# Jet Matching at Hadron Colliders

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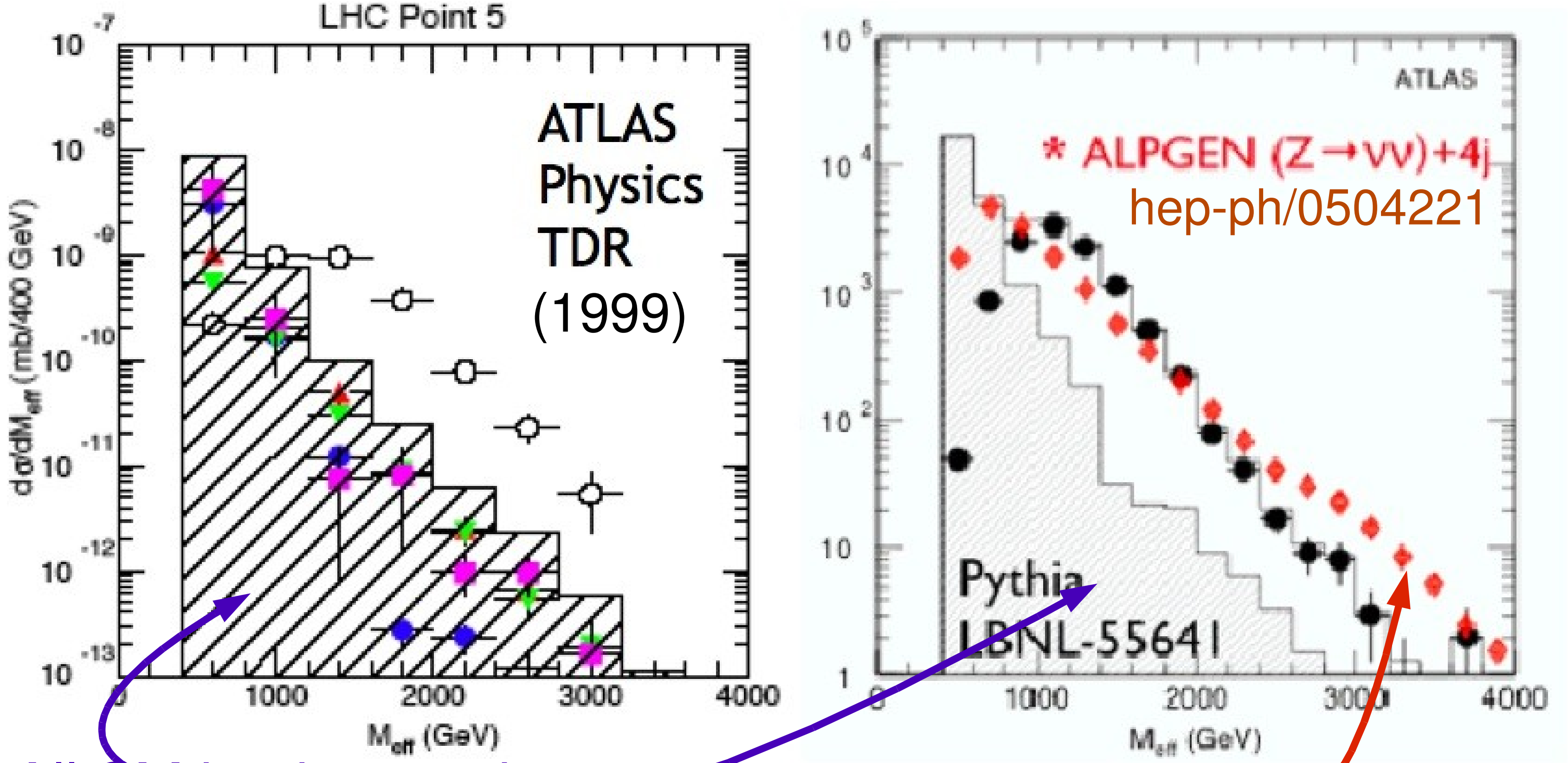
IPMU Focus week, Tokyo, Japan, 12 Nov 2009

# Why jet matching?

- Many (all) interesting New Physics signals at hadron colliders include hadronic jets (from decay or recoil)
- All Standard Model backgrounds to multijet-processes (except top) have the jets coming from QCD radiation

➔ Proper simulation of QCD radiation mandatory

# Why jet matching?




All SM backgrounds
(by parton shower MC)

Just Z+4 jets background
(by matrix element MC)

Same SUSY signal, after missing $E_T$- and 4 jet-cuts

# Why jet matching?

## Parton shower Monte Carlo generators:

- Simulate QCD radiation in the soft-collinear limits
- Successive emissions through Markov chain evolution – unlimited number of emissions
- Highly tunable to fit data, but extrapolation dangerous away from soft-collinear limits

## Matrix Element generators:

- Use the full matrix element of given jet multiplicity
- Reliable description far from soft-collinear limits
- Diverges in the soft and collinear limits

# Why jet matching?

How produce an inclusive background sample?

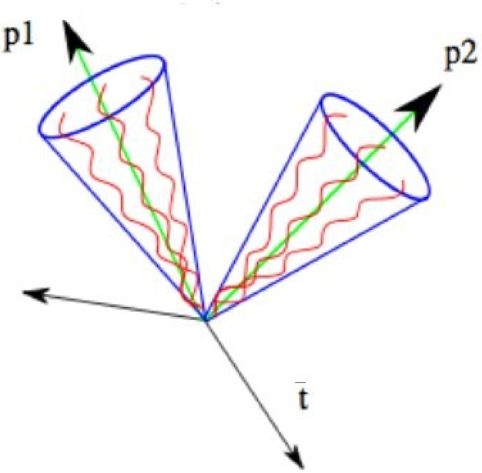
- Need reliable simultaneous description of multiple jet multiplicities
- Need to allow using different cuts to optimize discovery of different signals

Criteria:

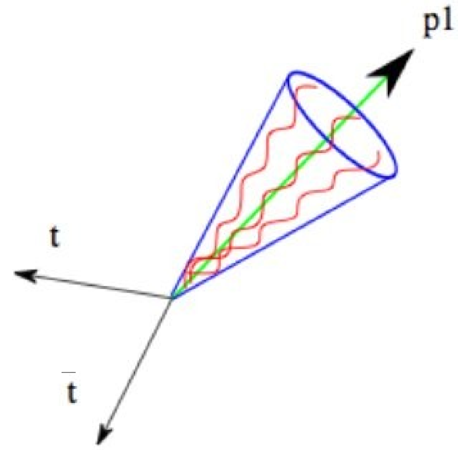
- No overcounting or undercounting of radiation
- Reproduce the inclusive cross section
- Smooth distributions in all kinematical observables

# Why jet matching?

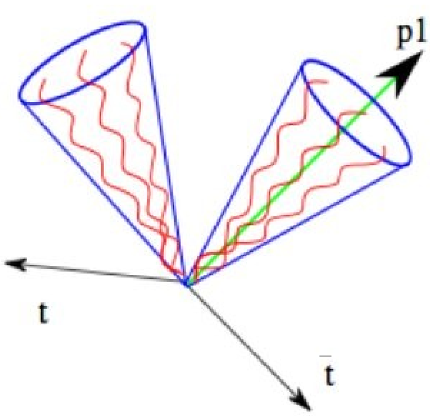
## Double-counting between multiplicity samples




2-parton sample
(no hard PS radiation)



