QCD radiation and New Physics production at the LHC

Johan Alwall, SLAC

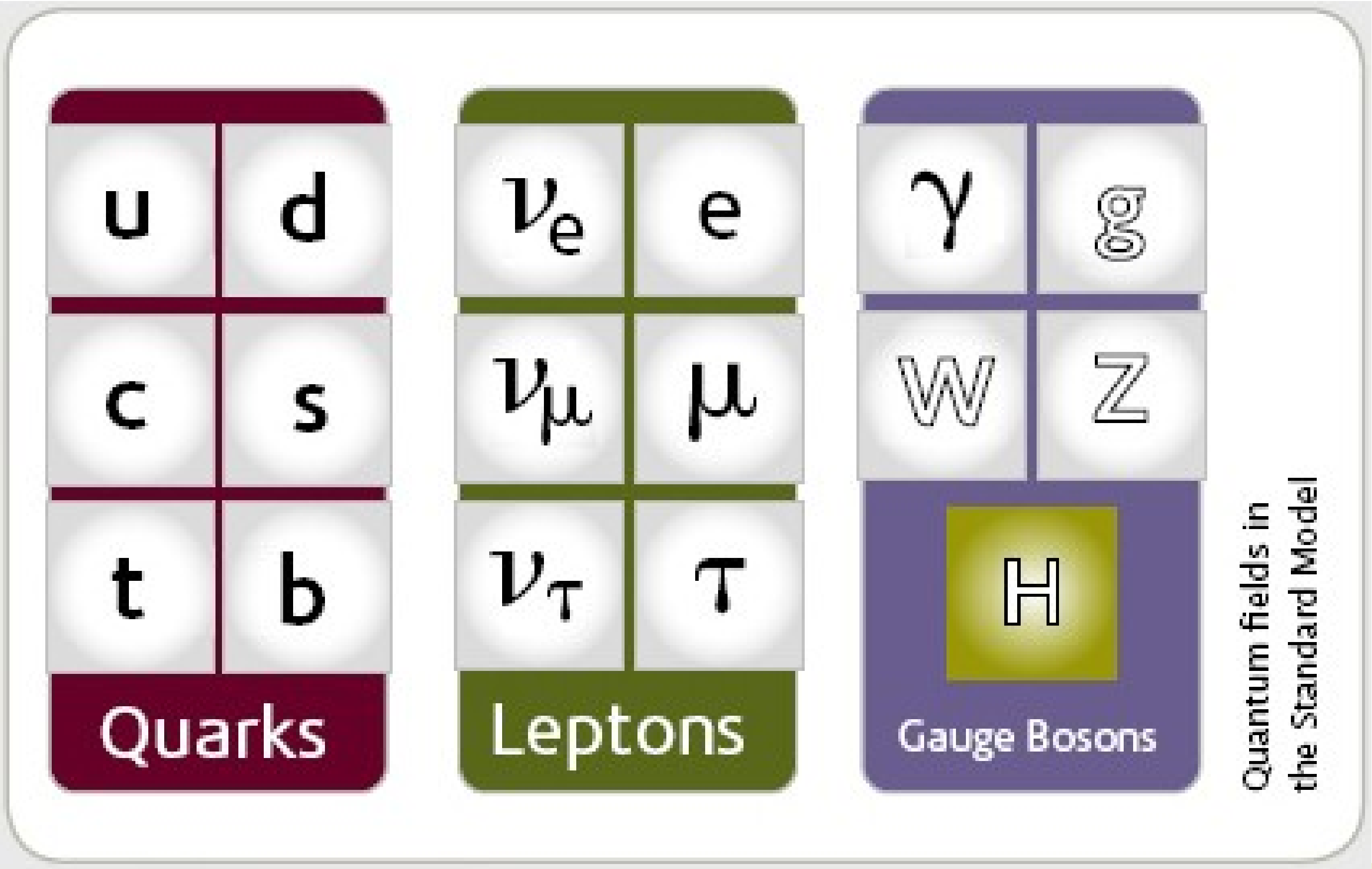
Fermilab Theory group, Feb 26, 2009

Outline

- Introduction: The Standard Model and the LHC
- SUSY-like signatures and their difficulties
- How to simulate QCD radiation
  - Parton showers and Matrix elements
  - Matching of jet production
- QCD radiation in New Physics processes
  - Difficulties in squark-gluino separation
  - Non-standard gluinos at the Tevatron
- Conclusions and outlook

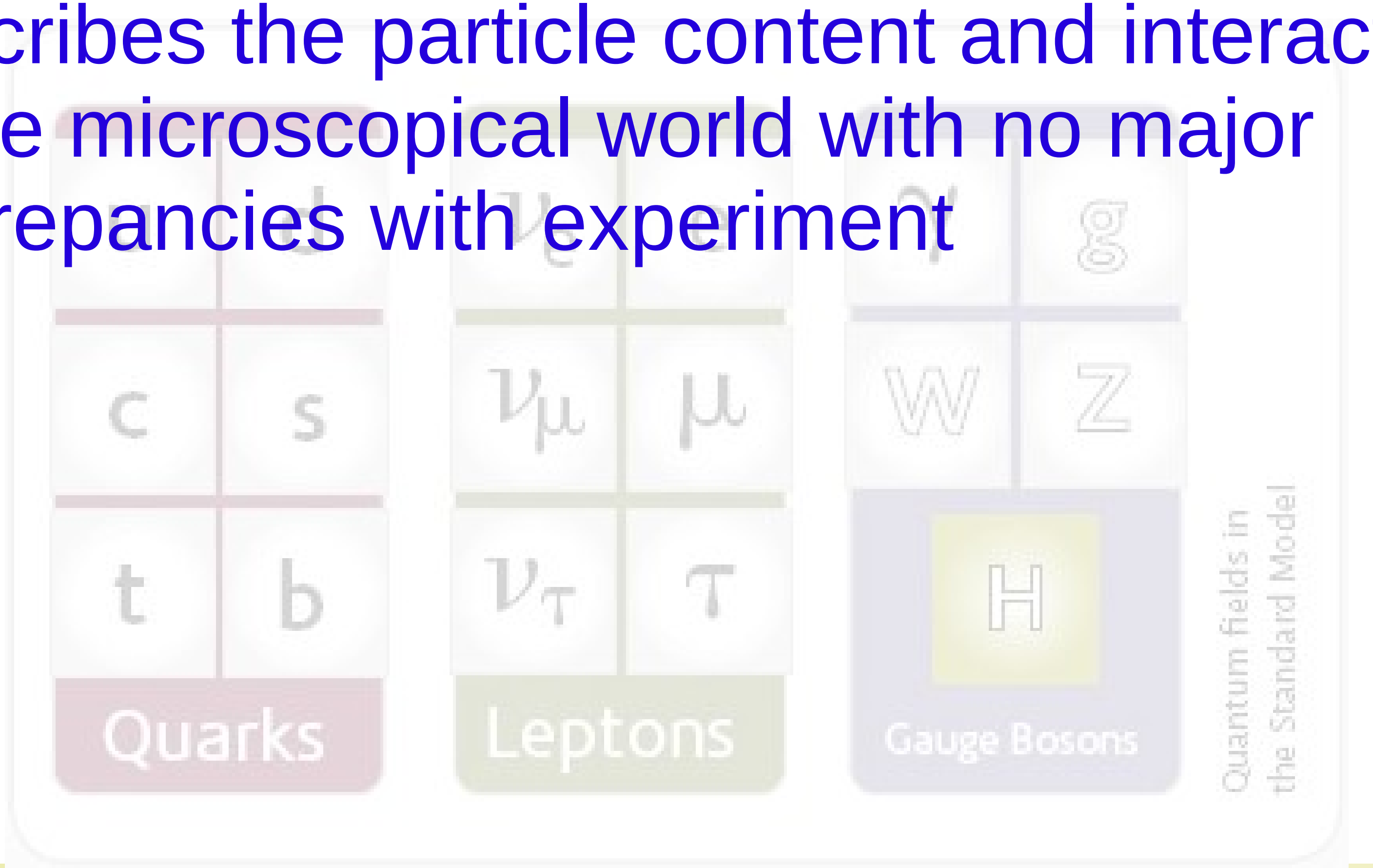
The Standard Model and the LHC

- The Standard Model – one of the most successful theories in the history of physics



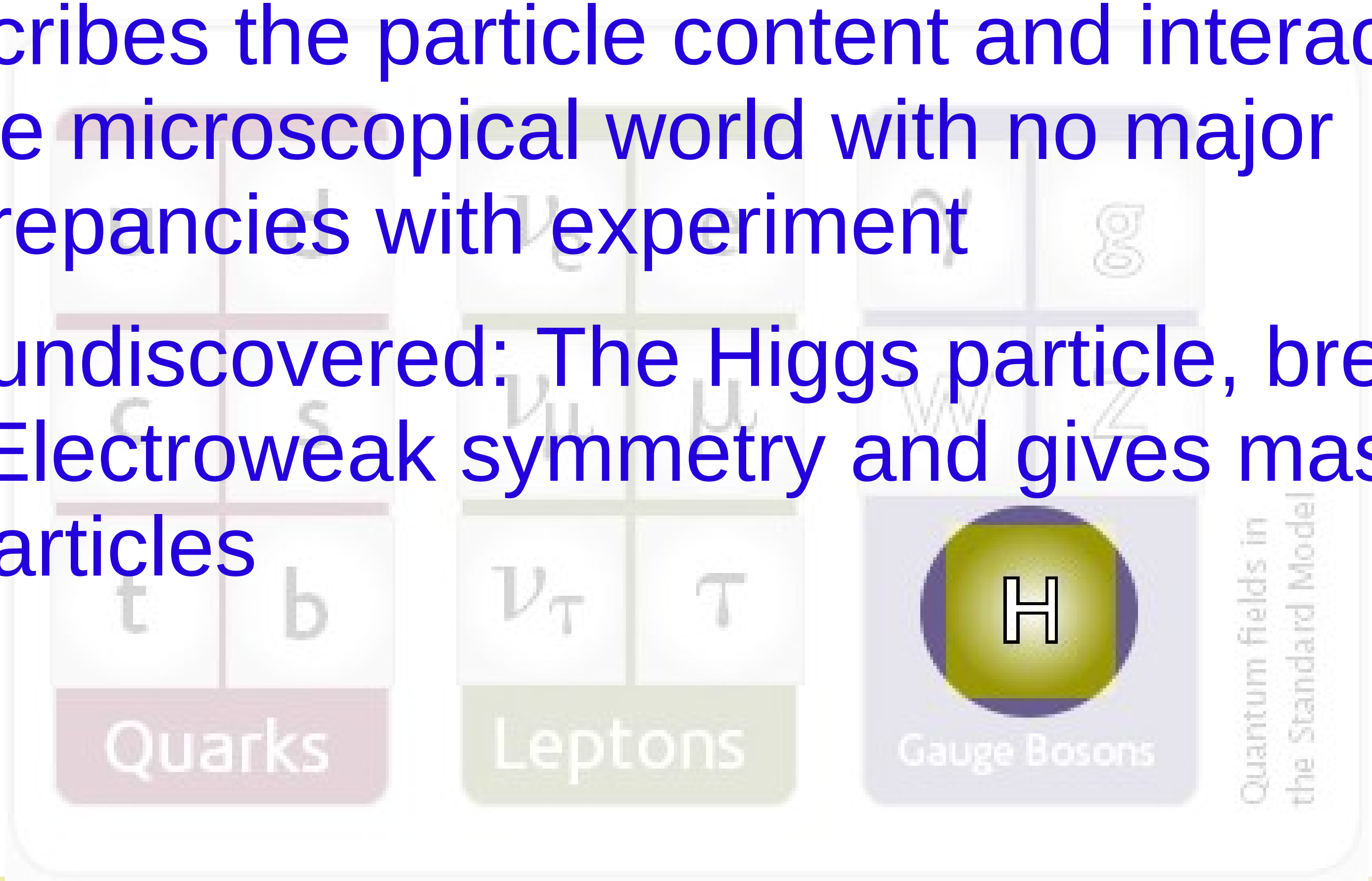
The Standard Model and the LHC

- The Standard Model – one of the most successful theories in the history of physics
- Describes the particle content and interactions of the microscopical world with no major discrepancies with experiment



The Standard Model and the LHC

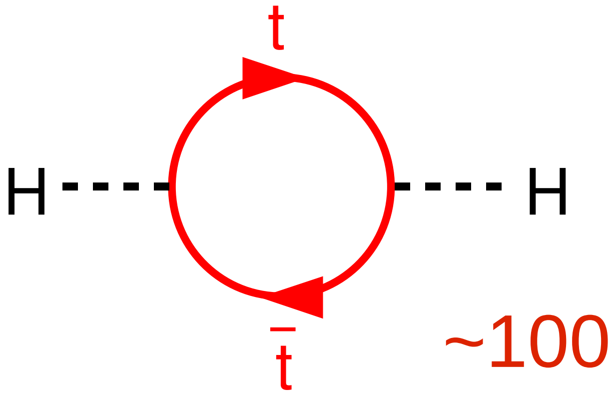
- The Standard Model – one of the most successful theories in the history of physics
- Describes the particle content and interactions of the microscopical world with no major discrepancies with experiment
- Yet undiscovered: The Higgs particle, breaks the Electroweak symmetry and gives mass to all particles



