Simulating Hadron Collider Interactions

This introduction is loosely based on Ch 2, Dobbs Ph.D Thesis and hep-ph/0403045.

Les Houches Guidebook to Monte Carlo Generators for Hadron Collider Physics

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Outline

- Intro
- Types of Simulations
  - Tree Level Simulations
  - Showering and Hadronization Generators
    - parton density functions
    - hadronization
    - decay packages
    - underlying event
  - Fixed Order Generators
  - Analytic Resummation
  - Mixing NLO with Parton Shower (e.g. MC@NLO)

Our standard example will be:
$pp \to Z \to l^+l^-$

Why?

- Monte Carlo generators provide our theoretical expectation for collider experiments. They encompass our knowledge of the theory. A great many measurements couldn't be made without them.

- MC Authors love backgrounds.
  - simulating new physics is (almost) always easy. Usually its leading order. You can do it, they can do it, anyone can.
  - Modeling the subtle effects of the Standard Model is the difficult part.

Should I trust them?

- Hell no!

- Not unless you
  - understand them fully.
  - are operating them in their region of validity
  - have independent theoretical cross check
    - e.g. another MC generator, preferably using different approximations
  - and have verified them against experimental data in a regime not sensitive to the thing you are studying.

Can I live without them?

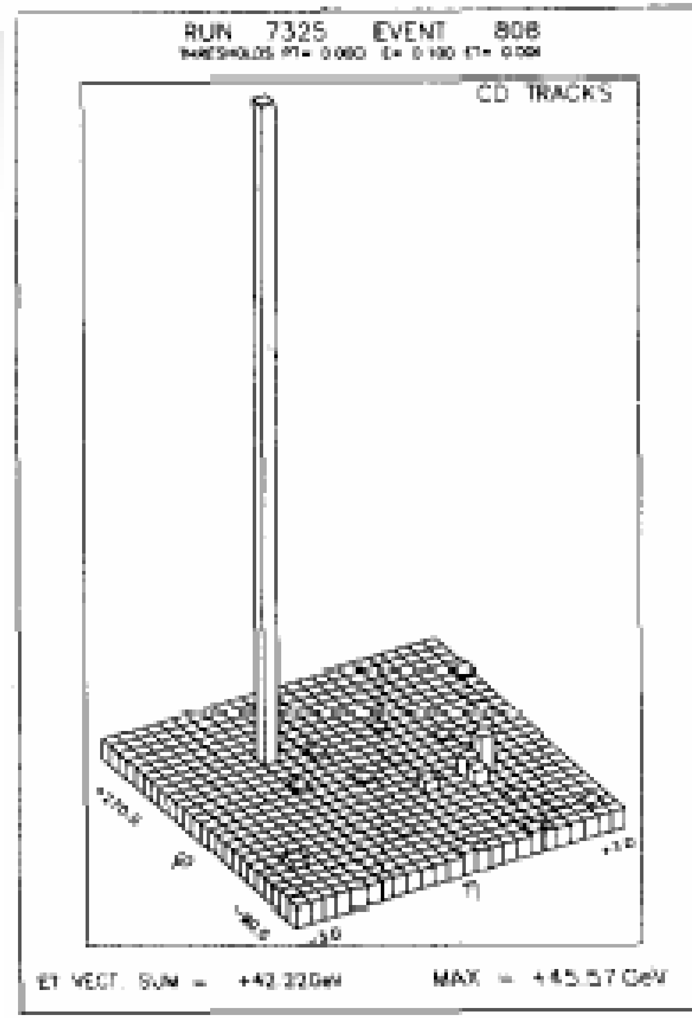
- well, no, not really.
  - we need them to plan
    - plan future facilities
    - design detectors
  - experimentally for
    - find efficiency of isolation cuts
    - correct for finite detector acceptance
    - jet energy (out of cone) corrections
  - theoretically to
    - map our predictions
    - understand coloured partons in terms of observable hadrons
    - optimize cuts for physics measurements/discoveries

Example: Monojets

EXPERIMENTAL OBSERVATION OF EVENTS WITH LARGE MISSING TRANSVERSE ENERGY ACCOMPANIED BY A JET OR A PHOTON (S) IN $p\bar{p}$ COLLISIONS AT $\sqrt{s}$ = 540 GeV

UA1 Collaboration, CERN, Geneva, Switzerland

  - was easy to come up with and simulate theories that matches the observations (roughly 282 explanations!)
- but the careful simulation and calculation of higher order corrections was the culprit.