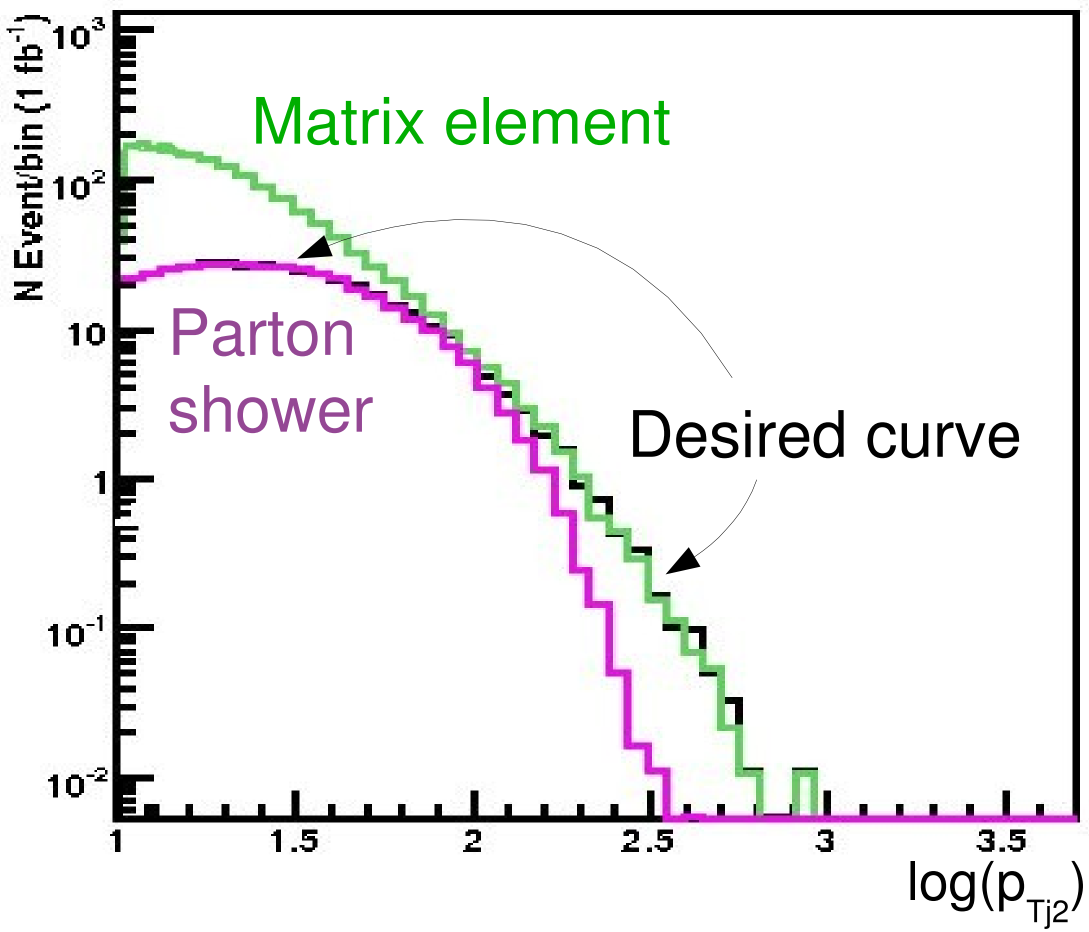

1-parton sample
(no hard PS radiation)




1-parton sample
+ hard PS radiation

# Why jet matching?

## Reglarization of matrix element divergence




2nd QCD radiation jet in top pair production at the LHC

# LO jet matching techniques

## The one-sentence "slogan" version

For comparison, see arXiv:0706.2569

- MLM matching - AlpGen, MadGraph
  - Reject unmatched events after shower
- CKKW matching - Sherpa
  - Analytic NLL Sudakovs + vetoed showers
- CKKW-Lönnblad matching - Ariadne
  - Staged shower rejection (for each emission)
- Shower reweighting - Geneva, Vincia
  - Correct shower splittings with matrix element

# LO jet matching techniques

## Pros and cons - my one-sentence slogan version

- MLM matching - AlpGen, MadGraph
  - + Works for any shower with minimal modifications
  - – Low efficiency, theoretically not (perfectly) well-controlled
- CKKW matching - Sherpa
  - + No loss of events, theoretically well-controlled
  - – Complicated shower treatment, matching unclear
- CKKW-Lönnblad matching - Ariadne
  - + Perfect matching to shower, theoretically well-controlled
  - – Low efficiency, complicated shower treatment
- Shower reweighting - Geneva, Vincia
  - + Elegant and efficient, theoretically well-controlled
  - – All new showers, still only final-state

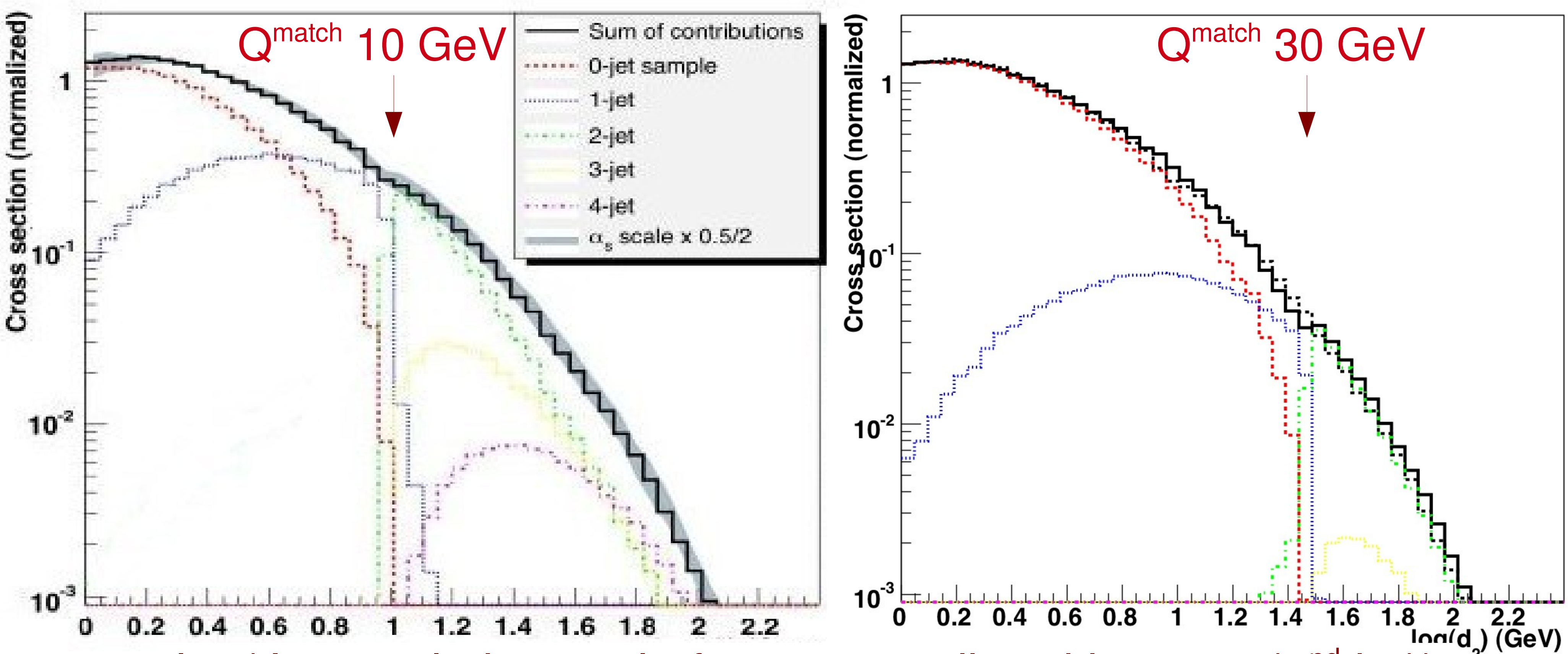
# MLM matching

M.L. Mangano [2002, AlpGen home page]
cf. J.A. et al [arXiv:0706.2569]

## Algorithm (in a nutshell):

1) Generate ME event with phase space cut $Q^{ME}$
2) Reweight $\alpha_s$ using scales for emissions in “shower history” corresponding to event (e.g., using $k_T$-clustering)
3) Shower event with starting scale = $\mu_F$ = $M_T$
4) Cluster shower emissions (before hadronization, using “hook” in shower MC) to jets using $Q^{jet} > Q^{ME}$. Keep event if each jet matches to one parton in the ME event
   - If highest parton multiplicity, allow extra jets < softest ME parton

# MLM matching




log(Jet resolution scale for 1 → 2 radiated jets ~ $p_T$(2nd jet))

W+jets production at the Tevatron
MadEvent+Pythia ($k_T$-jet MLM scheme)

# CKKW matching

Catani, Krauss, Kuhn, Webber [hep-ph/0109231]
Krauss [hep-ph/0205283]

Prerequisite:

## The inner workings of a parton shower

- The Sudakov form factor $\Delta(Q_1,Q_2)$ =

  P(no QCD emission between $Q_1$ and $Q_2$) =

$$= \exp\left\{-\int_{Q_1^2}^{Q_2^2}\frac{dq^2}{q^2}\frac{\alpha_s(q^2)}{2\pi}\int\frac{dz}{z}P_{ij}(z)\right\}$$