The Standard Model and the LHC

Problems with the Standard Model

- Quadratic quantum corrections to the mass of the Higgs particle → hierarchy problem



$\Delta M_H^2 \sim M^2_{\text{new physics}}$

~100 GeV

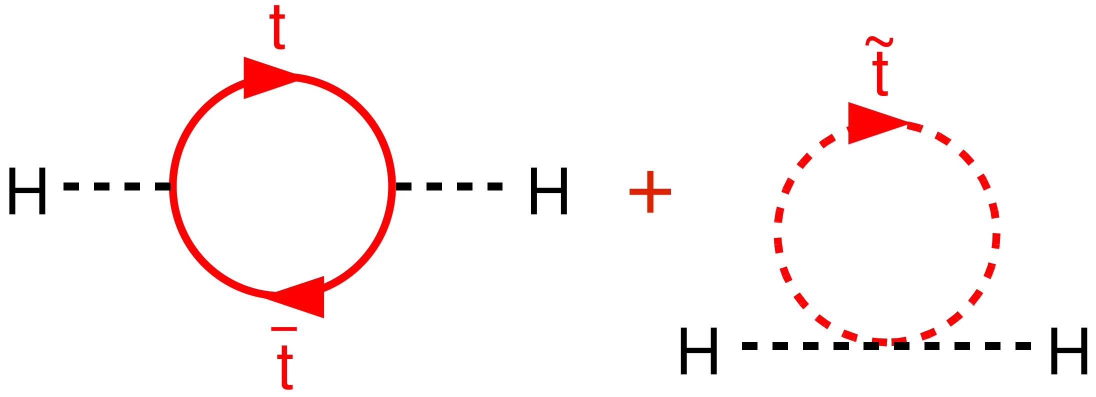
$M_{Pl} \sim 10^{19}$ GeV

- Dark matter observations in the sky
- Grand unification

The Standard Model and the LHC

Solutions (to hierarchy problem)

- New weakly interacting particles and symmetries that cancel the quadratic loops



$\sim M^2_{\tilde{t}} - M^2_t$

~1 TeV 175 GeV

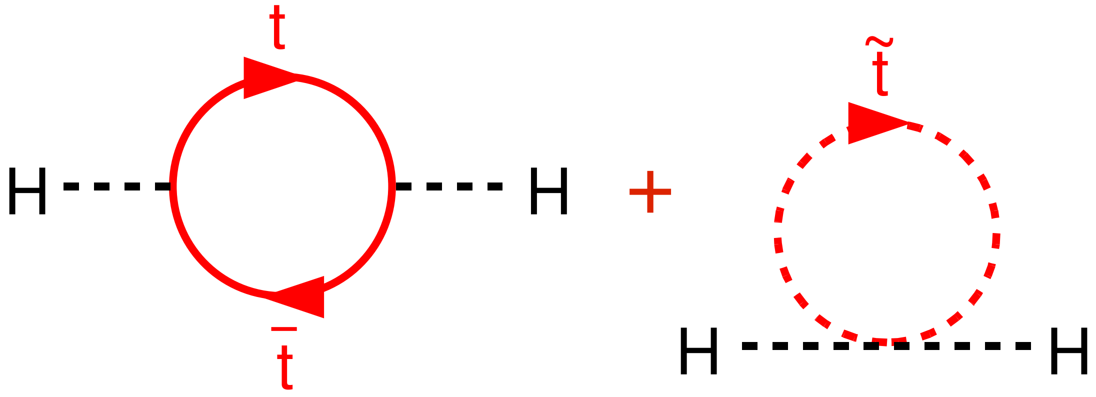
- Composite Higgs (new strong interactions, Technicolor)
- Removing the hierarchy by strengthening gravity (extra spacial dimensions)

The Standard Model and the LHC

Solutions (to hierarchy problem)

Most popular: SUSY

- New weakly interacting particles and symmetries that cancel the quadratic loops



$\sim M^2_{\tilde{t}} - M^2_t$

~1 TeV 175 GeV

- Composite Higgs (new strong interactions, Technicolor)
- Removing the hierarchy by strengthening gravity (extra spacial dimensions)

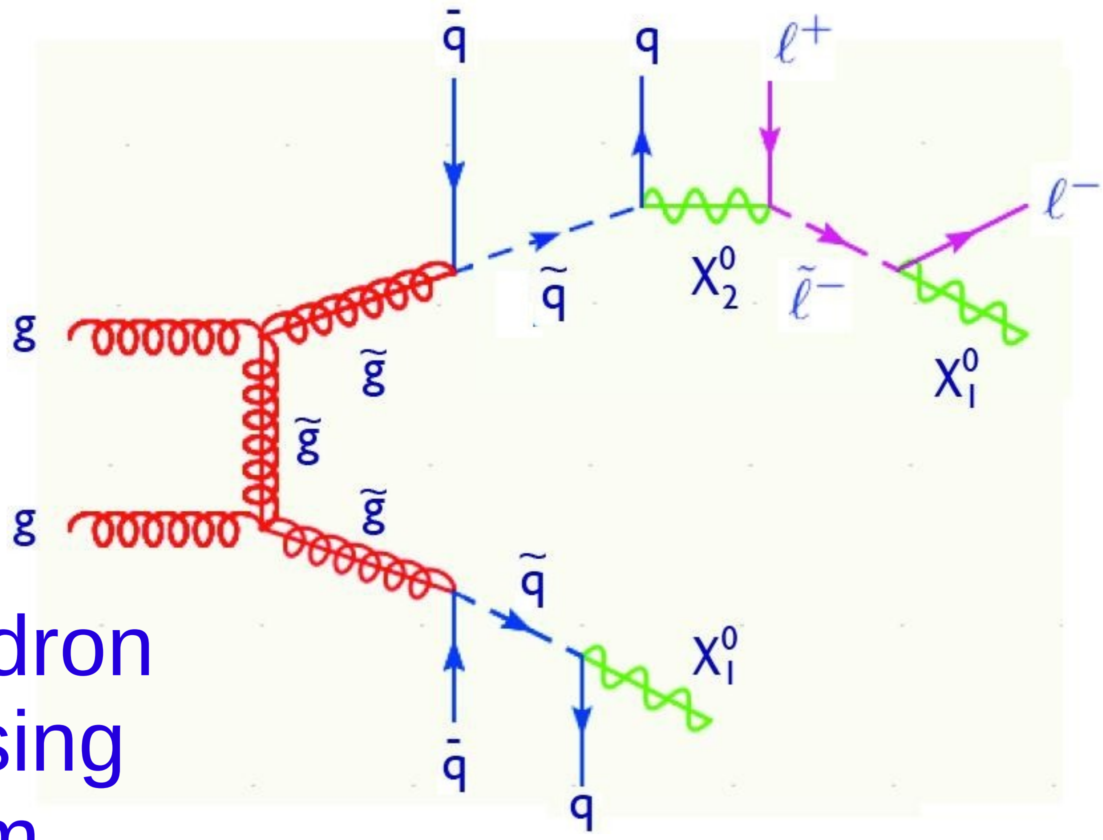
The Standard Model and the LHC

Solutions to the hierarchy problem predict new particles which protect the Higgs mass

- Particle masses must be around 100 GeV-1 TeV – within reach for the 14 TeV LHC
- Some new particles charged under QCD – easy to produce at a hadron collider
- We are (quite) confident that something new will be discovered at the LHC!

Typical SUSY-like signatures

- At the LHC, mainly particles charged under QCD (quark and gluon partners) will be directly produced
- Decay through "cascades" emitting quarks and leptons until reach lightest particle (dark matter)
- Signature: High-E hadron jets, leptons and missing transverse momentum



Difficulties with SUSY-like signatures

- No visible resonances – no simple features above Standard Model backgrounds
- Complicated to measure jets and missing transverse momentum
- Difficult determining overall mass scale – only mass differences readily observable
- QCD radiation generates extra hard jets besides the decay products

Main topic of this talk

QCD radiation

Main backgrounds for SUSY-like signatures:

- W and Z production + jets
- Top quark pair production + jets
- Very high-energy pure QCD jet production

“Plus jets” = additional quarks and gluons emitted in QCD bremsstrahlung radiation from incoming or outgoing quark/gluon-lines

QCD radiation

Main backgrounds for SUSY-like signatures:

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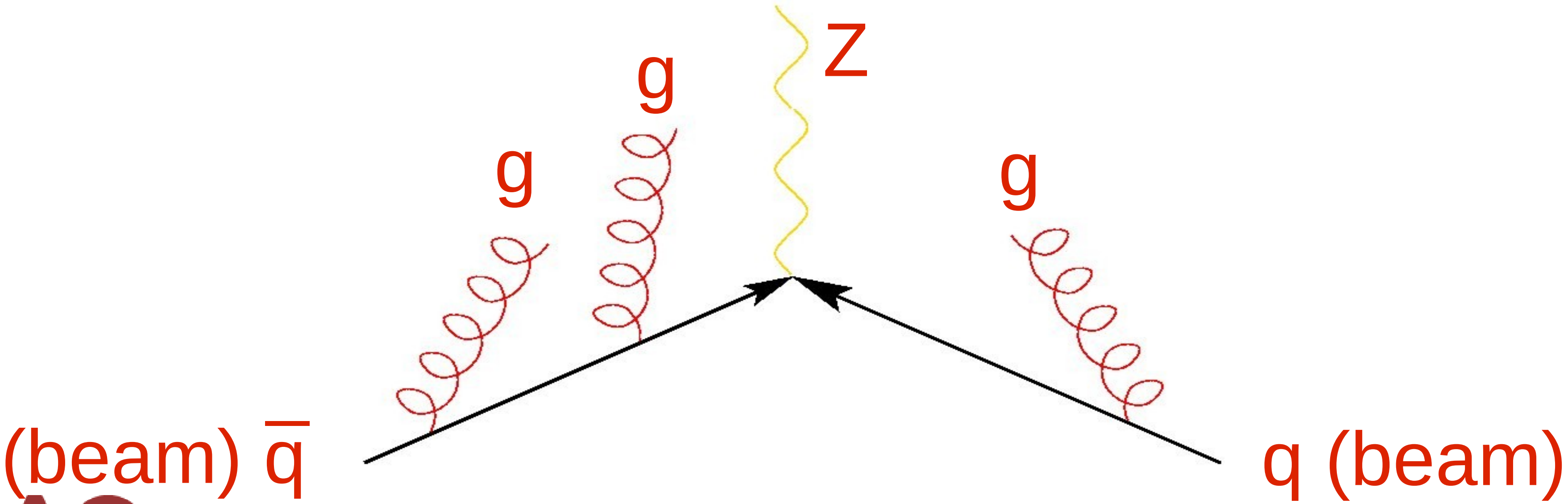
- Very high-energy pure QCD jet production



How to simulate QCD radiation

- Traditional method (~20 years):

  Parton showers

- Since ~10 years:

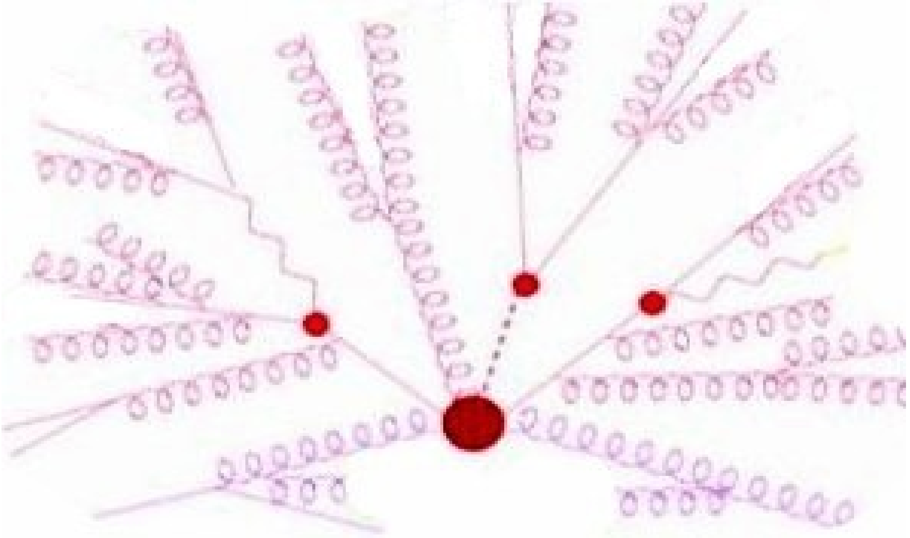
  Automatic calculation of tree-level multi-parton matrix elements

Strengths and weaknesses with both approaches!