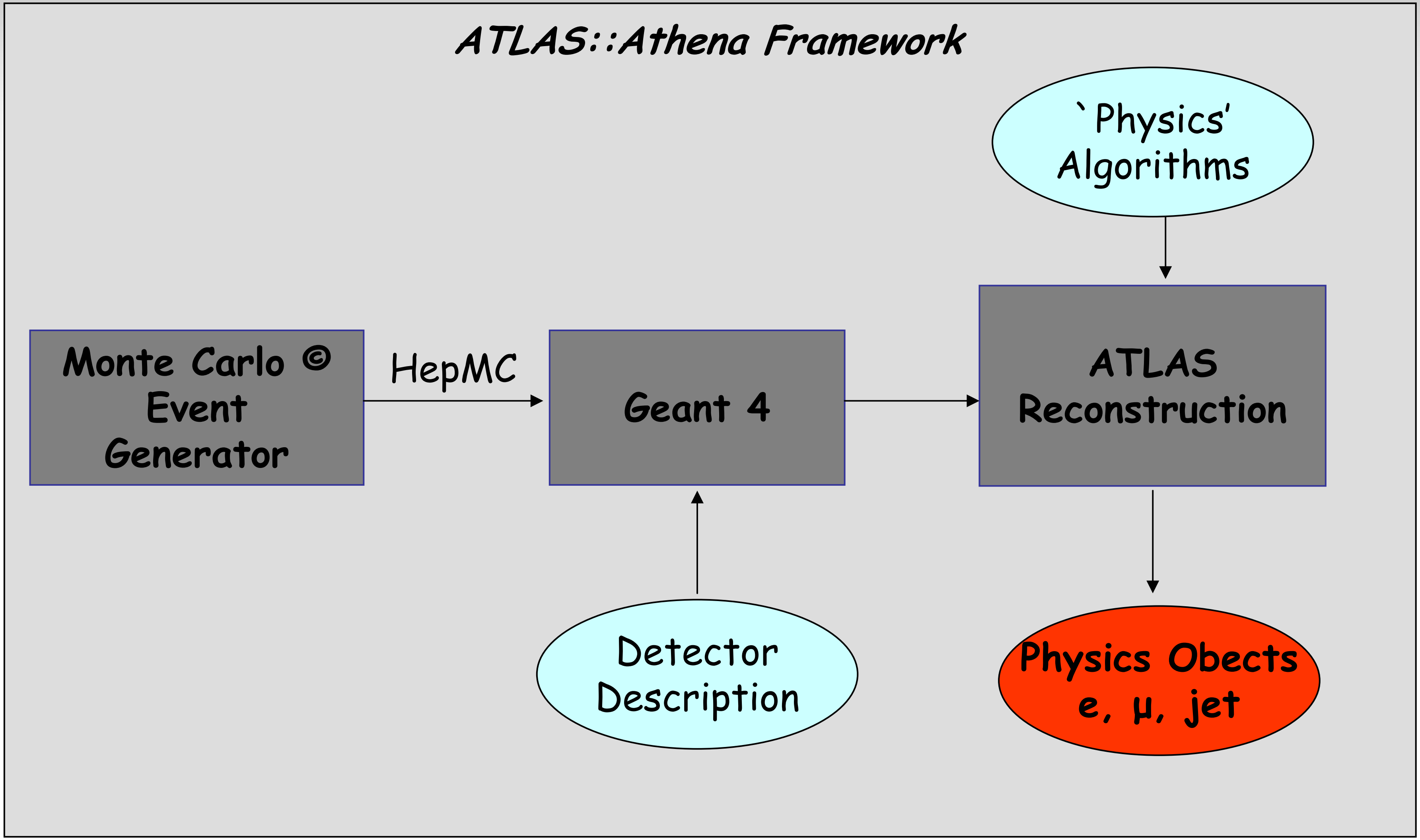


Monte Carlo Basics

- Monte Carlo Technique
  - technique for numerically evaluating complicated integrals by sampling randomly chosen *phase space points*

- In HEP jargon, the words “Monte Carlo” are often over-loaded to mean “Monte Carlo Shower evolution”.

