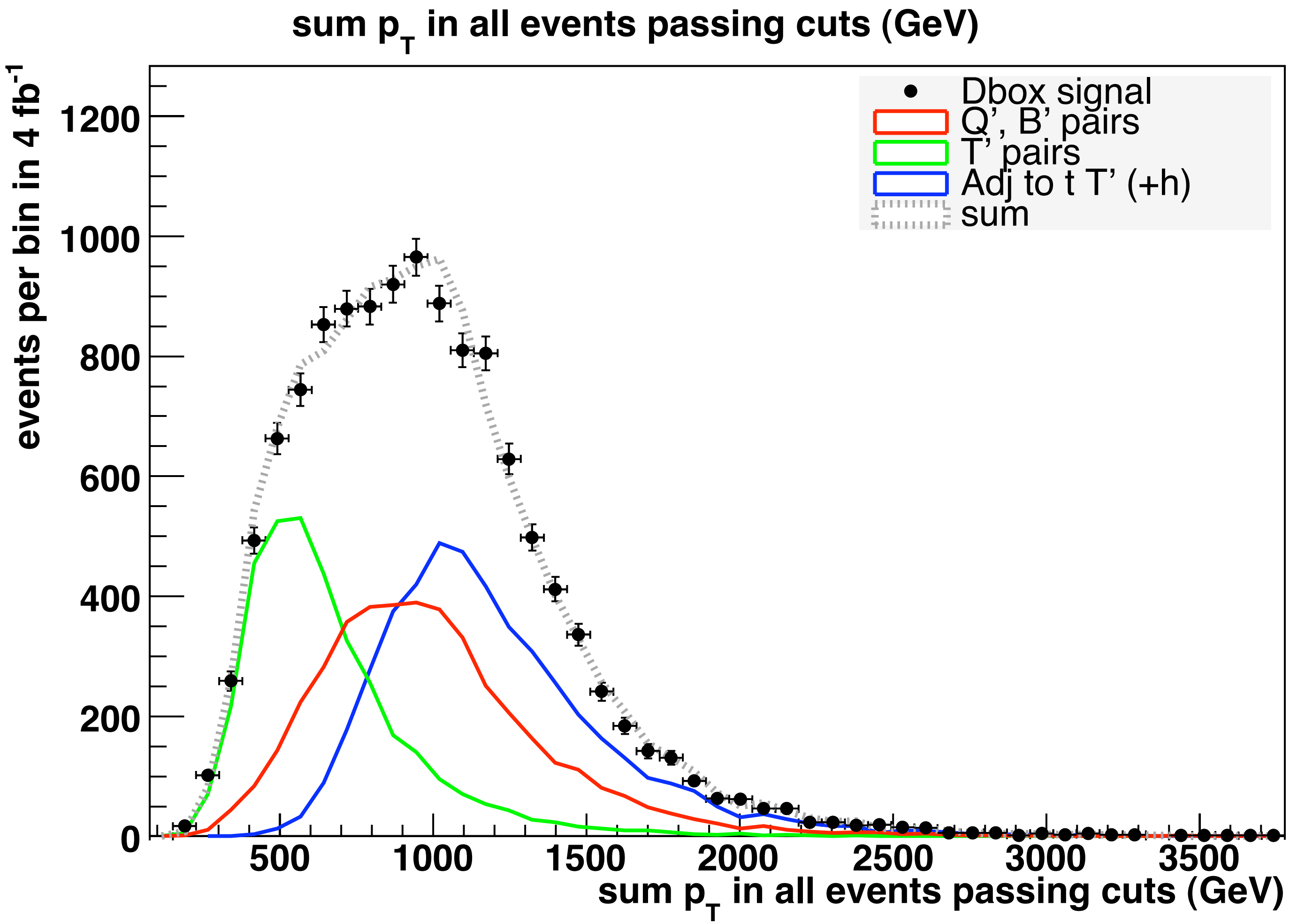


rate consistent with QCD production through fermion only...