- Since ~5 years:

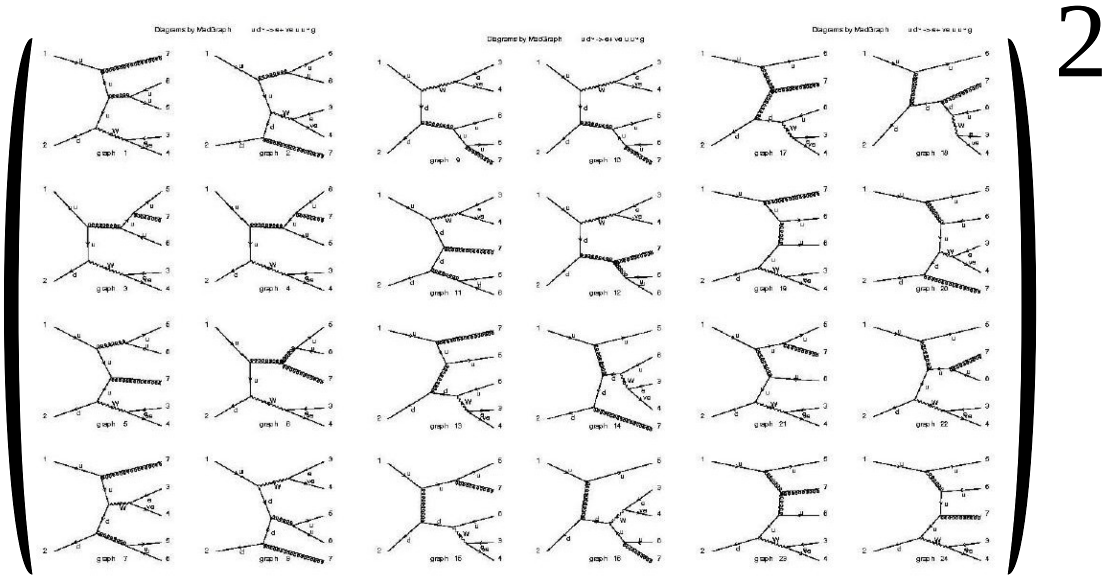
  Matching of partons showers and matrix elements

Parton Showers (PS)



- Based on soft-collinear approximation
- Step-by-step subsequent QCD emissions
  - Fast, computationally cheap (1→2 splittings)
  - No limit on particle multiplicity
- Necessary for interfacing to hadronization
- Formally correct only close to collinear region

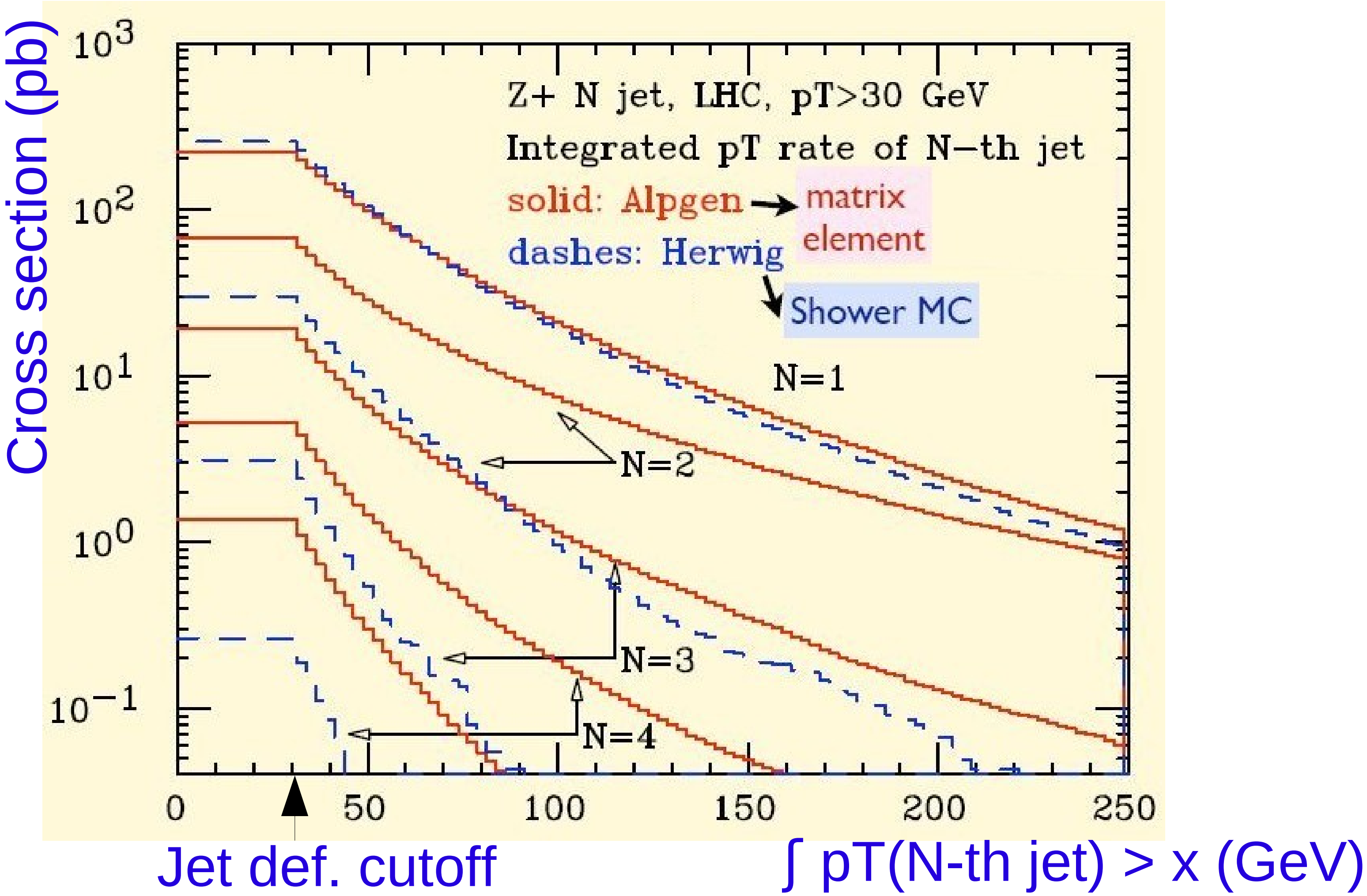
Matrix Elements (ME)



Diagrams for $u\bar{d} \to e^+\nu_e u\bar{u}g$ by MadGraph

- Correct description away from the collinear region
  - – diverges in the collinear region
- Includes interference and finite terms
- Necessary for calculation of high-energy jets
- Fixed particle multiplicity
- Slow, computationally heavy

Importance of Matrix Elements



Parton showers get multiple hard jet production from QCD radiation wrong by orders of magnitude

Matching ME and PS

Difficulties combining the two descriptions:

- Same phase space configuration can be described by both n+1-parton ME event and n-parton event + PS
  → Double counting
- Transition between ME and PS should be smooth
- Cross section should not be affected
- Minimize dependence on highest ME multiplicity

Solutions:

- Catani, Krauss, Kuhn, Webber [2001]
- Lönnblad [2001]
- M.L. Mangano [2002, 2006]

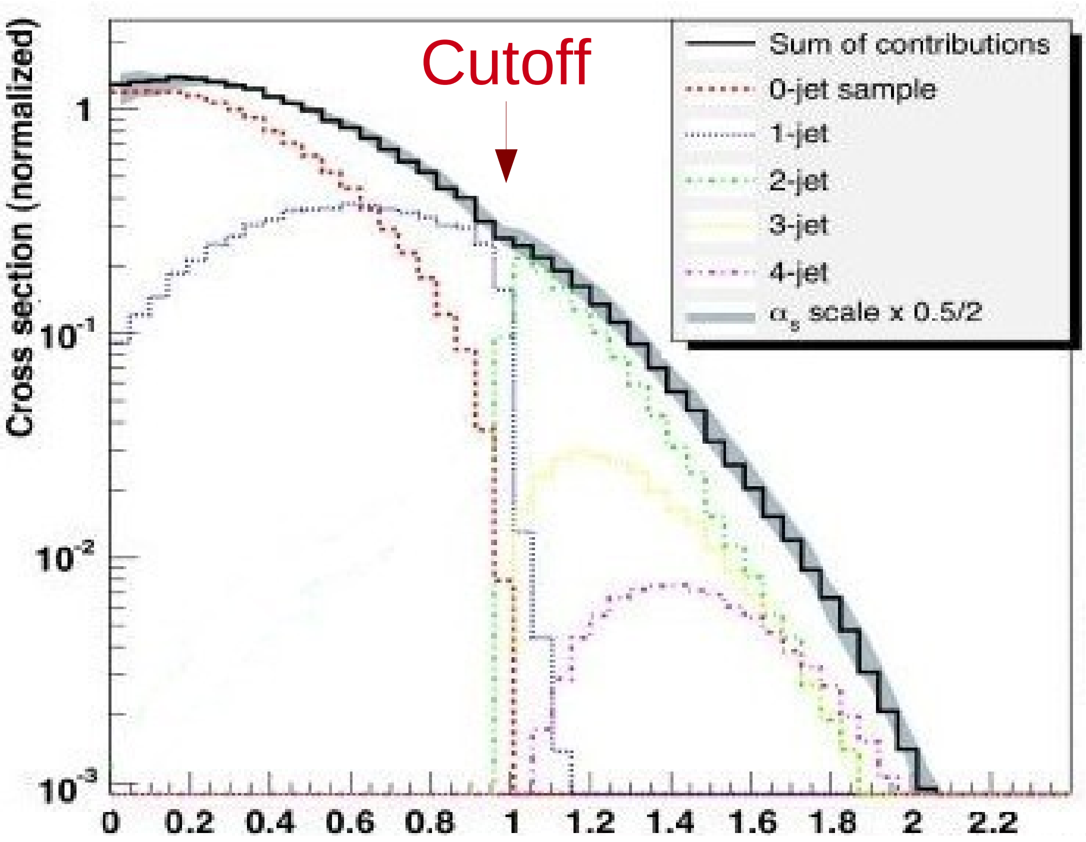
Matching ME and PS

Common approach for all matching schemes:

- Separate "hard jet" and "soft/collinear jet" regions using phase-space cutoff
- Allow ME jets to populate only "hard" region and PS emissions only "soft" region
- Modify ME description to mimick the parton shower near the cutoff
  - Reweighting of α_s in each emission vertex
  - Sudakov reweighting to account for no PS emissions in hard region and ensure stable cross section