For initial state

$$\frac{f_i(x_i/z,q^2)}{f_j(x_i,{}^2\,)}$$

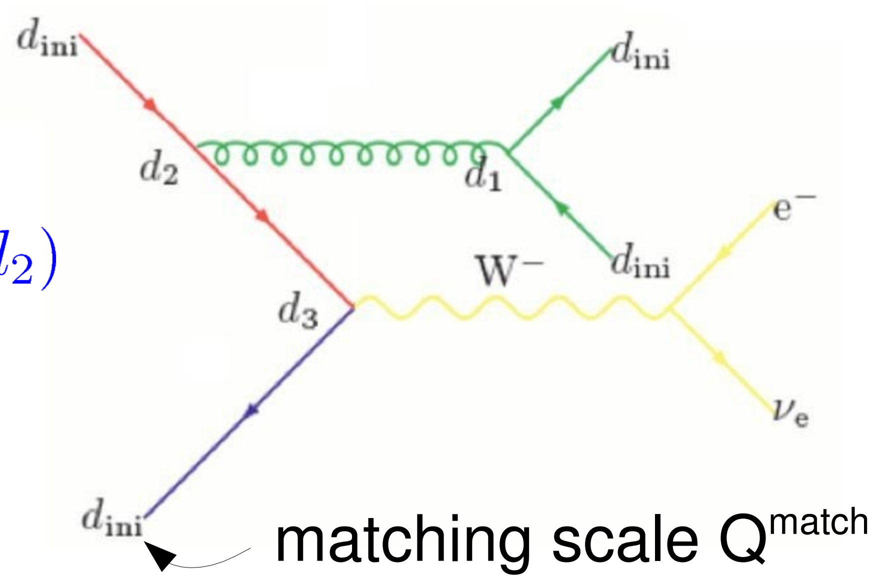
- Parton shower starts from starting scale ~ $\mu_F$, picks emission scale based on P(emission at scale Q)

$$\frac{d}{dQ^2}(1-\Delta) = \frac{\alpha_s(q^2)}{2\pi q^2}\int\frac{dz}{z}P_{ij}(z)\times\Delta(Q_1,Q)$$

# CKKW matching

Probability for particular parton configuration after shower:

$$\Delta_q^{IS}(d_2,d_3)\frac{\alpha_s(d_2^2)}{2\pi d_2^2}P_{qq}(z_2)\frac{x_1' f(x_1',d_2^2)}{x_1 f(x_1,d_2^2)}$$
$$\times\Delta_q^{IS}(d_{ini},d_2)\Delta_q^{IS}(d_{ini},d_3)\Delta_g^{FS}(d_1,d_2)$$
$$\times\frac{\alpha_s(d_1^2)}{2\pi d_1^2}P_{qg}(z_1)\times\Delta_q^{FS}(d_{ini},d_1)^2$$
$$\times d\sigma_{2\to1}f_q(x_1,d_3)f_{\bar{q}}(x_2,d_3)$$




Red terms should be replaced by 2 $\to$ 3 matrix element

$\Rightarrow$ To get improved shower description, need

ME + $\alpha_s$ reweighting + PDF reweighting + Sudakovs

# CKKW matching

- All reweightings done in Matrix Element generator
- Next: Run shower to get emissions below $Q^{match}$
- If:
  - ME cutoff variable & Sudakov evolution variable identical to shower evolution variable
  - Shower is Markovian, i.e., gives the same result if started, stopped and restarted as if run the whole way

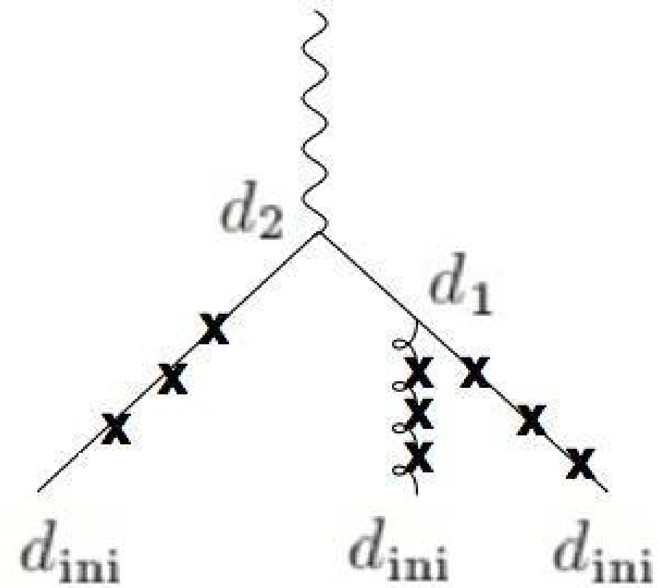
  Then: Just start the shower at $Q^{match}$
- Otherwise: Use vetoed showers

# CKKW matching

## Vetoed showers

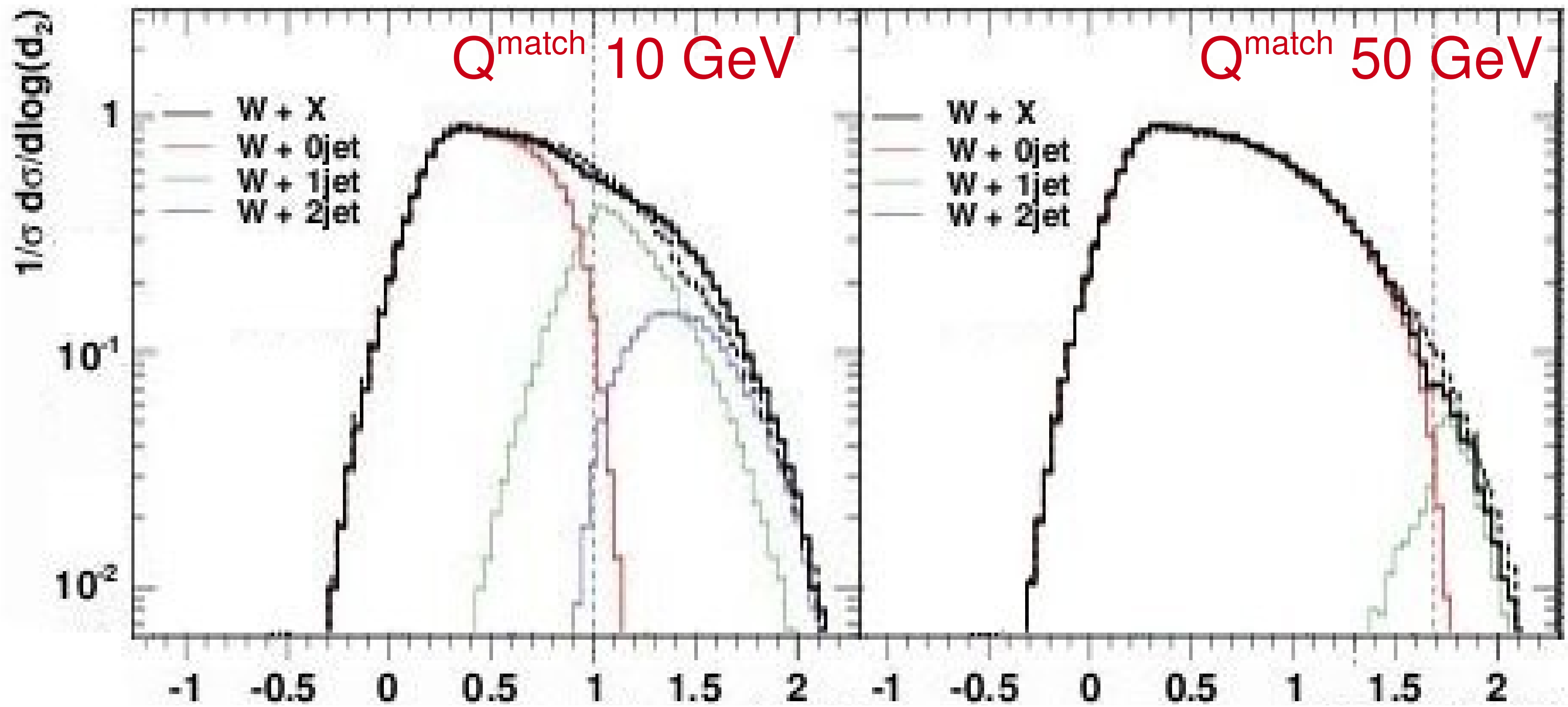
If matrix element cut is not aligned with shower evolution variable

1) Shower events, starting from central scale ~ $\mu_F$
2) If an emission is generated, check if it has $Q < Q^{match}$
3) If it does, keep it. Otherwise, ignore the emission and continue shower



# CKKW matching

Differential jet rates in W+jets at the Tevatron by Sherpa




log(Jet resolution scale for 0 → 1 radiated jets ~ $p_T$($1^{st}$ jet))

dotted: $Q^{match}$ = 30 GeV

[Talk by S. Schumann, 2004]