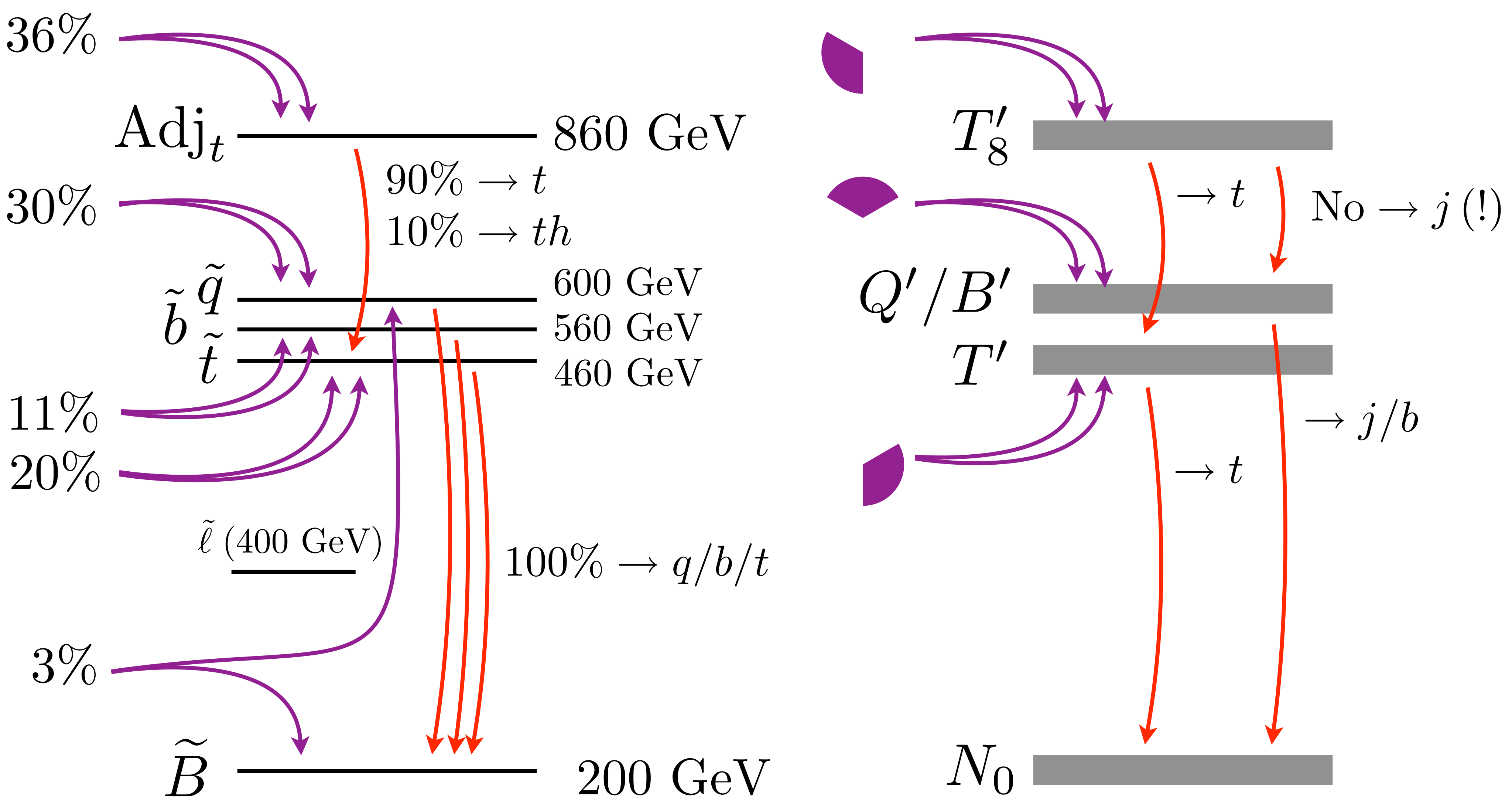
...and no associated production with squark.

It's not a gluino!