Done differently in different schemes

Results of matching

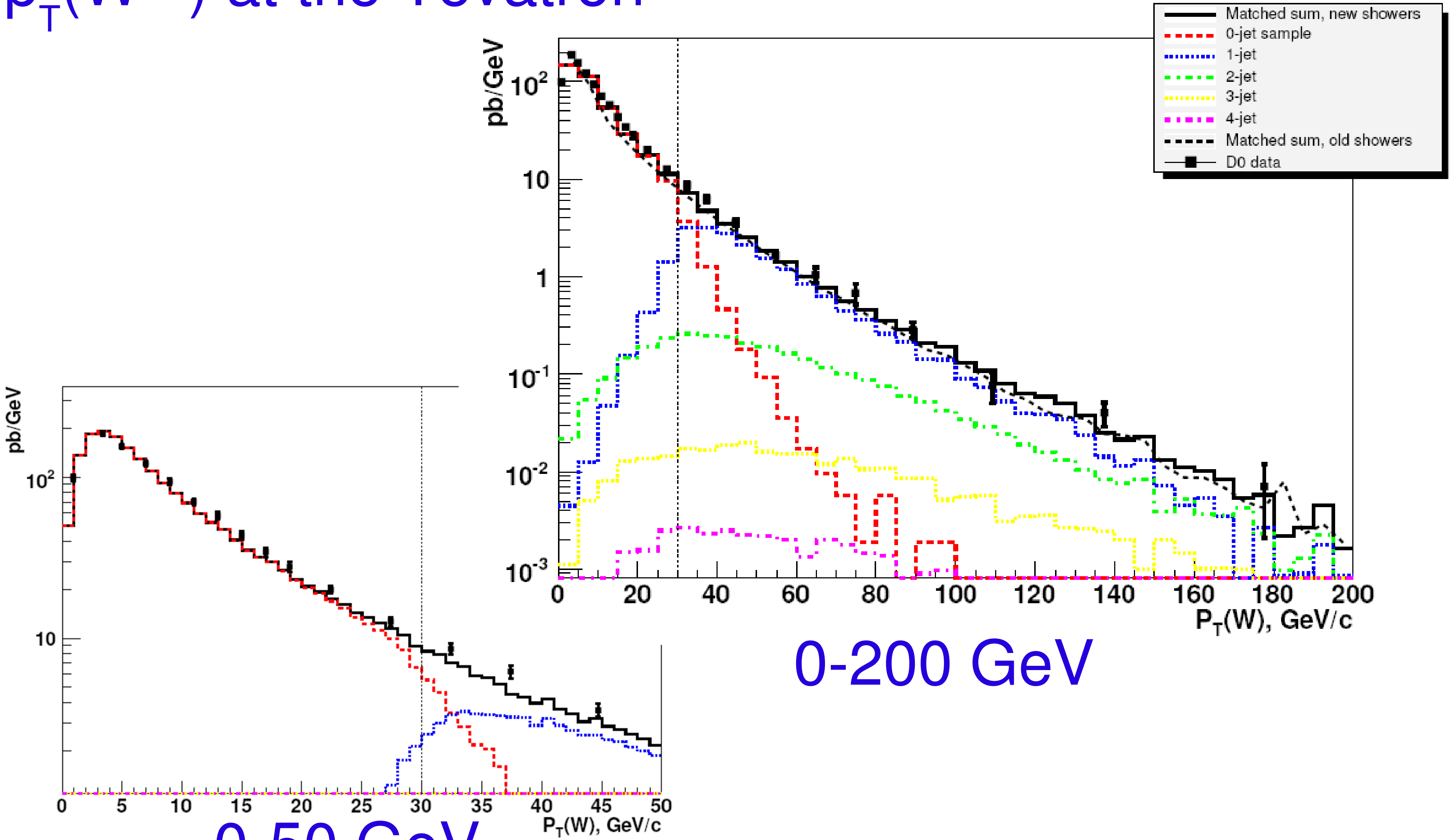


log(Jet resolution scale for 1 → 2 radiated jets ~ p_T(2^{nd} jet))

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

Comparison with Tevatron Data

$p_T(W^{+/-})$ at the Tevatron



0-200 GeV

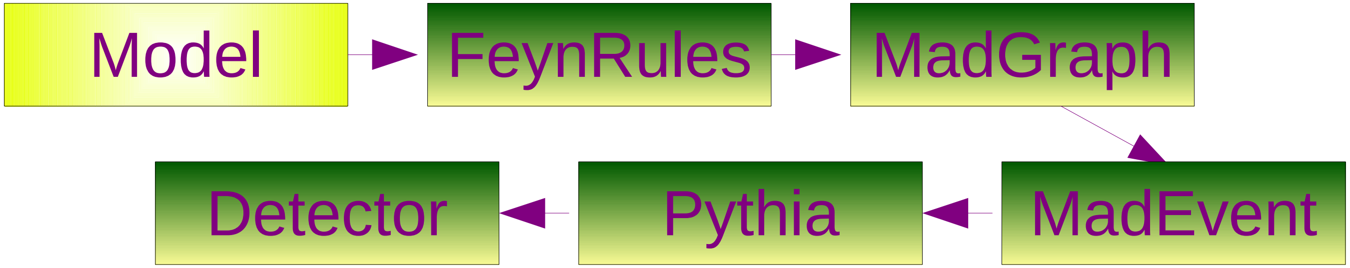
0-50 GeV

MadGraph/MadEvent

Steltzer, Maltoni [1994,2003], J.A. et al [arXiv:0706.2334]

- MadGraph/MadEvent – an automatized Matrix Element and event generator
- On-demand simulation of (almost) any process in the SM or beyond (at tree level)
- Web-based or local simulation
- Interfaces to parton showers and detector simulations – full simulation chain!

Welcome to visit us at http://madgraph.hep.uiuc.edu !



Model

FeynRules

MadGraph

MadEvent

Pythia

Detector

MadGraph/MadEvent+Pythia

J.A. et al [arXiv:0706.2334]

- Matching schemes implemented: k_T and cone jet MLM schemes, new “shower k_T” scheme
- Both Q^2- and p_T-ordered Pythia parton showers
- CKKW-style matching with Pythia p_T-showers underway (with P. Skands)
- Extensively validated, W+jets compared with other generators [J.A. et al, arXiv:0706.2569]
- Allows matching in (most) SM and BSM processes

Matching in New Physics production

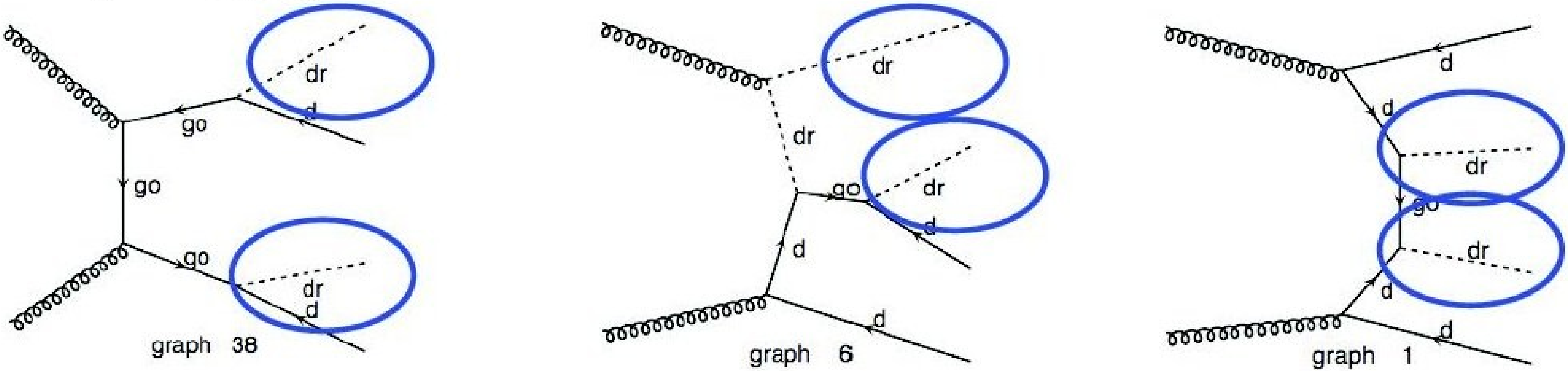
J.A., de Visscher, Maltoni [arXiv:0810.5350]

- 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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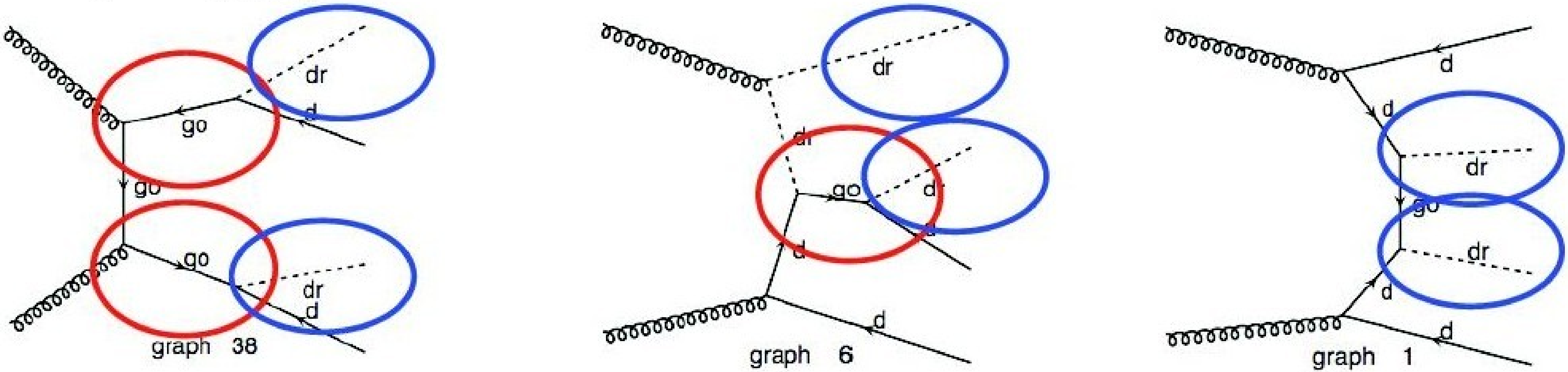
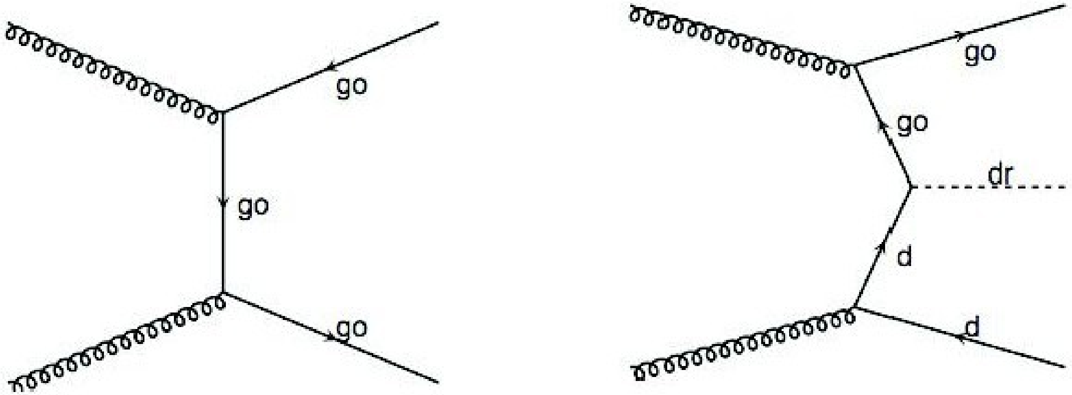
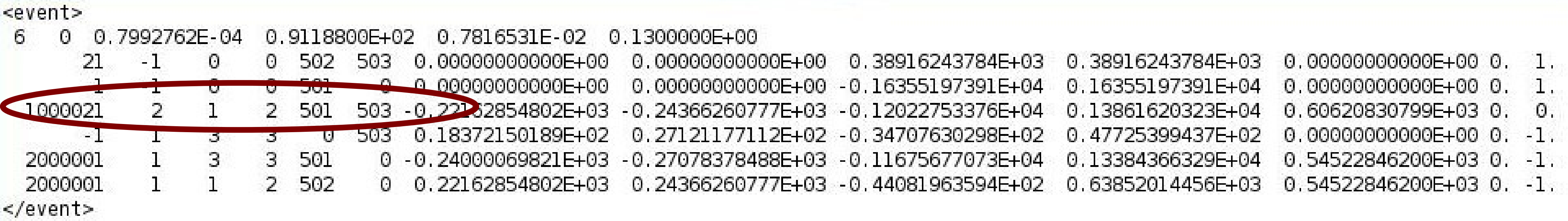




Double-counted with on-shell gluino prod with $\tilde{g} \rightarrow \tilde{d}_R + q$

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!)