# CKKW matching

- Results good (clearly at NLL accuracy), but matching to shower not perfect (Sudakovs differ)
- Solutions:

  1) Move to Lönnblad-inspired scheme, using shower to calculate Sudakovs through successive rejection

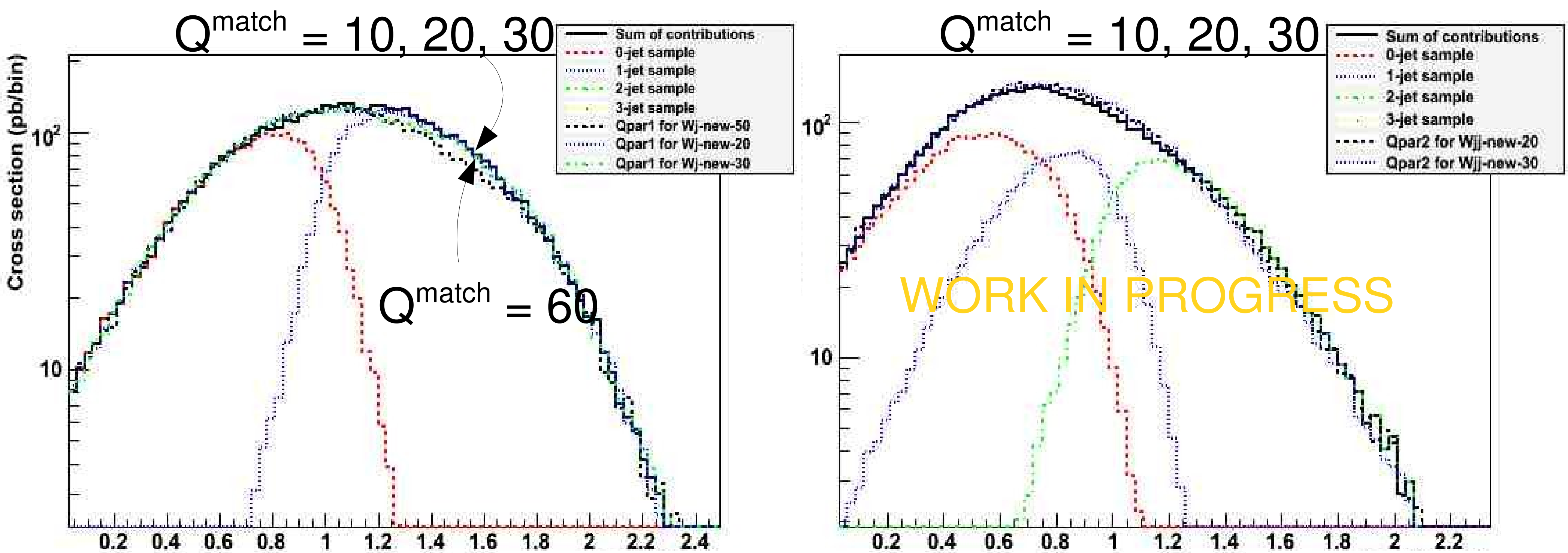
     ➔ New Sherpa, see arXiv:0903.1219

  2) Use identical Sudakovs as in shower + fully Markovian shower

     ➔ MadGraph/MadEvent + Pythia 6.4/8 (in progress)

# MadGraph + Pythia (CKKW)

With perfect matching to shower – no dependence on matching scale (in shower region of validity)




Only ISR log(~ $p_T$(1st jet))

ISR+FSR log(~ $p_T$(2nd jet))

Differential jet rates in W+jets at the LHC by MG/ME+Pythia

# MadGraph + Pythia (CKKW)

## Advantages:

- No loss of events in matching (factor ~3-5 gain)
- No special shower interface (just run the shower!)
- Full theoretical control
- "Difficult" processes (where I do not trust shower + MLM matching to give good Sudakov description)
  - Processes with b-quarks (pp $\rightarrow H^{+/-}t\bar{b}$, pp $\rightarrow Hb\bar{b}$)
  - Processes with colorless t-channel exchange (WBF, t-channel single top)
- Allows for efficient phase space integration (poles regulated)

# Matching in New Physics production

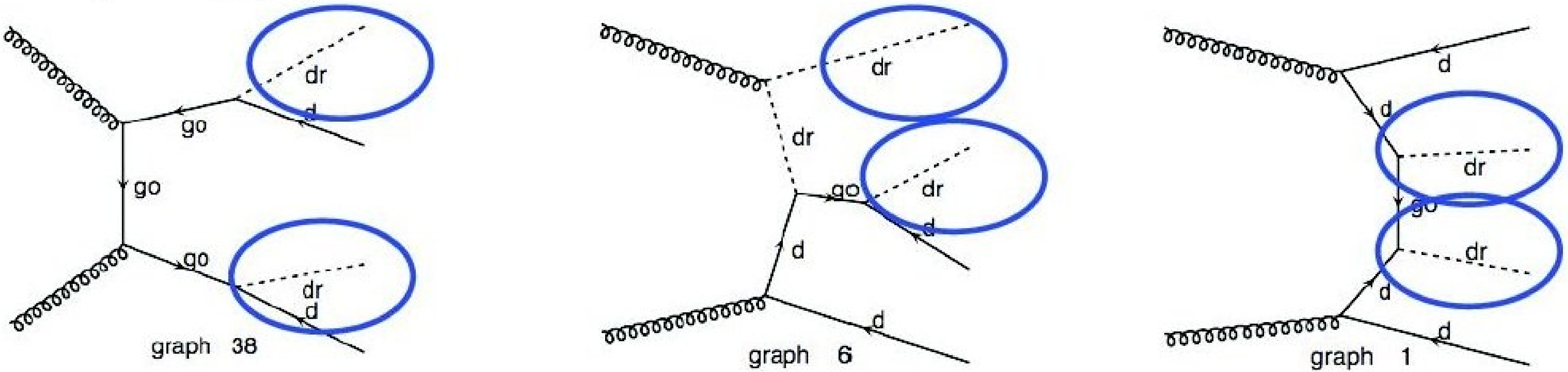
J.A., de Visscher, Maltoni [arXiv:0810.5350]

- We know that matching of ME+PS is vital for jet production in SM backgrounds
- But is it relevant for heavy BSM particle production?
  - Very hard jets from decays
  - Parton showers expected to be more accurate for larger masses
- Using gluino and squark production as example
- Turns out there are many cases where matching is necessary for precise description!

# Double counting

Special difficulty in SUSY matching – double counting between squark and gluino production

Example: $\tilde{q}\tilde{q}jj$



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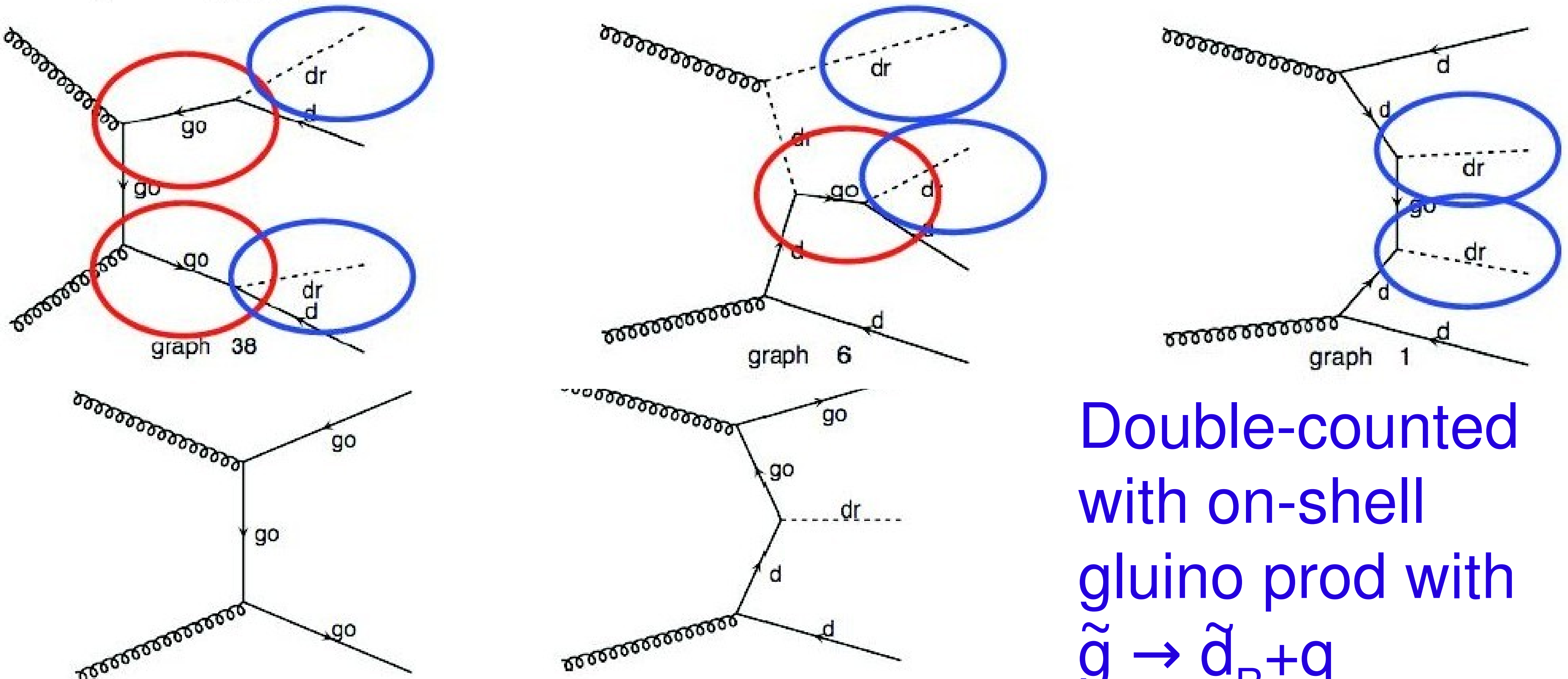