Simulating an ATLAS Event



Tree Level Simulations

$$u\bar{u} \rightarrow Z/\gamma^* \rightarrow e^+e^-$$

- fictitious 45 GeV u-quark collider
  - predict the electron distributions.
- 20 minute homework:
  - roll cos θ, φ randomly (not necessarily flat)
  - plug them into the squared matrix element
    - $$d\hat{\sigma} = \frac{1}{2\hat{s}} \left| M(u\bar{u} \rightarrow Z \rightarrow e^+e^-) \right|^2 \frac{d\cos\theta \, d\phi}{8(2\pi)^2}$$
  - ***Event Integrator***:
    - histogram each event with weight dσ(cos θ, π)
  - ***Event Generator:***
    - if $d\sigma(\cos\theta, \pi)/d\sigma_{MAX} > g$, accept the event, and histogram it with weight +1.
    - Produces "events" with the distribution predicted by the theory (e.g. *the frequency we expect them to appear in nature*).

Exact leading order result.
(not exact or correct!)

Misnomer:
NLO ←→ "Exact"

2 DoF: cosθ φ

Tree Level Simulations

$$u\bar{u} \to Z/\gamma^* \to e^+e^-$$

- you can't make a living doing this type of calculation anymore.
  - symbolic matrix element generators have taken over
    - MADGRAPH, COMPHEP, AMEGIC++, GRACE, OMEGA
      - try MADGRAPH online at: http://madgraph.hep.uiuc.edu/, it's fun!
      - e.g. u u~ > e+ e- gives you the Feynman diagrams and squared matrix elements for this process.

Tree Level Simulations & PDFs

$$pp \rightarrow u\bar{u} \rightarrow Z/\gamma^{*} \rightarrow e^{+}e^{-}$$

$$d\sigma = f_q(x_{1,}Q^2)\, f_{\bar{q}}(x_{2,}Q^2)\, d\hat{\sigma}(\cos\theta,\phi)\, dx_1 dx_2$$

4 DoF: cosθ, φ, x1, x2

- (we should be summing over all parton species)
- The parton density functions encapsulate the non-perturbative part of the theory.
  - we don't know how to calculate them. So we measure them.
  - WARNING:
    - The interpretation of the measurements depends crucially on what has gone into the simulation: LO, NLO(MSbar), NLO(dis).
    - The PDF you choose MUST match the factorization strategy used in your calculation.
- You still can't make a living doing these calculations, but you can make a living measuring the PDFs.
  - PDFs aren't boring.
  - ATLAS needs people who DON'T think PDFs are boring.

Tree Level Overview

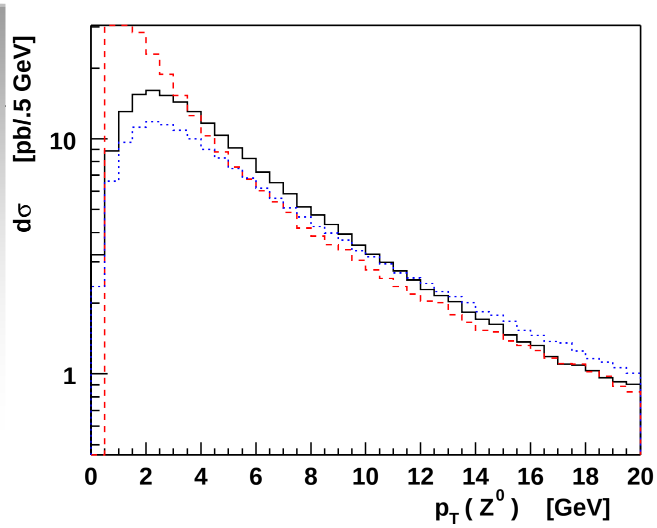
- Leading order matrix element calculations describe explicit, many-particle topologies
  - Well-separated partons
  - Full spin correlations
  - Color flow
- Many computer programs
  - Different approaches to the same problem
    - Analytic vs Numeric
    - Matrix Element vs Phase Space