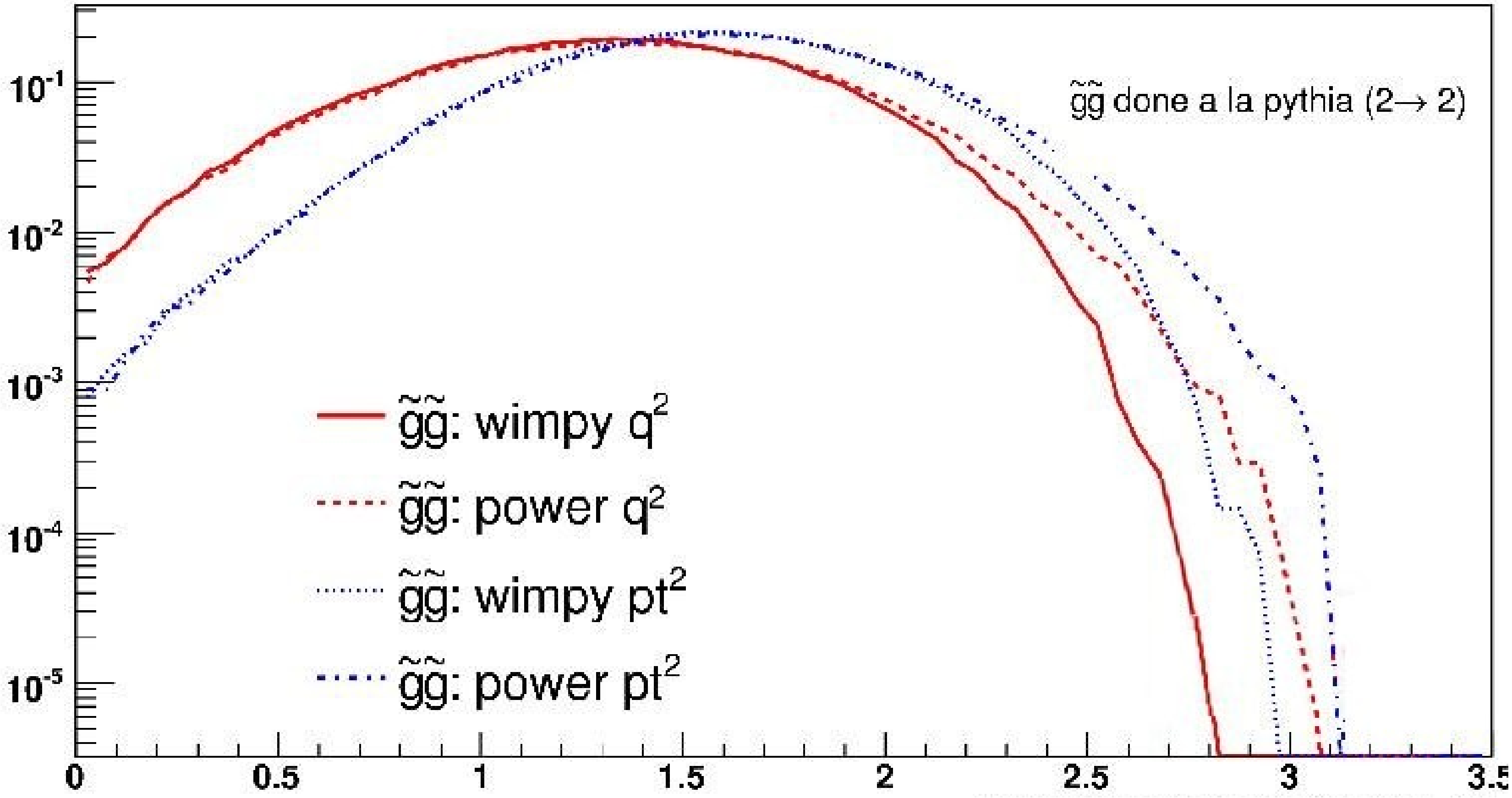
→ Excellent agreement

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

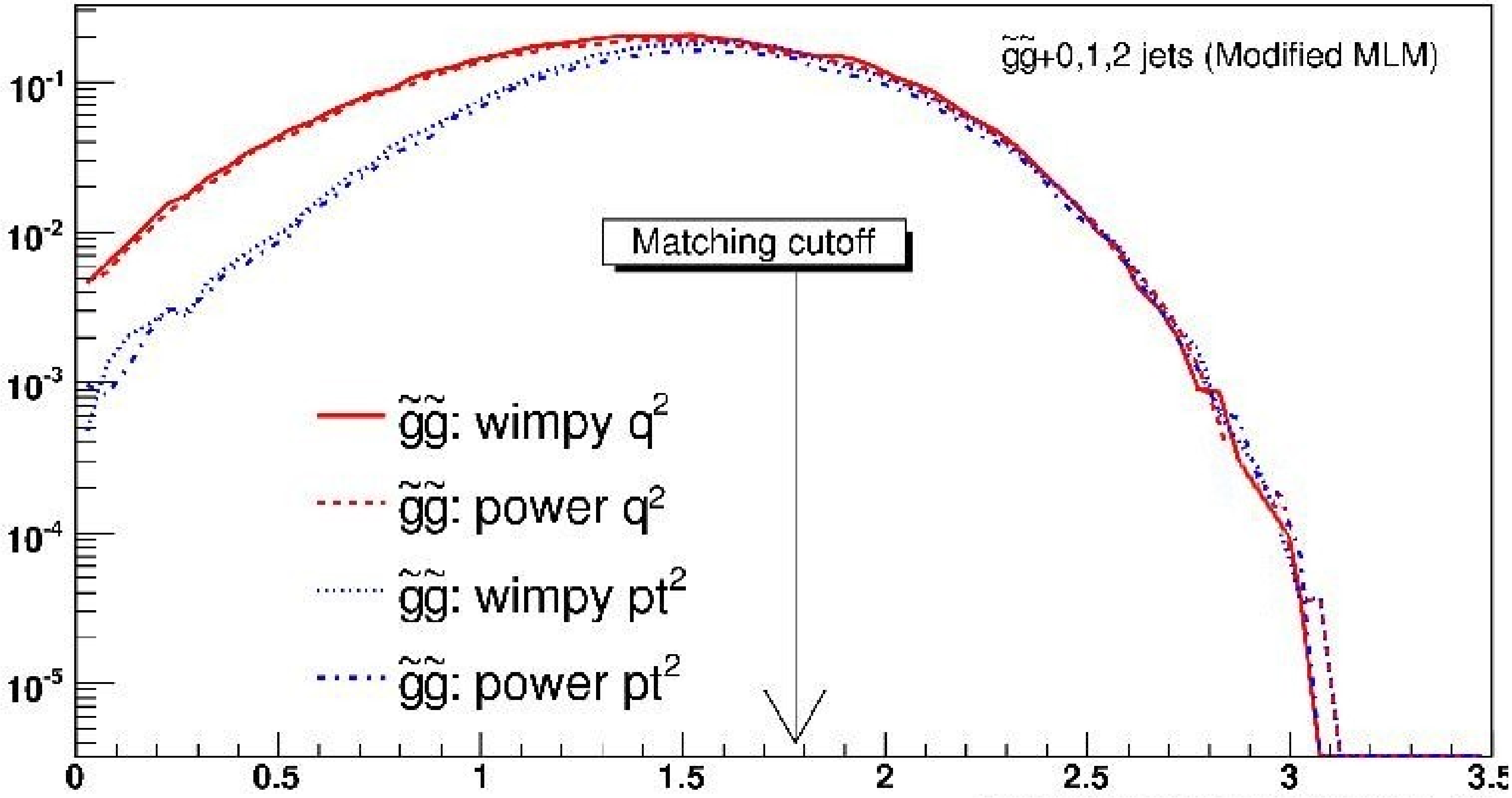


log(Jet resolution scale for 1 → 2 radiated jets) (GeV)

600 GeV gluino pair production at the LHC

Shower parameter dependence

QCD radiation after matching with MG/ME



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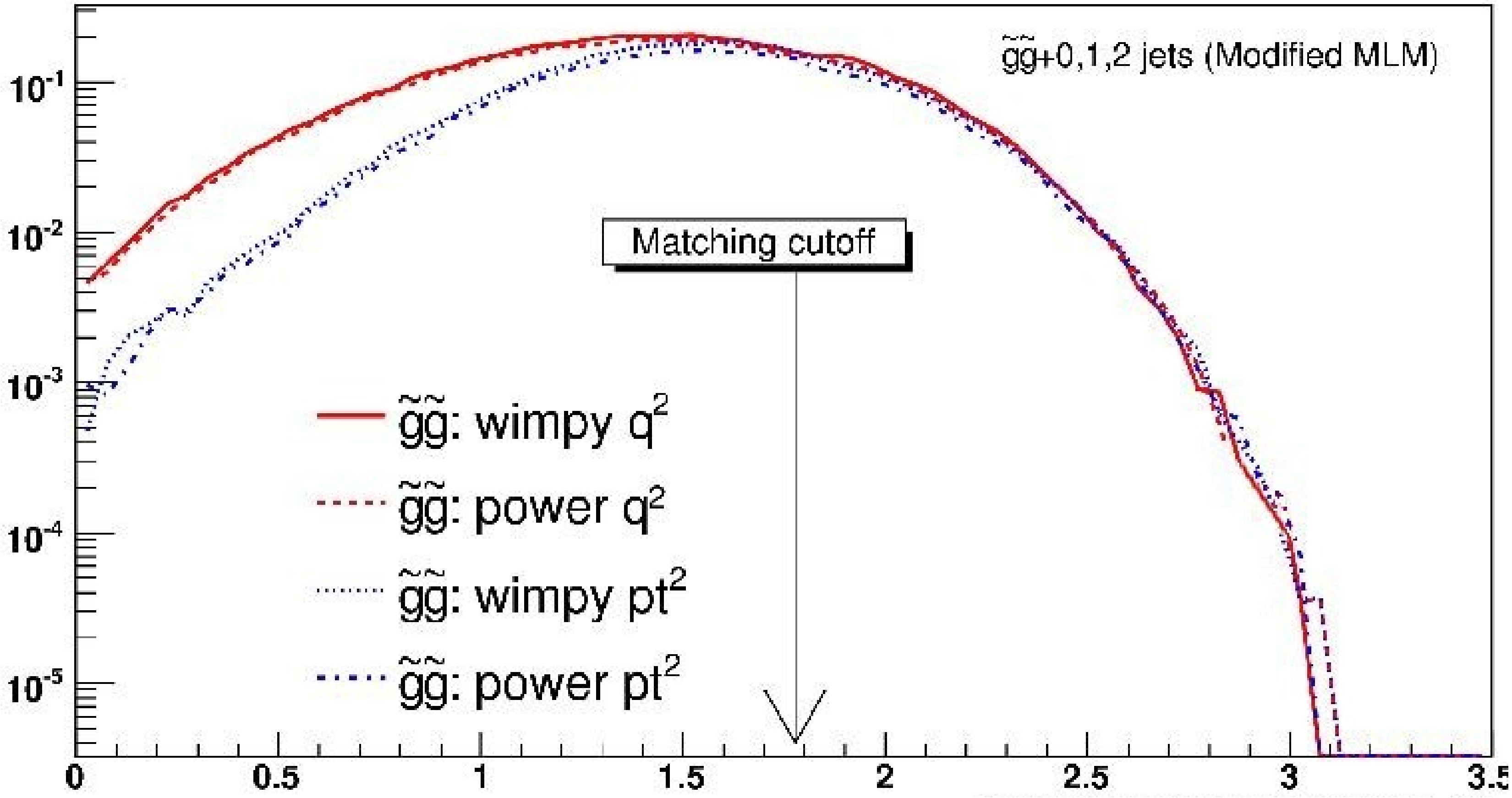
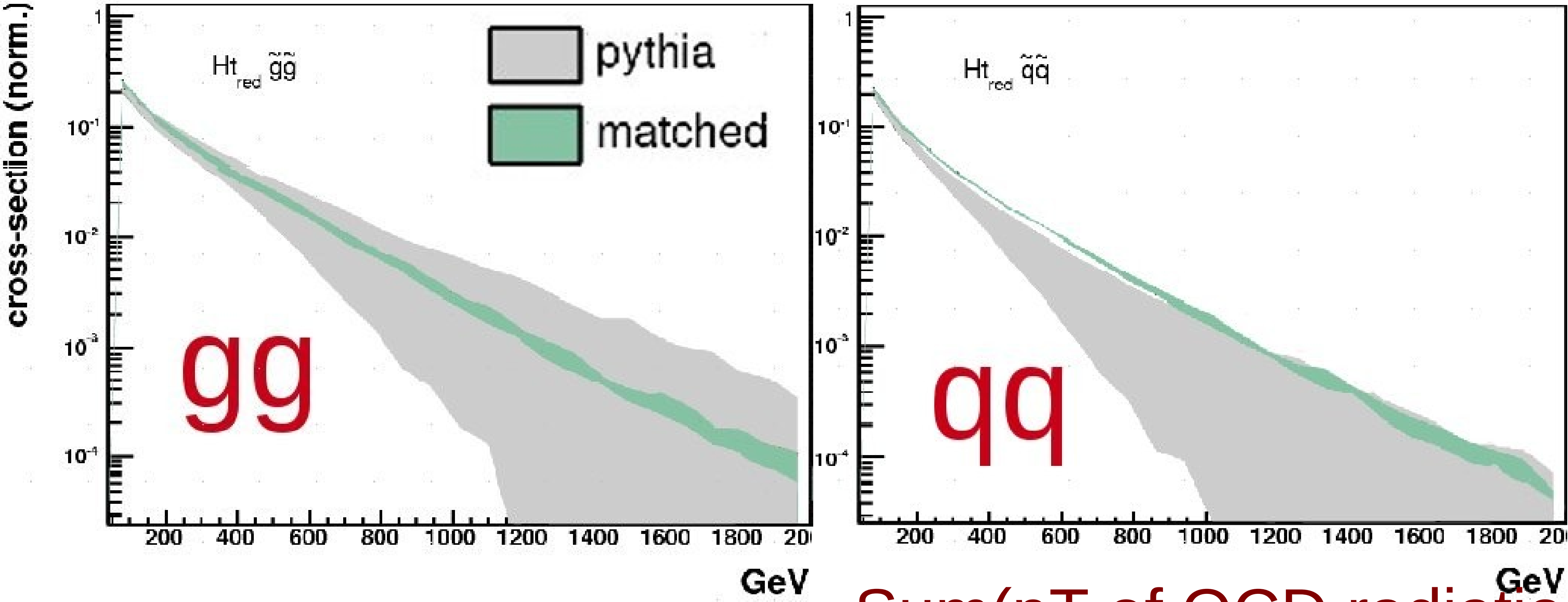


log(Jet resolution scale for 1 → 2 radiated jets) (GeV)