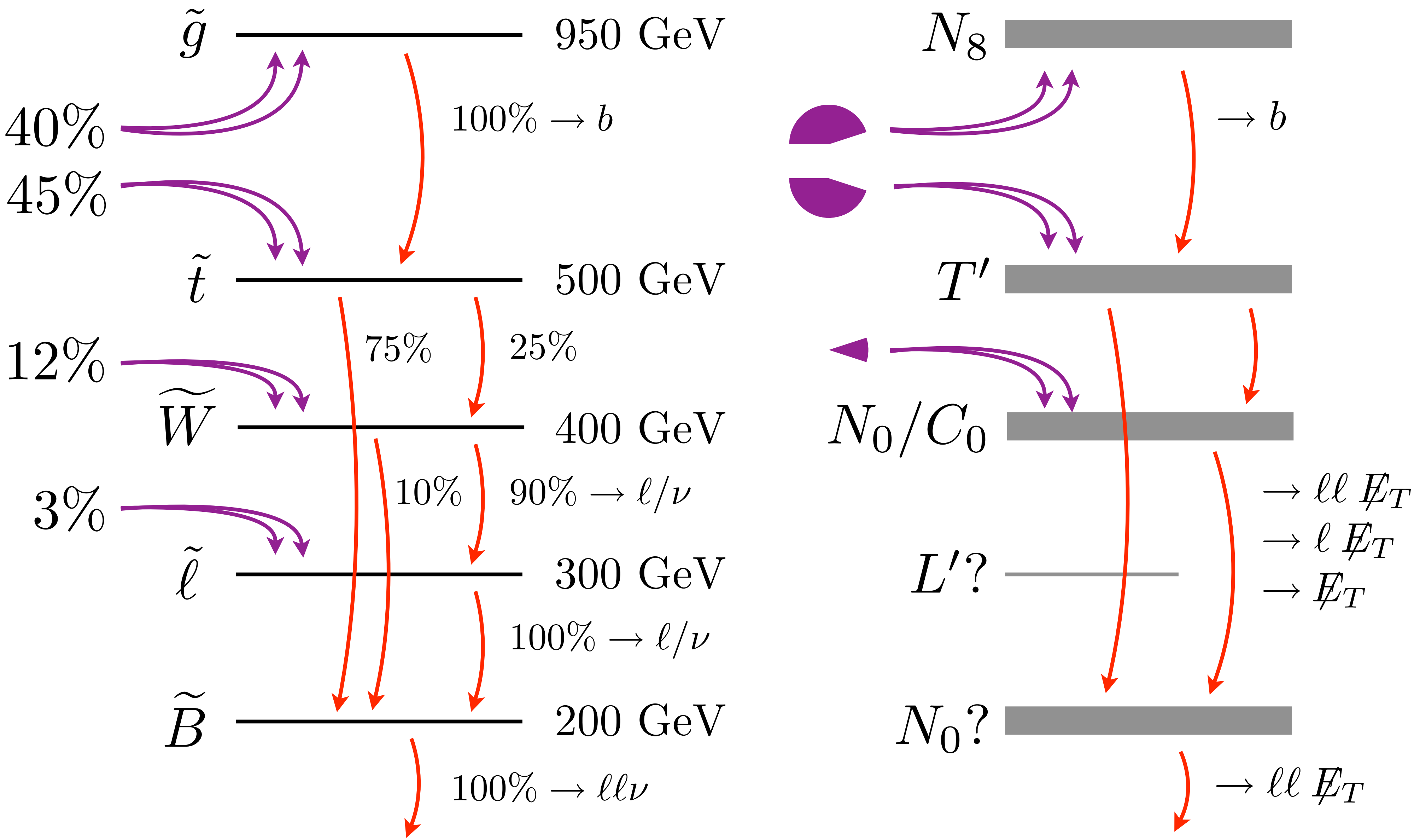
$$H_T = \sum_i E_T^i + \not{E}_T$$

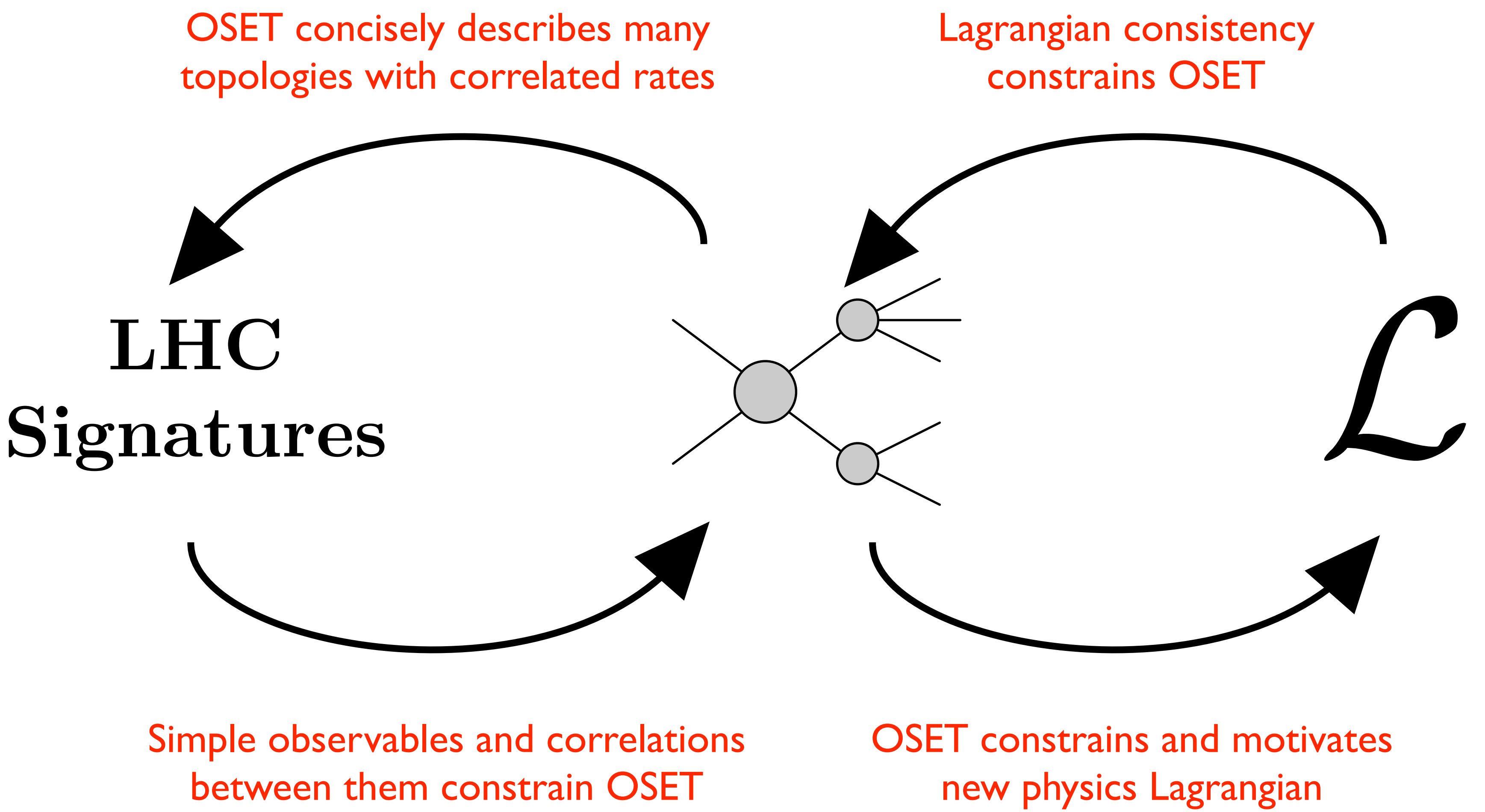
DBox


36%
30%
11%
20%
3%
Adj_t
860 GeV
90% → t
10% → th
$\tilde{q}$
$\tilde{b}$
$\tilde{t}$
600 GeV
560 GeV
460 GeV
$\tilde{\ell}$ (400 GeV)
100% → $q/b/t$
$\widetilde{B}$
200 GeV
T'_8
→ t
No → j (!)
Q'/B'
T'
→ j/b
→ t
N_0

ABox (RPV SUSY)

Variant of Rutger's Blackbox (3rd LHC Olympics)





A successful Lagrangian characterization may be derived from the top down or from the bottom up, and will be most convincing when understood in both ways.