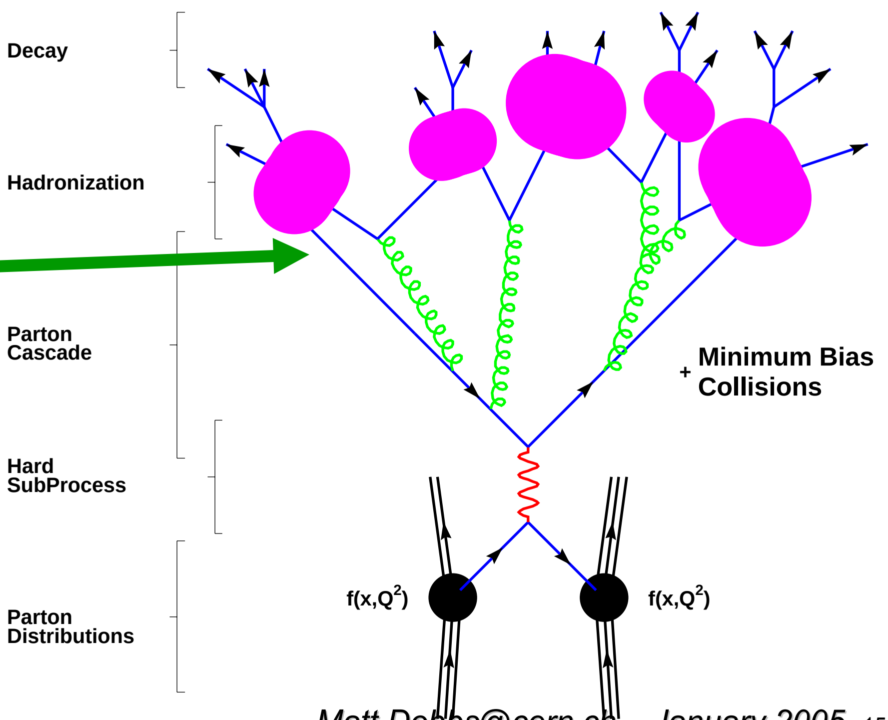
- CompHep
  - SM + MSSM + editable models
  - Symbolic evaluation of squared matrix element
  - 2 $\rightarrow$ 4-6 processes with all QCD and EW contributions
  - color flow information
  - outputs cross sections/plots/etc.
- Grace
  - similar to CompHep
- Madgraph
  - SM + MSSM
  - helicity amplitudes
  - "unlimited" external particles (12?)
  - color flow information
  - not much user interface (yet)
- Alpha + O'Mega
  - does not use Feynman diagrams
  - gg$\rightarrow$10 g (5,348,843,500 diagrams)

This slide from S. Mrenna.

But what about $P_T(Z)$??

- QCD corrections provide a kick or recoil to the Z
- simulate this with:
  - "exact" N^nLO event integrators
  - analytic resummation (inclusive)
  - parton shower (exclusive) event generators
    - PYTHIA, HERWIG, SHERPA, ISAJET