Predictive → can now analyze QCD radiation

Dependence on the initial state: gg, qq

600 GeV gluino vs. squark pair production at LHC

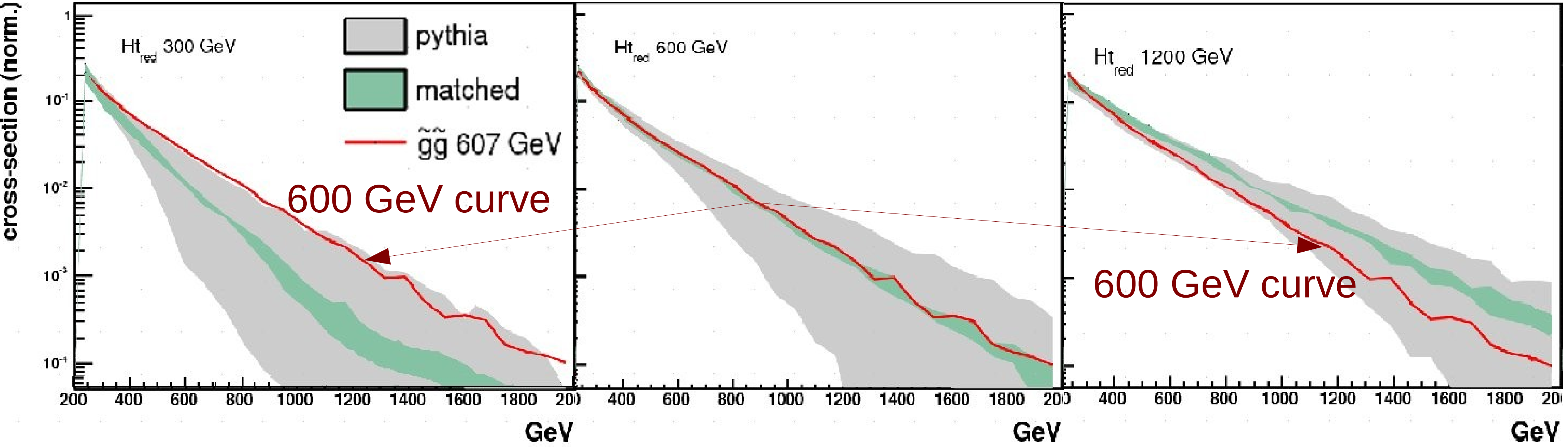


Sum(pT of QCD radiation)

No single shower tune for all initial states!

Dependence on SUSY particle mass

300 GeV gluinos 600 GeV 1200 GeV



600 GeV curve

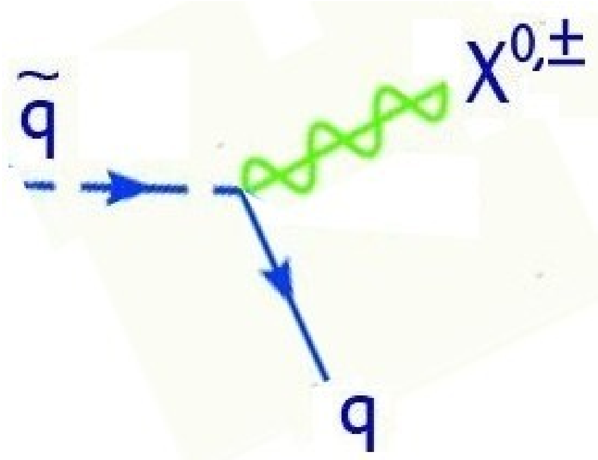
600 GeV curve

Sum(pT of QCD radiation)

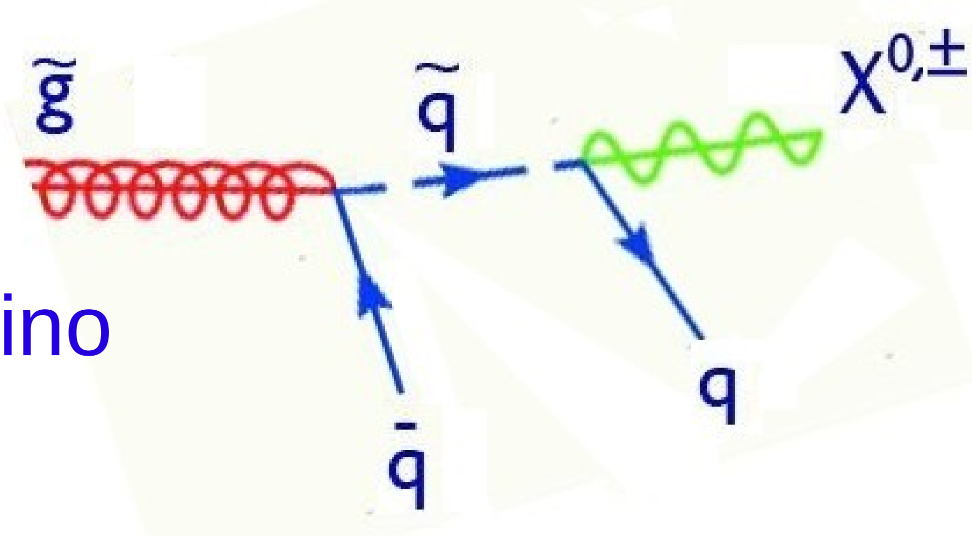
Can QCD rad. help determine overall mass scale?
Possibly for particles below ~ 1 TeV!

Squark/Gluino separation

- Squark decay
  → quark + weak gaugino



- Gluino decay
  → squark + quark
  → 2 quarks + weak gaugino



- Differ by 1 jet – hard/soft depending on Δ(mass)

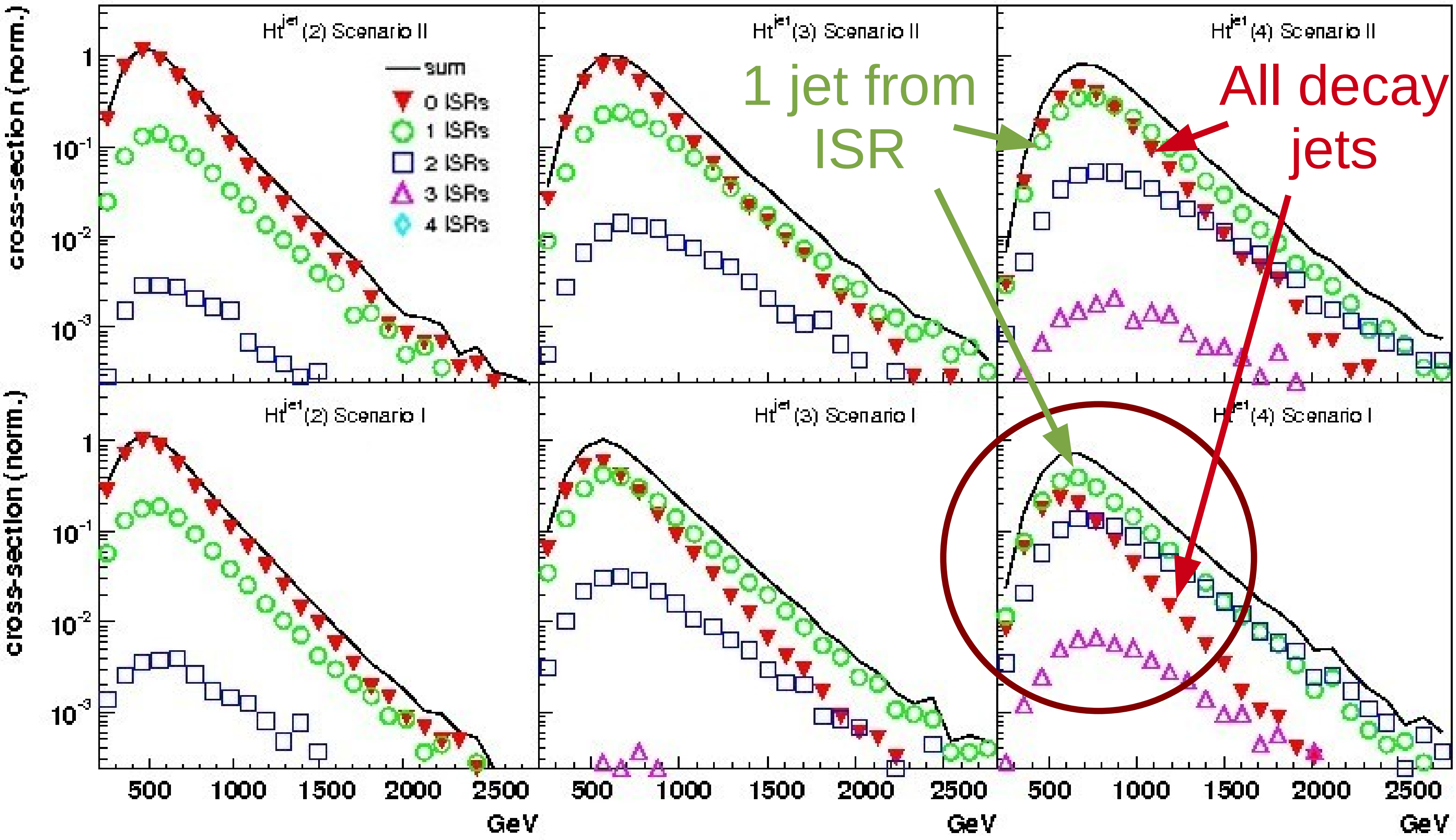
Jet counting in gluino decay

600 GeV gluino pair production

3-body $\tilde{g}$ decay

(squarks heavy)

M_g-M_q= 50 GeV



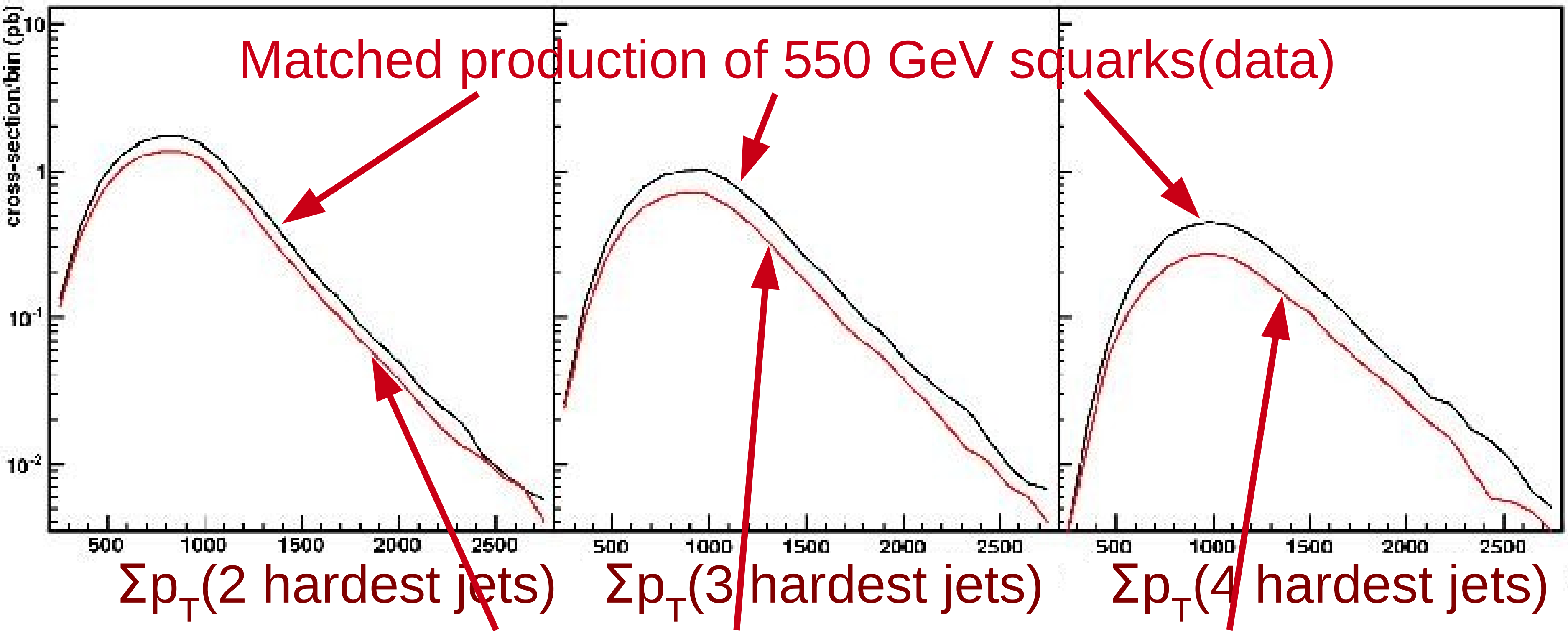
1 jet from ISR

All decay jets

Σp_T(2 hardest jets) Σp_T(3 hardest jets) Σp_T(4 hardest jets)