Double-counted with on-shell gluino prod with $\tilde{g} \rightarrow \tilde{d}_R + q$

# Double counting

- Solved by keeping track of on-shell resonances in the production event files

```
<event>
 6   0   0.7992762E-04   0.9118800E+02   0.7816531E-02   0.1300000E+00
         21    -1     0     0   502   503   0.00000000000E+00   0.00000000000E+00   0.38916243784E+03   0.38916243784E+03   0.00000000000E+00 0.   1.
         -1    -1     0     0   501     0   0.00000000000E+00   0.00000000000E+00  -0.16355197391E+04   0.16355197391E+04   0.00000000000E+00 0.   1.
    1000021     2     1     2   501   503  -0.22162854802E+03  -0.24366260777E+03  -0.12022753376E+04   0.13861620323E+04   0.60620830799E+03 0.   0.
         -1     1     3     3     0   503   0.18372150189E+02   0.27121177112E+02  -0.34707630298E+02   0.47725399437E+02   0.00000000000E+00 0.  -1.
    2000001     1     3     3   501     0  -0.24000069821E+03  -0.27078378488E+03  -0.11675677073E+04   0.13384366329E+04   0.54522846200E+03 0.  -1.
    2000001     1     1     2   502     0   0.22162854802E+03   0.24366260777E+03  -0.44081963594E+02   0.63852014456E+03   0.54522846200E+03 0.  -1.
</event>
```

Allows to remove double-counted events at later step

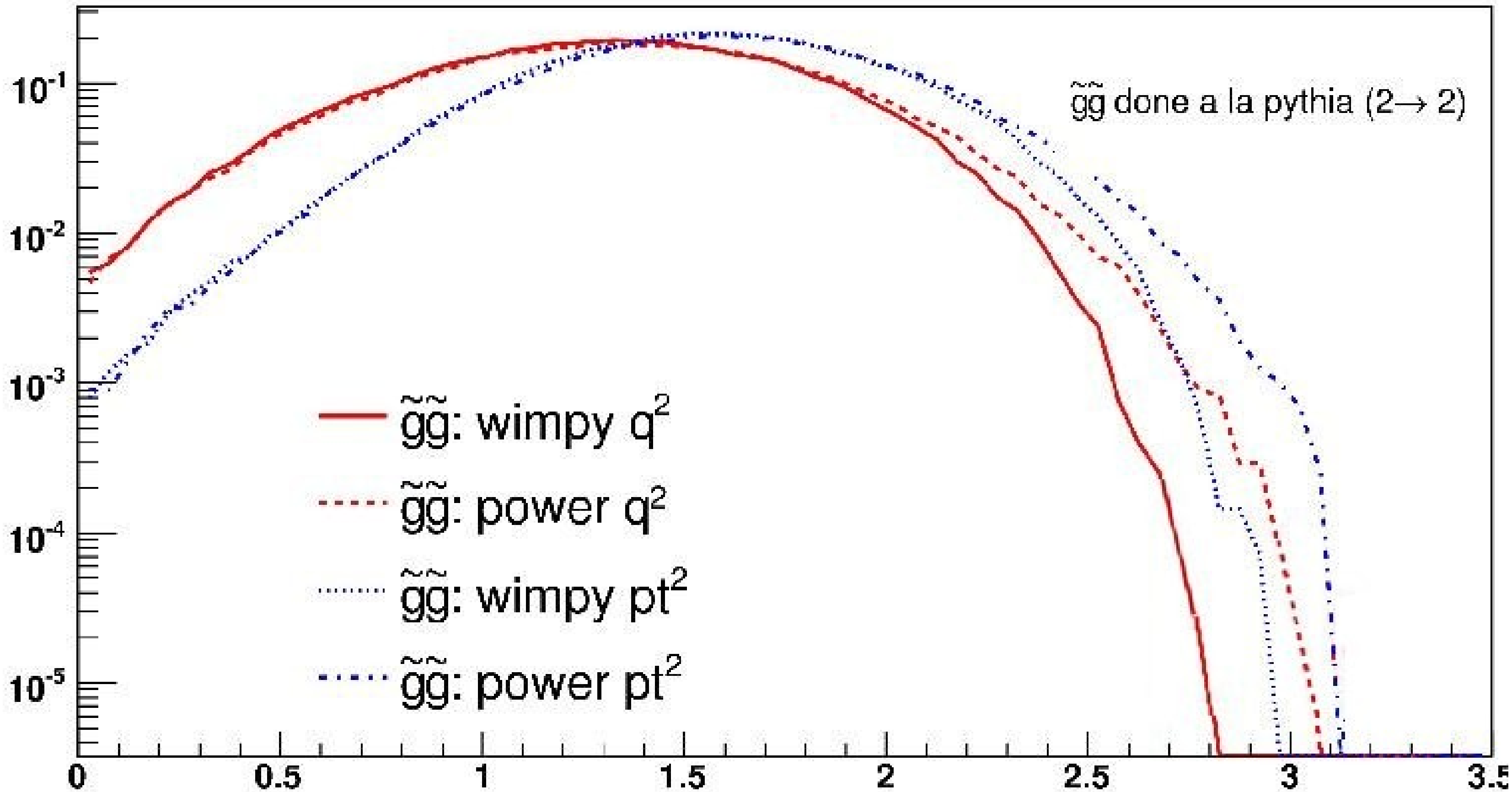
- Double-check – perform generation without resonant diagrams (gauge-inv. only in NWA)
  - → Automatized (specify forbidden s-channel by $)
  - → Excellent agreement

# Shower parameter dependence

- Shower "tweakable"
  - Strength for fitting data (after-the-fact)
  - Weakness for predictivity
- Most important parameters used here:
  - Type of shower ($Q^2$ or $p_T$-ordered)
  - Shower starting scale
    - Factorization scale (mass of produced particle) - "wimpy"
    - Total energy of collider (14 TeV) - "power"
- Wide range of predictions from shower