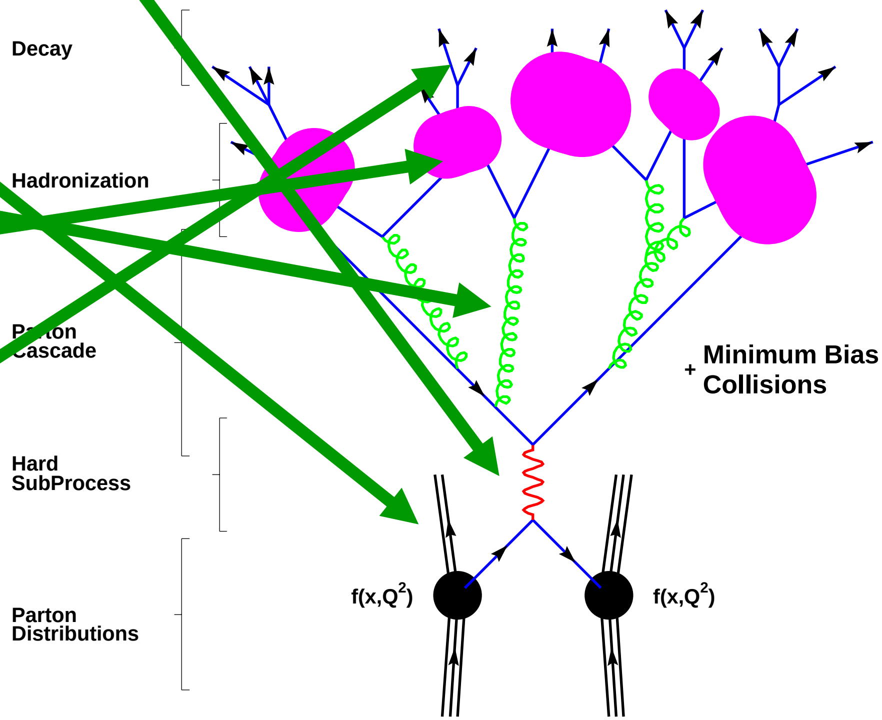




Showering & Hadronization Generators

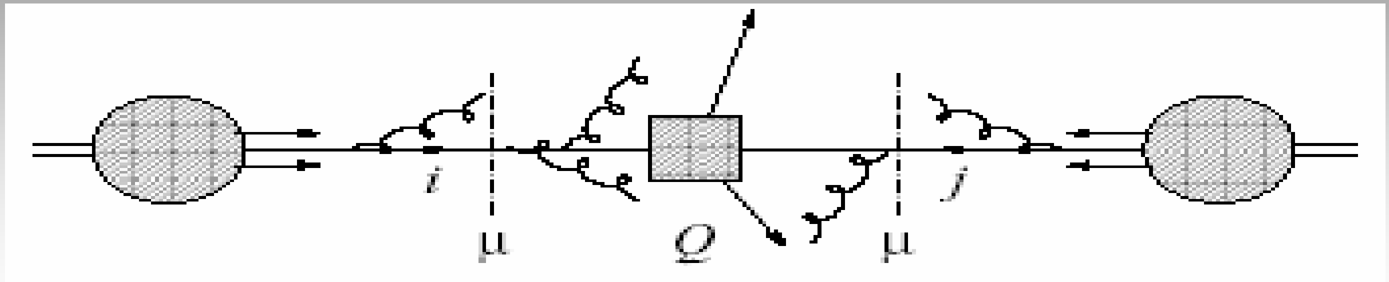
SHG event generators Components

- select a hard process topology based on hit and miss + PDFs
- Add an underlying (non-pertubative) event
  - + multiple interactions
- `evolve' the partons through initial and final state parton showers
  - QED showers too
- Hadronize soft partons into colour singlet hadrons
  - PYTHIA = string model
  - HERWIG = cluster model
- Decay resonances
  - external decay packages can be plugged in: Tauola, Photos, EVTGEN



today I'm focusing on the perturbative QCD part.

The Parton Shower Approach



this figure: B. Webber, 1999 CERN QCD Academic Training

(Pythia, Herwig, Isajet)

- **Sudakov** form factor

$$\Delta_i(Q^2) = \exp\left[-\sum_{jk}\int_{Q_0^2}^{Q^2}\frac{dq^2}{q^2}\int dz\,\frac{\alpha_S}{2\pi}\hat{P}_{i\to jk}(z)\right]$$

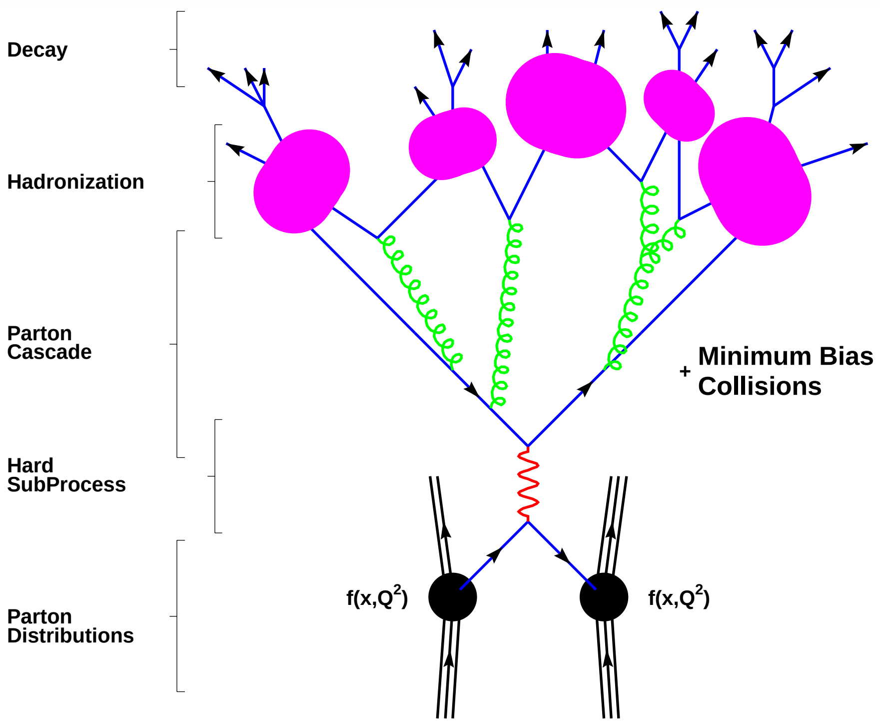
- sums all orders in towers of logarithms (LL, almost NLL)
- easily formulated as Monte Carlo
- initial state: backwards evolution, space-like branchings
  - PDFs enter(!)
- sums enhanced virtual-loop contributions to all orders via unitarity (sum of branching and no branching probability is unity)
  - shower proceeds with unit probability