Squark/Gluino separation

Scenario: squark pair production only
(gluinos too heavy to be produced)



Matched production of 550 GeV squarks(data)

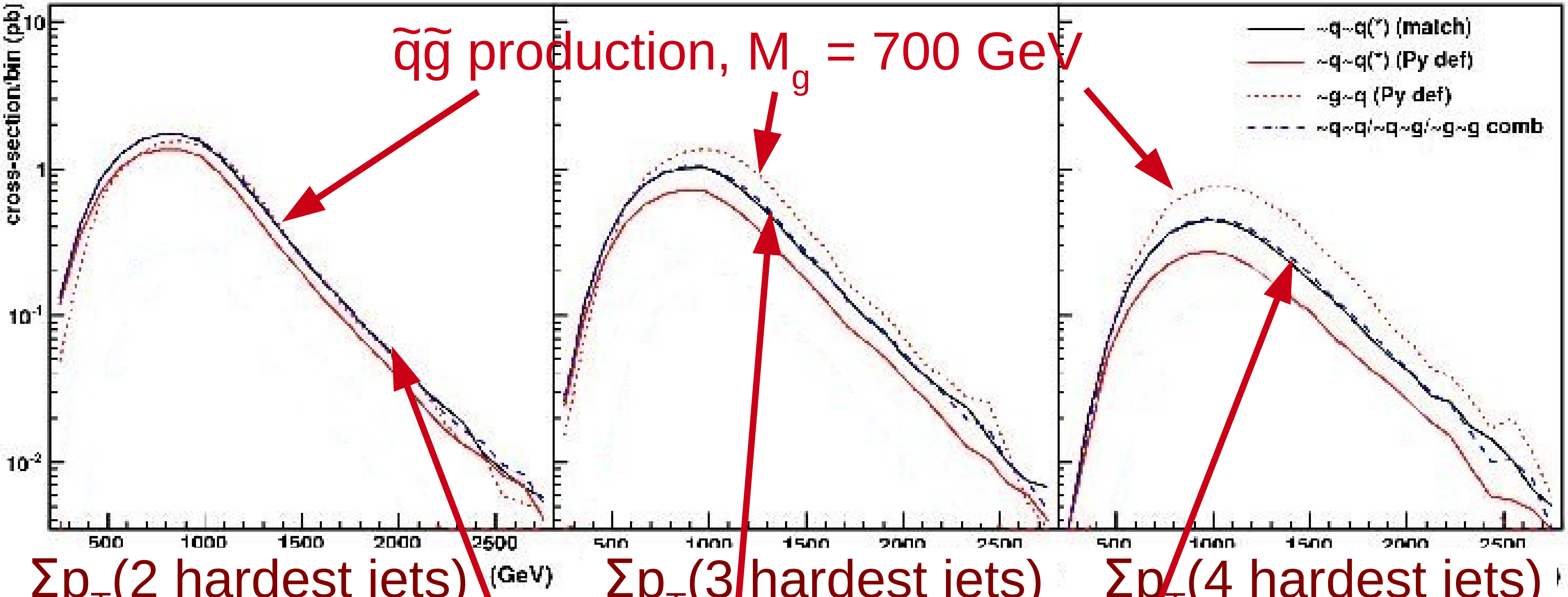
Σp_T(2 hardest jets) Σp_T(3 hardest jets) Σp_T(4 hardest jets)

Unmatched production (simulation, Pythia default)

Looks like we're missing hard jet component!

Squark/Gluino separation

Scenario: squark pair production only
(gluinos too heavy to be produced)



$\tilde{q}\tilde{g}$ production, M_g = 700 GeV

Σp_T(2 hardest jets) Σp_T(3 hardest jets) Σp_T(4 hardest jets)

Unmatched $\tilde{q}\tilde{q}$ + 25% $\tilde{q}\tilde{g}$ (fits “data”)

Easy misinterpretation: squark-gluino component

Non-standard gluinos

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

Many models/ideas for physics beyond the Standard Model at the LHC giving signatures with leptons, jets and missing energy

- Differences between models often subtle – difficult to distinguish in early data
- Many models (cf. SUSY) have many parameters – most unmeasurable at LHC
- Constrained versions of models introduce strong relations between observables
- See further J.A., Schuster, Toro [arXiv:0810.3921], J.A., Le, Lisanti, Wacker [arXiv:0809.3264]

Non-standard gluinos

- Most common experimental approach: Exclusions in model space of minimal model (mSUGRA/mGMSB/mAMSB) with few (~4-5) parameters
- Problems:
  - Fixed relations between parameters, e.g. $m_{\tilde{g}}:m_{\tilde{W}}:m_{\tilde{B}} \sim 6:2:1$ LSP
  - Light flavor squark masses $\gtrsim$ gluino mass
  - Fixed decays and branching ratios
  - Not all possible parameter space covered

Non-standard gluinos

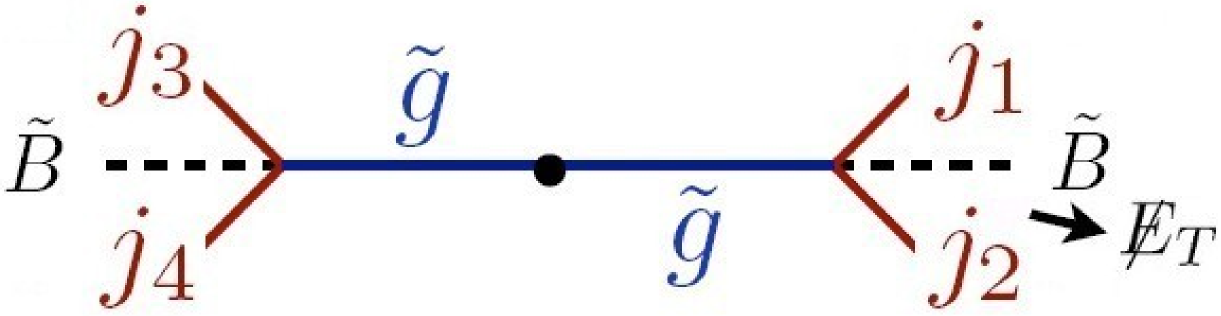
Non-unified/non-standard SUSY scenarios, and other models, can have $m_{\tilde{g}}:m_{\tilde{B}}$ ratio free

- A priori unclear where Tevatron is sensitive
- Need combination of $\not{E}_T$+1-jet, 2-jet, 3-jet and multijet searches to cover whole $\tilde{g}$-$\tilde{B}$ mass plane

Non-standard gluinos

Special difficulty when decay products nearly mass-degenerate with produced particle:

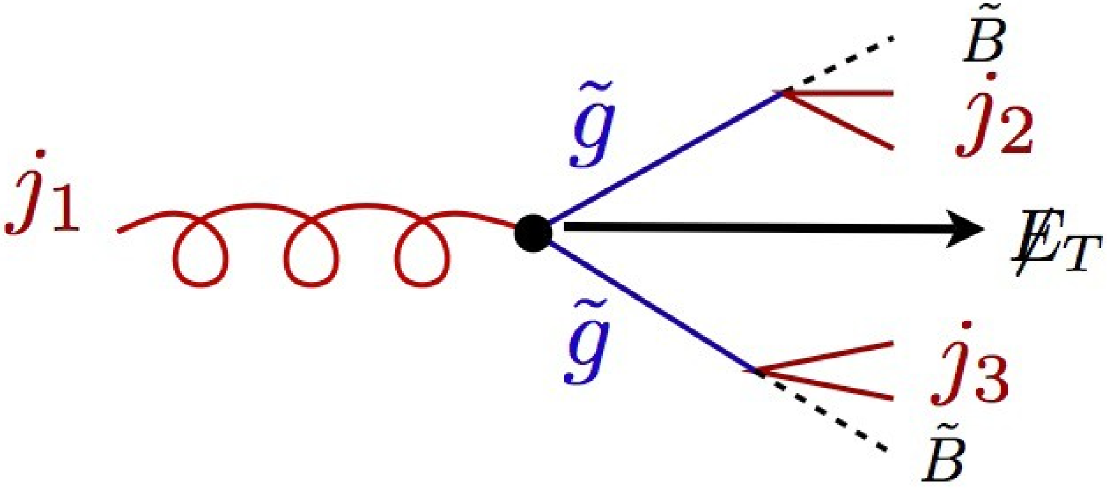
- No (small) missing transverse energy in decay



Non-standard gluinos

Special difficulty when decay products nearly mass-degenerate with produced particle:

- No (small) missing transverse energy in decay
- Need recoil against jets to get $\not{E}_T$ signature