# Shower parameter dependence

QCD radiation for different Pythia shower params

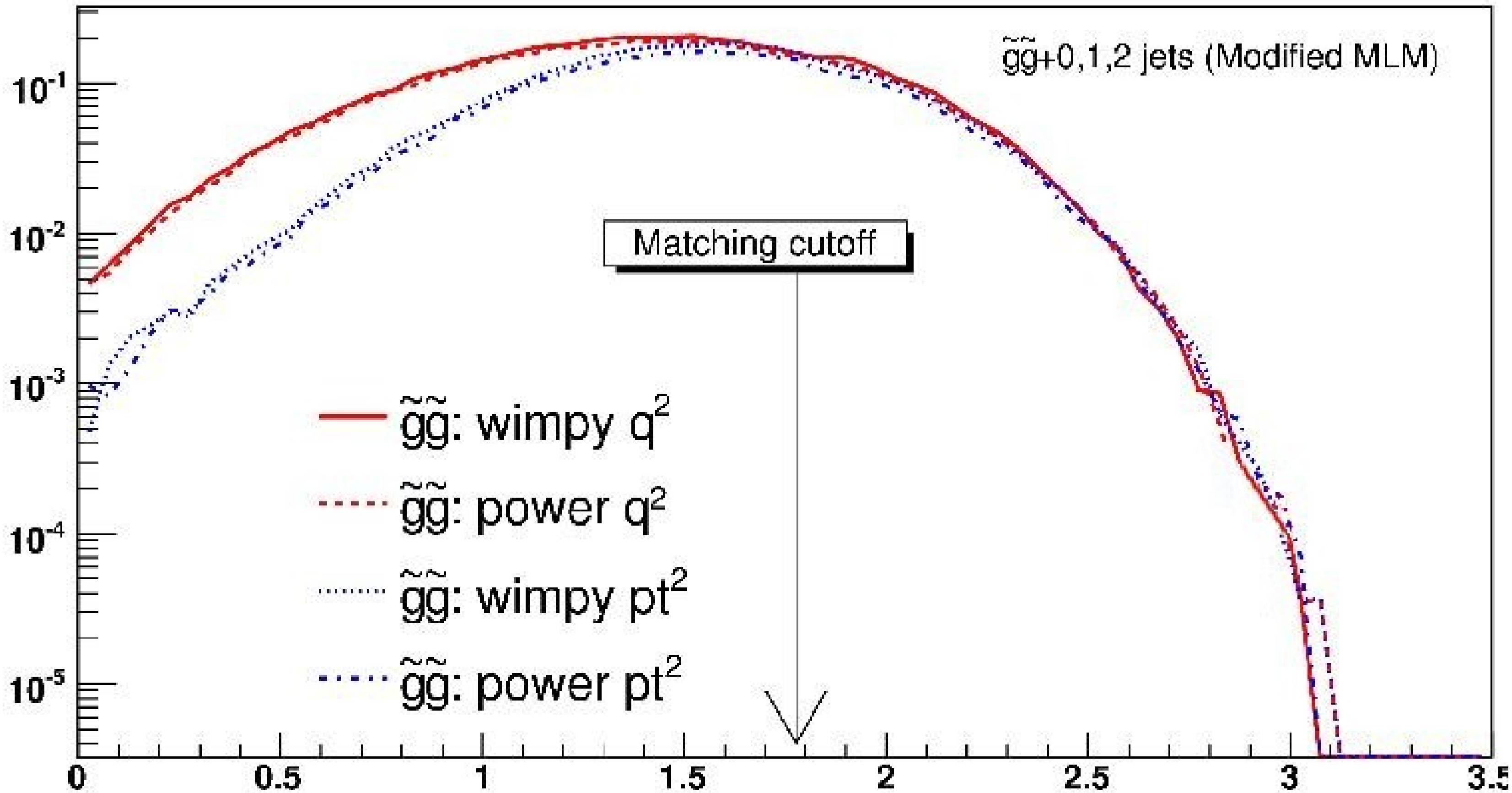



log(Jet resolution scale for 1 → 2 radiated jets) (GeV)

600 GeV gluino pair production at the LHC

# Shower parameter dependence

## QCD radiation after matching with MG/ME

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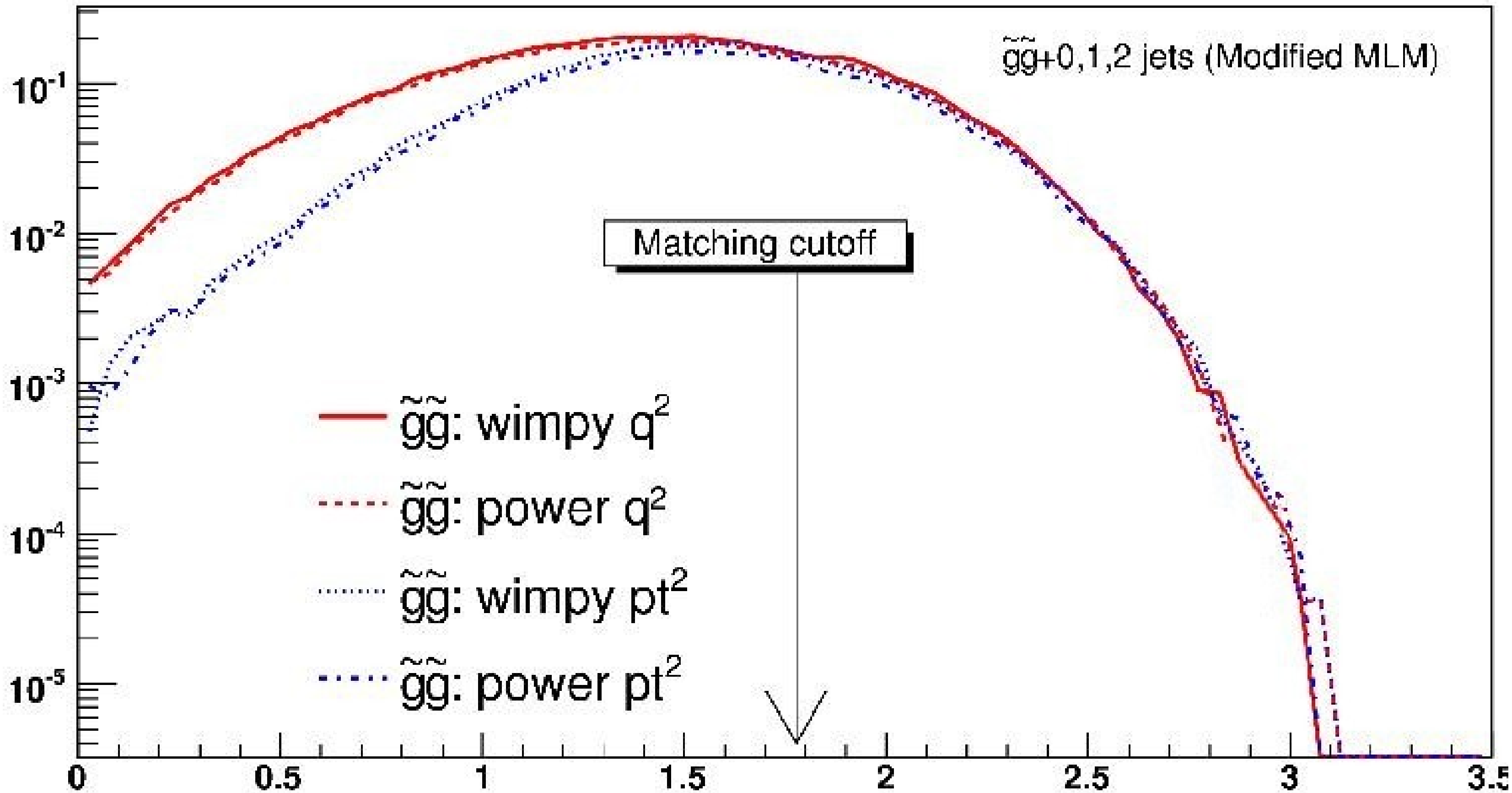
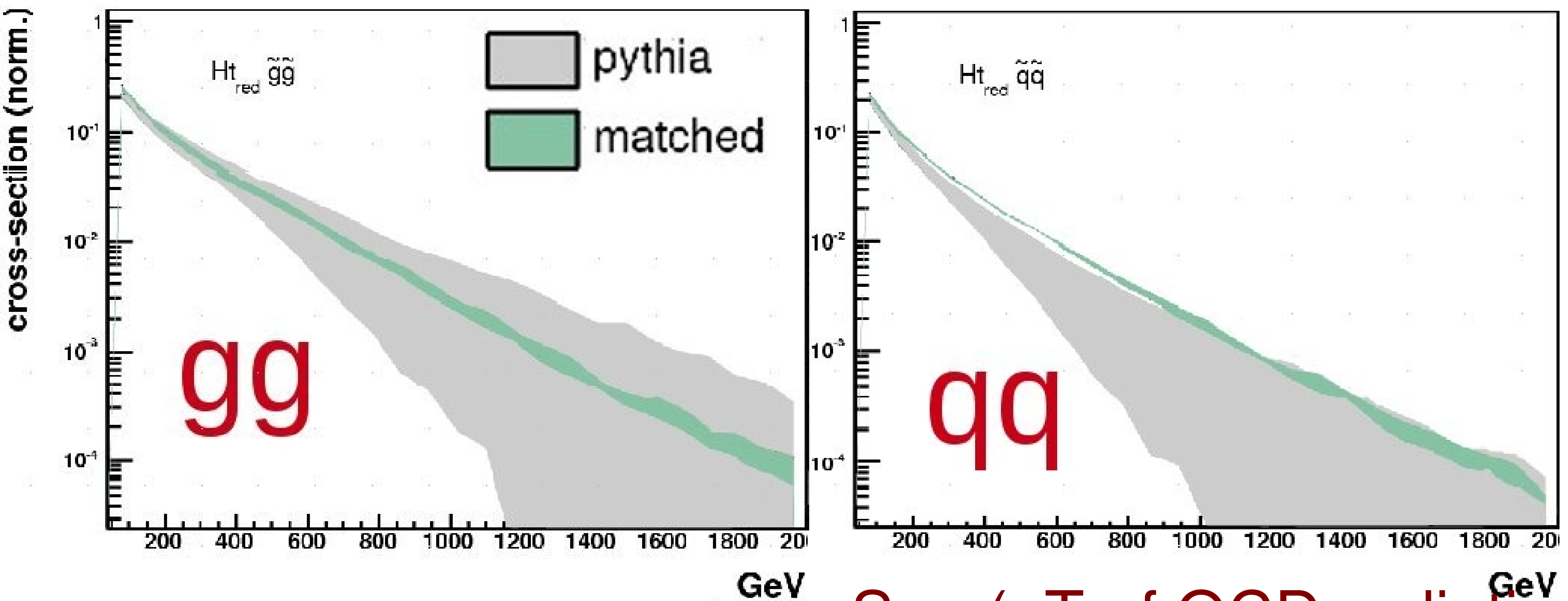