Simulating QCD Corrections

2 common approaches

Showering event Generators

(Pythia, Herwig, Isajet)



Next-to-leading order

“event integrators”

Matt.Dobbs@cern.ch **Diboson Feynman Graphs at NLO** *LaTeX-ed on June 18, 2001* 3

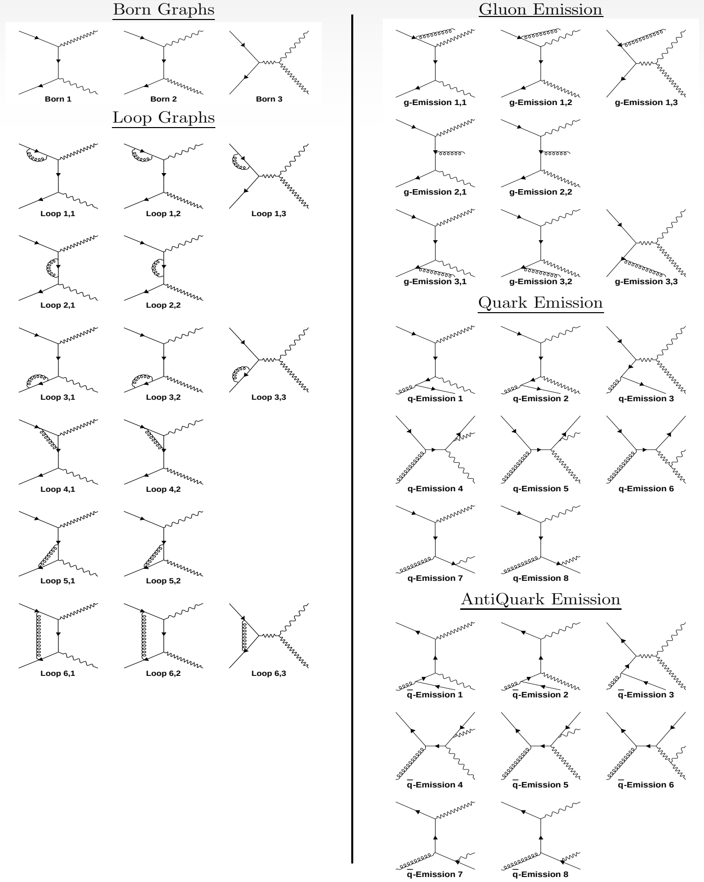
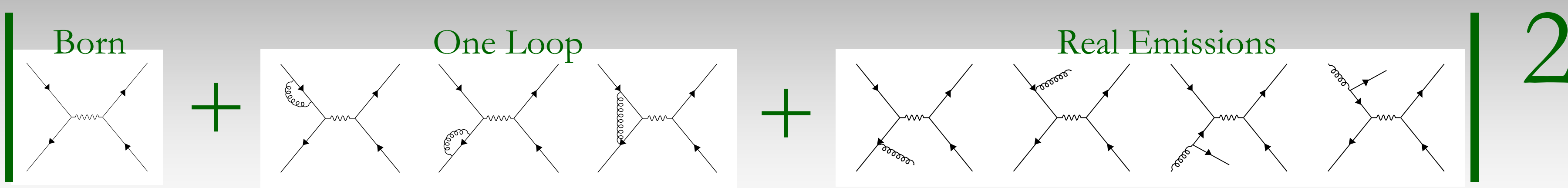


Figure 1: Feynman graphs contributing to hadronic diboson production at NLO.

NLO 'event integrators' $pp \rightarrow Z+X \rightarrow l^+l^- + X$



$$\sigma_{\mathrm{NLO}} \propto \underbrace{\overbrace{\mathcal{M}^2_{\mathrm{Born}}}^{\mathrm{LO}} + \mathcal{M}_{\mathrm{Born}} \otimes \mathcal{M}_{\mathrm{OneLoop}}}_{\mathrm{n-body}} \;\tilde{+}\; \underbrace{\mathcal{M}^2_{\mathrm{RealEmission}}}_{\mathrm{(n+1)-body}}$$

$$\overbrace{\mathcal{M}_{\mathrm{Born}} \otimes \mathcal{M}_{\mathrm{OneLoop}} \;\tilde{+}\; \mathcal{M}^2_{\mathrm{RealEmission}}}^{\mathrm{NLO}(\alpha_S) \equiv \mathcal{O}(\alpha_S{}^1)}$$

[Regularization scheme blurs the boundary between n-body & (n+1)-body]