Non-standard gluinos

Matched

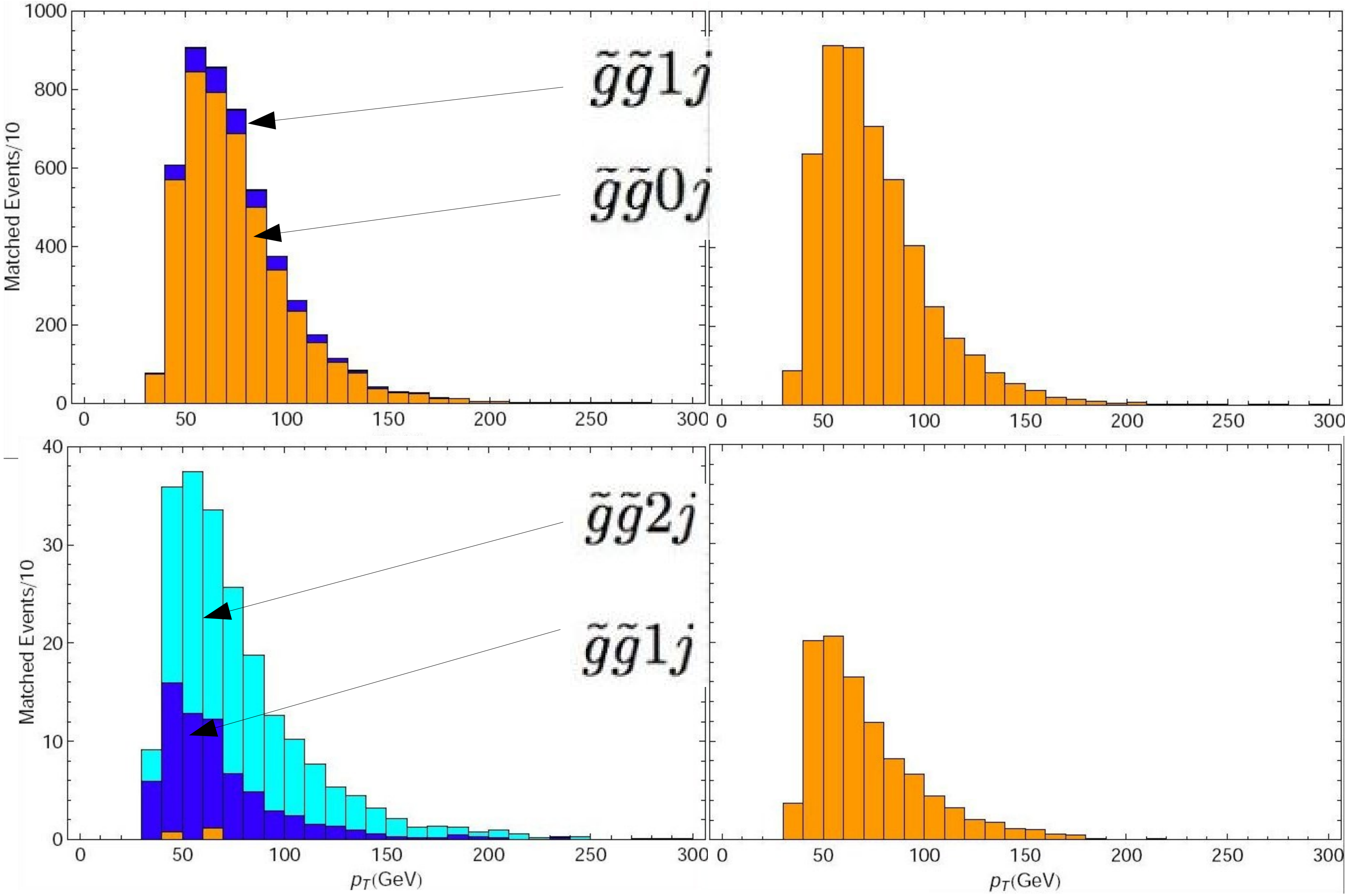
Unmatched

M_g=150 GeV

M_B=40 GeV

M_g=150 GeV

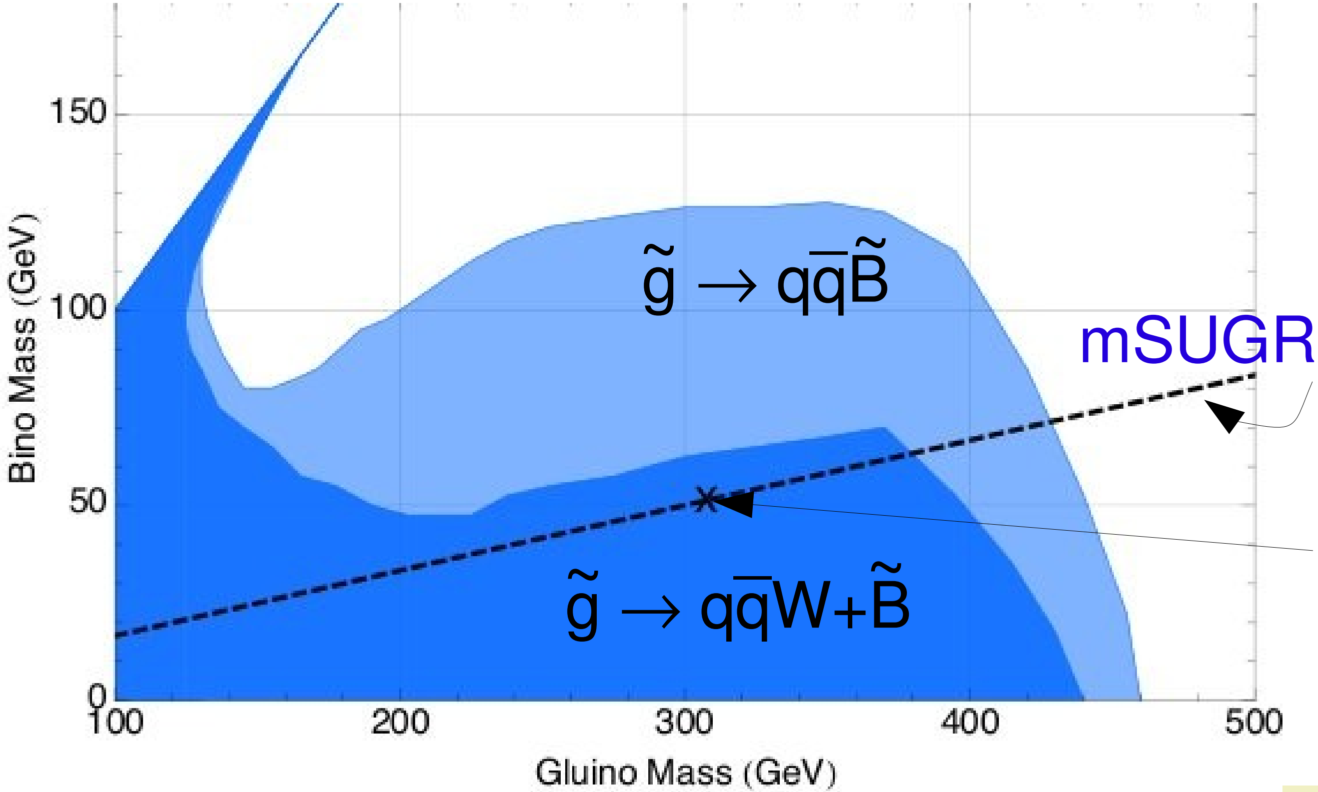
M_B=130 GeV



Tevatron, after 2-jet and missing E_T cuts

Non-standard gluinos

- Prejudice-free model scenario and improved simulation allows us to find exclusion region in $\tilde{g} - \tilde{B}$ mass plane



mSUGRA mass ratio

mSUGRA exclusion

Conclusions and outlook

- The LHC is coming! Are we prepared?
- Signals involving jets and missing energy will (probably) be crucial for discovery of new physics
- Precision simulations necessary, both for SM backgrounds and many New Physics scenarios
- Big advances in recent years, still much to do!
  - Automatization of next-to-leading order calculations
  - Further improvement of methods for model distinction
- Exciting times are ahead!

Backup slides

Details of matching schemes

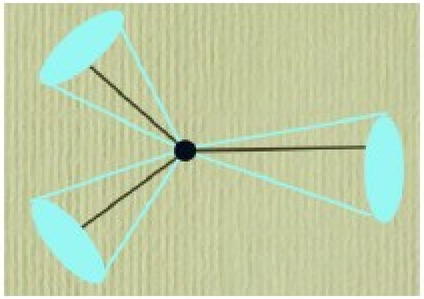
- CKKW scheme
  - Sudakov reweighting using analytical NLL Sudakovs
  - Analytically relatively well-understood
- Lönnblad scheme
  - Sudakov reweighting by using shower Sudakovs
- MLM scheme
  - Run shower and reject events with too hard emission
  - Can use any shower implementation

MLM matching

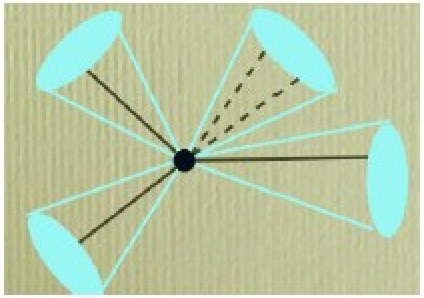
J.A. et al. [arXiv:0706.2569],
cf. M.L. Mangano [2002, Alpgen home page]

Use shower hardness to separate ME/PS

1. Generate multiparton event with cut on jet k_T
2. Cluster event and use k_T^2 for α_s scale
3. Shower event (using Pythia) starting from hard scale
4. Collect showered partons in k_T jets with $k_{T\mathrm{cut}} > k_{T\mathrm{min}}$
5. Keep event only if each jet matched to one parton
6. For highest multiplicity sample, allow extra jets softer than $k_{T\mathrm{min}}$

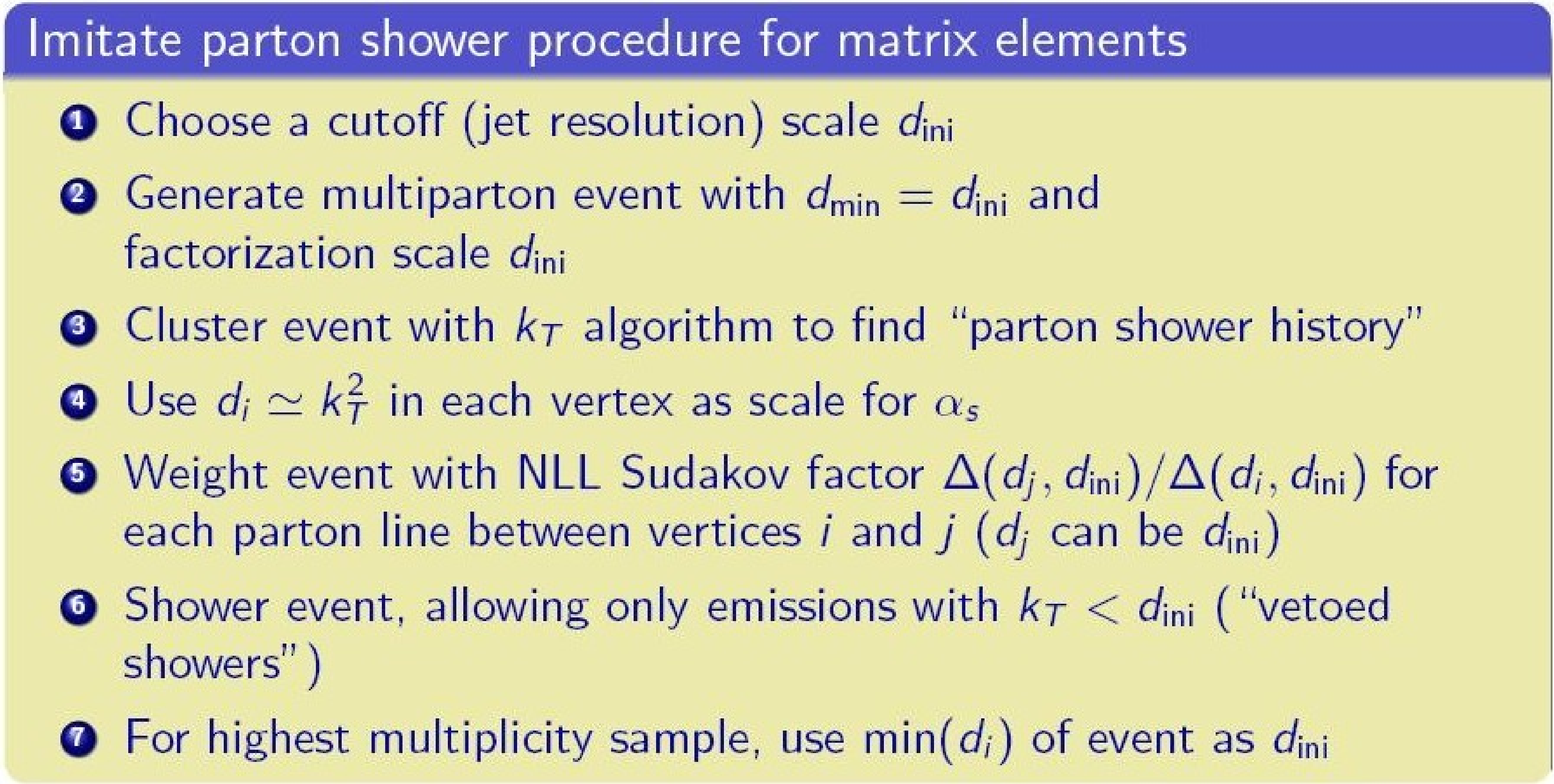


Keep



Discard unless highest multiplicity

CKKW matching



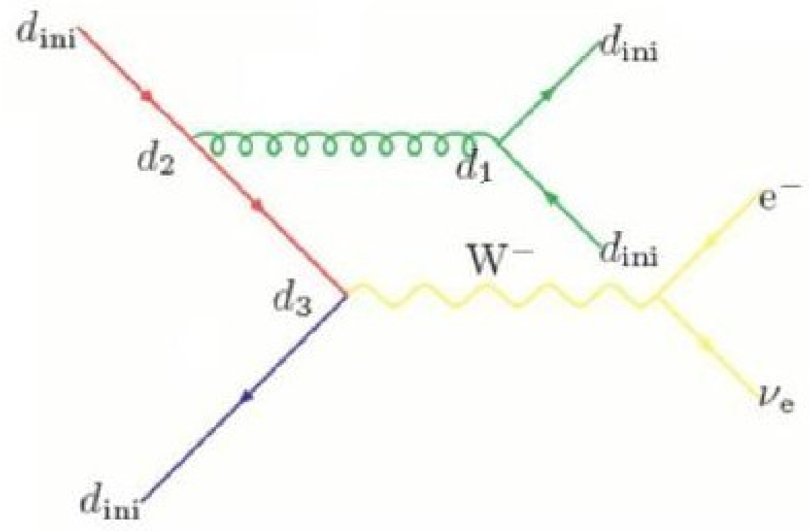
Imitate parton shower procedure for matrix elements

1. Choose a cutoff (jet resolution) scale $d_{\rm ini}$
2. Generate multiparton event with $d_{\rm min} = d_{\rm ini}$ and factorization scale $d_{\rm ini}$
3. Cluster event with k_T algorithm to find "parton shower history"
4. Use $d_i \simeq k_T^2$ in each vertex as scale for α_s
5. Weight event with NLL Sudakov factor $\Delta(d_j, d_{\rm ini})/\Delta(d_i, d_{\rm ini})$ for each parton line between vertices i and j (d_j can be $d_{\rm ini}$)
6. Shower event, allowing only emissions with $k_T < d_{\rm ini}$ ("vetoed showers")
7. For highest multiplicity sample, use $\min(d_i)$ of event as $d_{\rm ini}$

Boost-invariant k_T measure:

$$\begin{cases} d_{iB} = p_{T,i}^2 \\ d_{ij} = \min(p_{T,i}^2, p_{T,j}^2)F_{ij} \end{cases}$$

$$F_{ij} = 2\left\{\cosh(\eta_i - \eta_j) - \cos(\phi_i - \phi_j)\right\}$$



- For final-state showers: Combination of NLL Sudakov factors and vetoed NLL showers guarantees independenc of d_{ini} to NLL order
- For initial-state showers: No proof but works ok
- Problem in practice: No NLL shower implementation! (Sherpa uses Pythia-like showers)

Shower k_T scheme

- Keep/reject event based on k_T of hardest shower emission (as reported by Pythia)
- Highest multiplicity treatment as in CKKW, use min dparton as cutoff
- No jet clustering
- No need of "fiducial region", can use $k_T^{match} = d_{cut}^{ME}$
- Need similar kT definitions in ME and PS (only "new", p_T-ordered showers at present)