log(Jet resolution scale for 1 → 2 radiated jets) (GeV)

Predictive → can now analyze QCD radiation

# Dependence on the initial state: gg, qq

600 GeV gluino vs. squark squark production at LHC

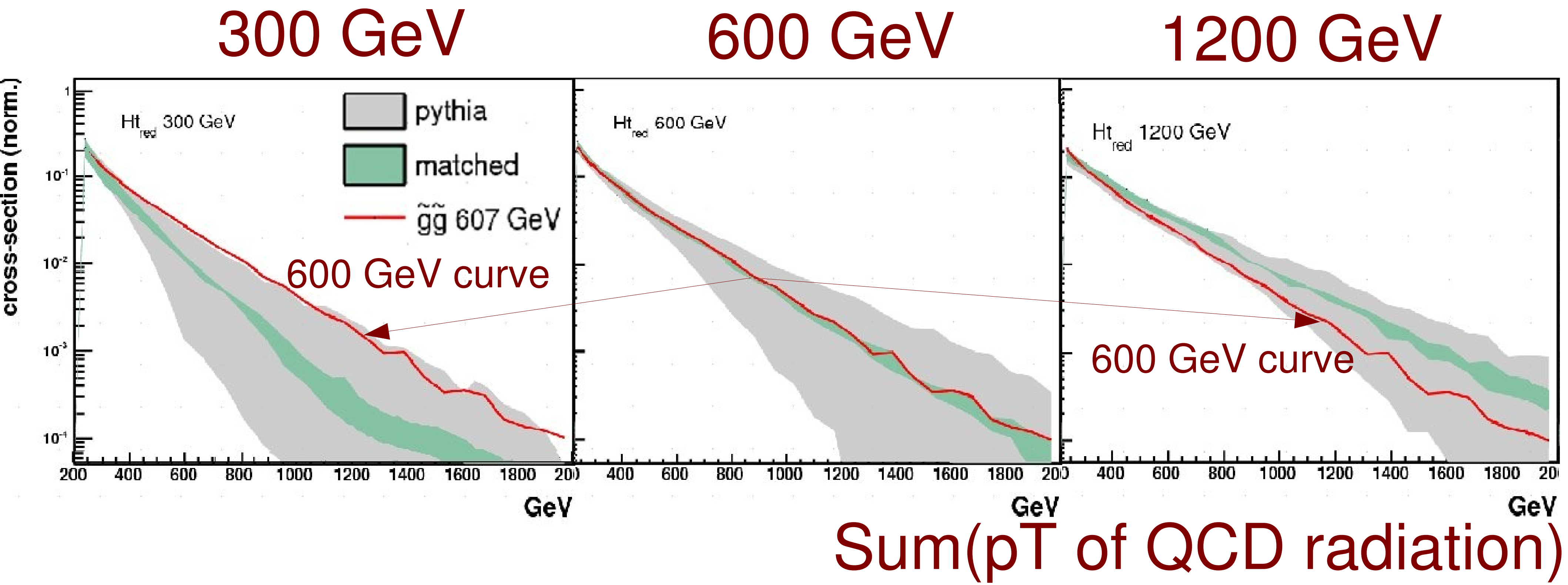



Sum(pT of QCD radiation)

No single shower tune for all initial states!

# Dependence on SUSY particle mass

Gluino production at LHC




Well-determined dependence of radiation on mass

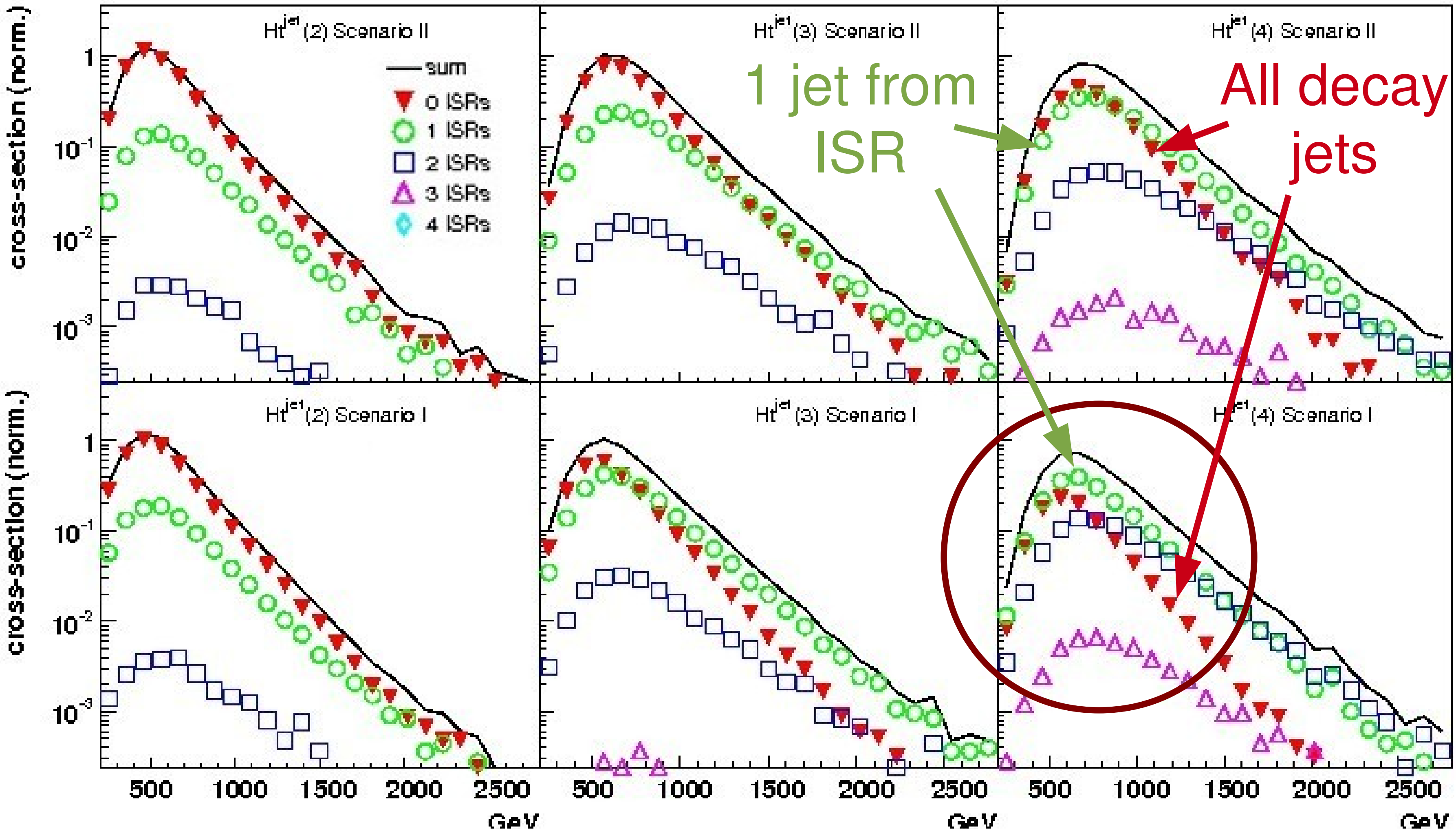
# Jet counting in gluino decay

## 600 GeV gluino pair production

3-body $\tilde{g}$ decay

(squarks heavy)