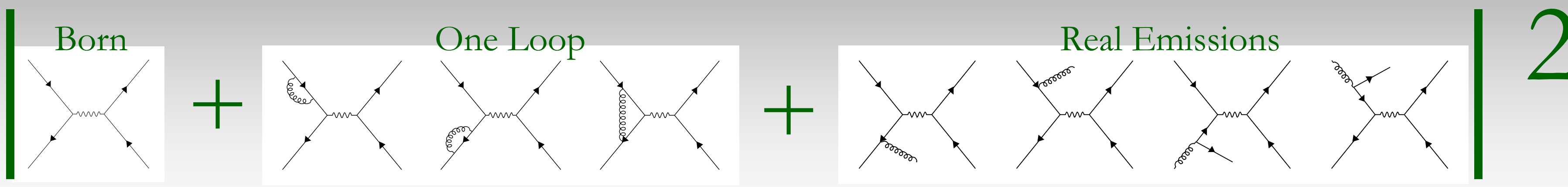
- Perturbative expansion goes like:

$$\frac{1}{\sigma}\frac{d\sigma}{dP_T^2} \cong \frac{1}{P_T^2} A_1 \alpha_s \ln\frac{M^2}{P_T^2} + A_2 \alpha_s{}^2 \ln^3\frac{M^2}{P_T^2} + A_3 \alpha_s{}^3 \ln^{2n-1}\frac{M^2}{P_T^2} + \ldots$$

- and becomes unreliable in the low P_T region as $\alpha_s \ln^2\frac{M^2}{P_T^2} \rightarrow 1$ and multiple gluon emission becomes important. (typically $P_T \approx 5$ GeV)

Most prominent example is MCFM. (Campbell & Ellis)

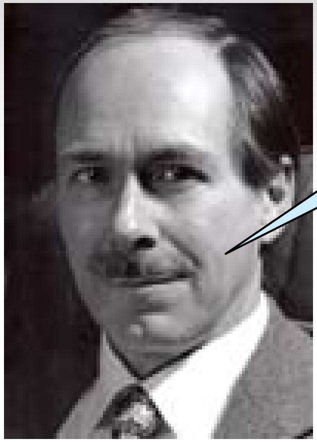
NLO 'event integrators' pp→Z+X→ l^+l^-+X



- Coding a "simple" process like Drell Yan at NLO isn't that difficult.
  - •Had you done it in 1979, you would have got tenure,
  - •now (with guidance from the literature) you can do it as homework in about a week.
    - An excellent step-by-step guide is:
      - •**THE TWO CUTOFF PHASE SPACE SLICING METHOD**, Harris and Owens hep-ph/0102128 v3.

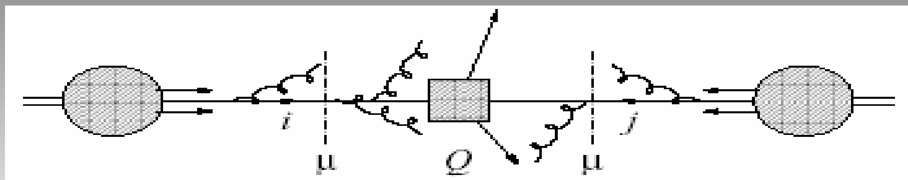
I predict
5.5 + ∞ -∞
events.

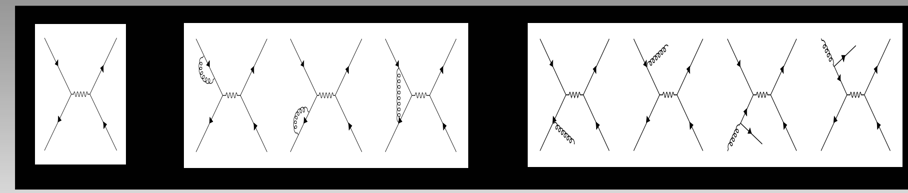
- What's the big deal?



- Experimenters have known how to avoid singularities for half-a century, why can't theorists do it?