$M_g$-$M_q$= 50 GeV

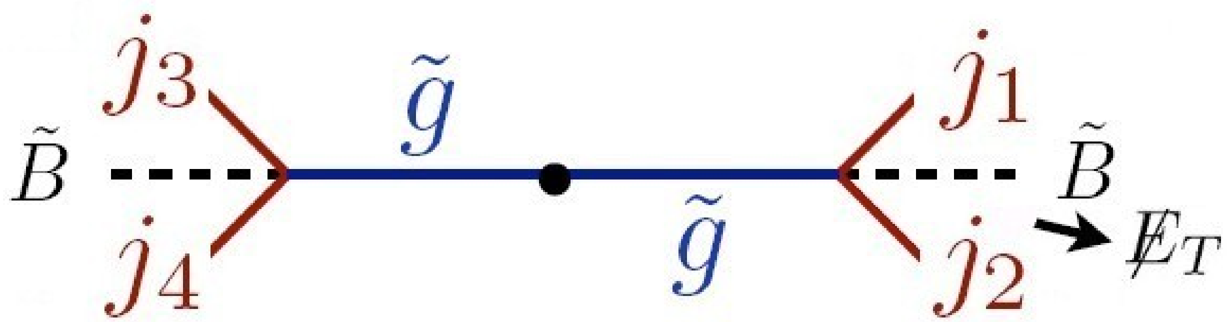



$\Sigma p_T$(2 hardest jets) $\Sigma p_T$(3 hardest jets) $\Sigma p_T$(4 hardest jets)

# Example

J.A., Le, Lisanti, Wacker [arXiv:0803.0019, arXiv:0809.3264]

- Example: Gluinos that decay to qq+LSP with free ratio of gluino/LSP mass
- Special difficulty when decay products nearly mass-degenerate with produced particle
  - No (small) missing transverse energy in decay



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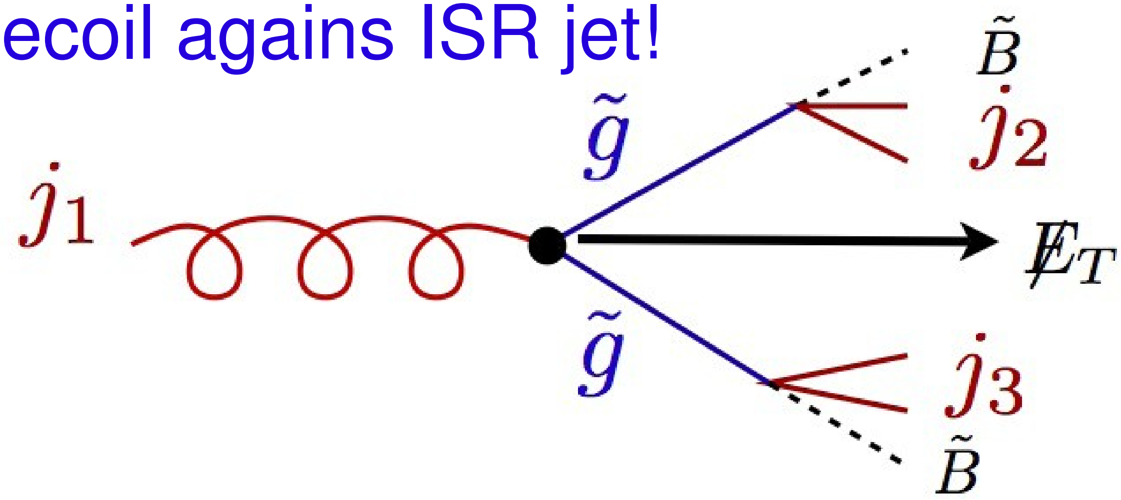
- Example: Gluinos that decay to qq+LSP with free ratio of gluino/LSP mass
- Special difficulty when decay products nearly mass-degenerate with produced particle
  - No (small) missing transverse energy in decay
  - Need recoil agains ISR jet!



# Example

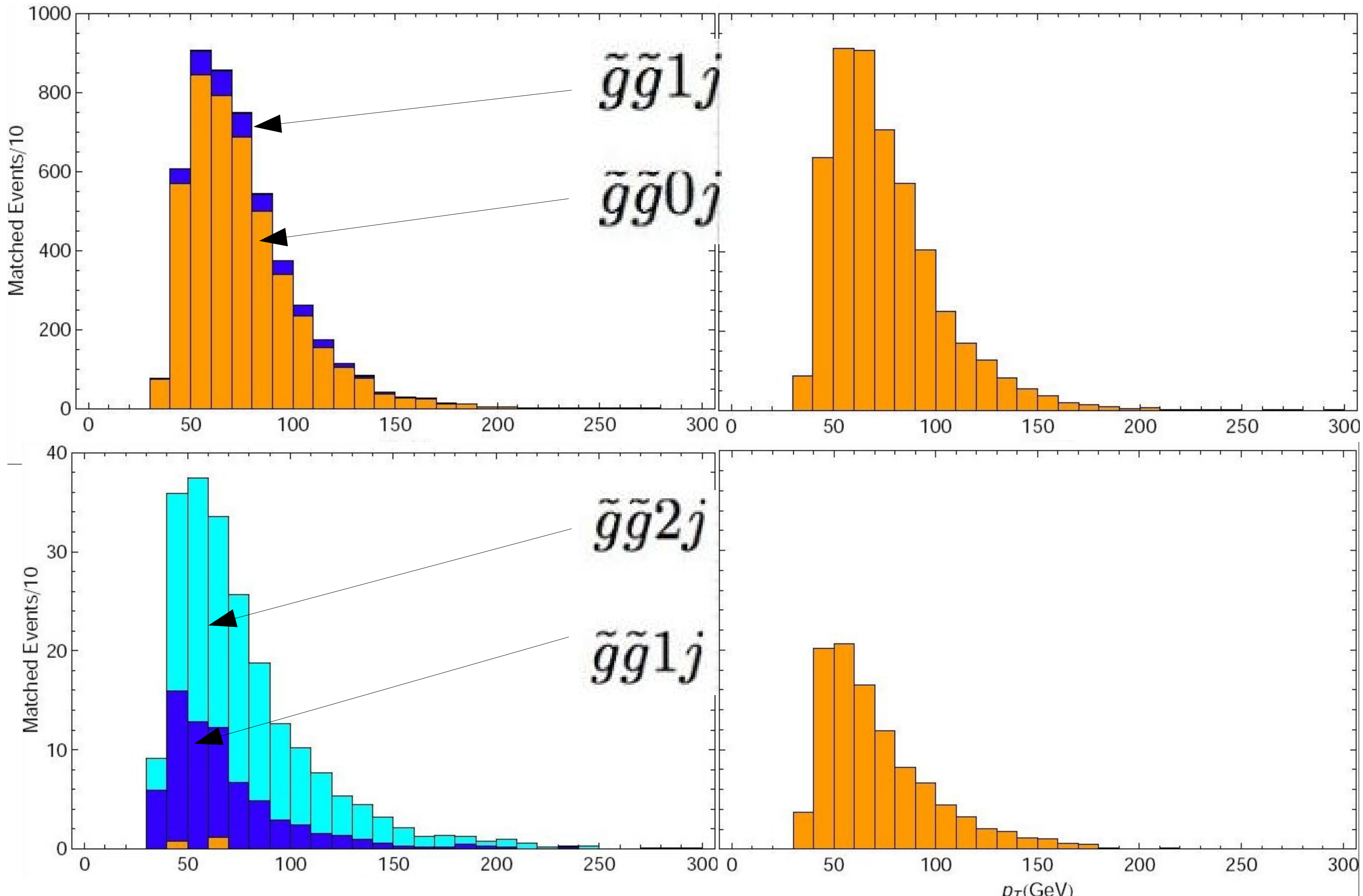
Matched | Unmatched

$M_g$=150 GeV

$M_B$=40 GeV

$M_g$=150 GeV

$M_B$=130 GeV




$p_T$(j1) at the Tevatron, after 2-jet and missing $E_T$ cuts

# Conclusions

- LO jet matching techniques are a powerful complement to matched NLO simulations
- Several approaches available, with different strengths and weaknesses
- Matching important also for simulation of new physics signals
- Continuous development / improvement
  - Sherpa (cf. arXiv:0903.1219)
  - MadGraph/MadEvent + Pythia (in progress)