Simulating QCD Corrections





Showering Event Generators

- ☺ exclusive prediction → you get the whole event record
- ☺ all orders approximation of multiple emissions
- ☺ valid in soft/collinear emission regions
- ☹ not accurate for hard, well separated partons
- ☹ normalization is LO

NLO Matrix Elements

- ☺ good prediction of hard central emissions
- ☺ best prediction of total X-section
- ☹ one order in αS

  → at most one "jet"
- ☹ fixed order perturbation is not valid for small PT(JET)
- ☹ event weights are negative (unphysical) in some phase space regions

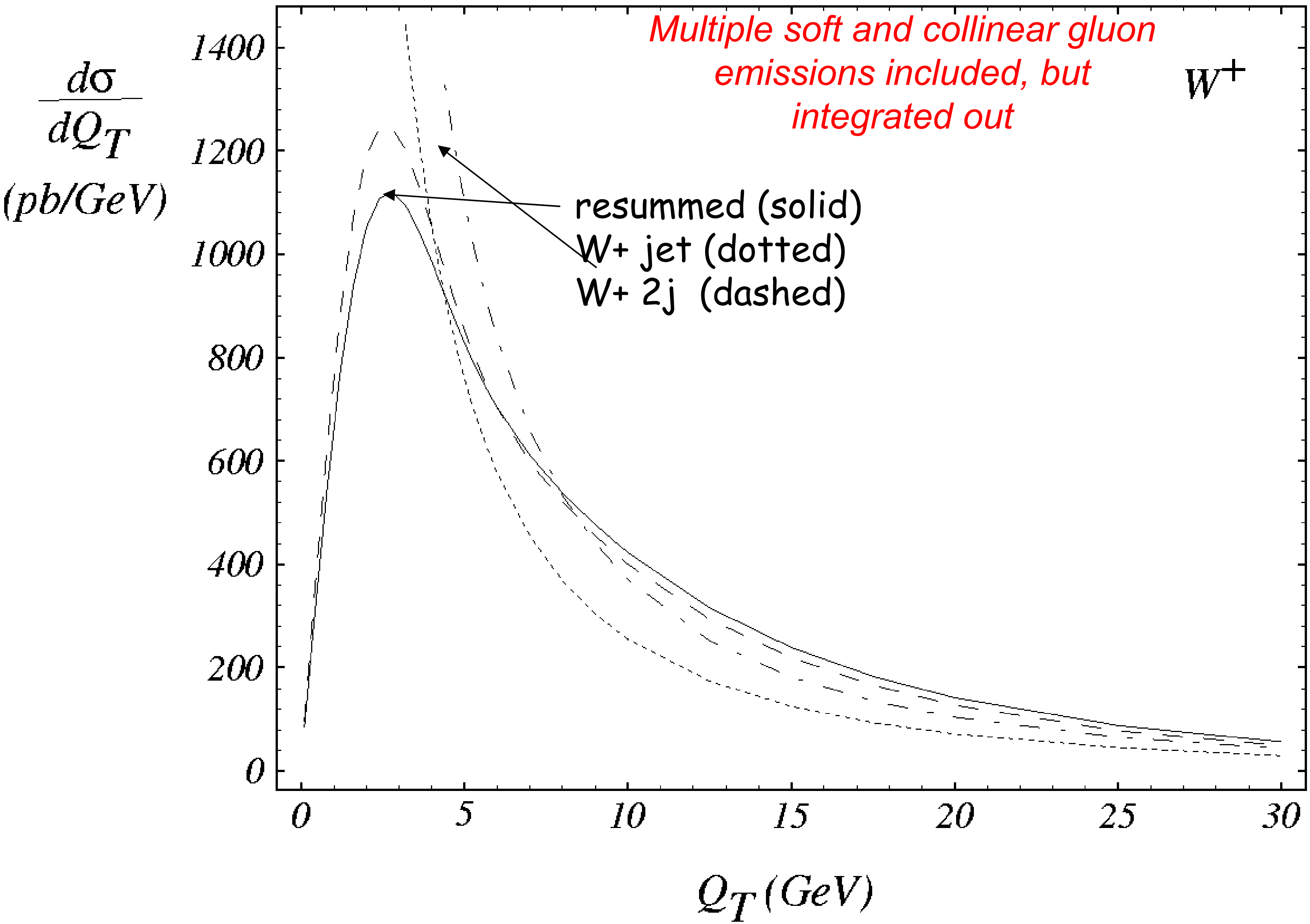
→ Complementary approaches ←

Analytic Resummation

- For certain distributions we can be clevor, and find that the leading logarithms in the infinite perturbative expansion exponentiates under certain conditions (e.g. when the emissions become collinear).
  - This allows us to resum that part of the perturbative expandion.
- sum the leading logarithms (or NLL) to all orders in perturbation theory for a particular observable (e.g. for $P_T(Z)$)
  - There is no event record. (inclusive!) Output is a distribution.
  - There is nothing to pass through detector simulation.
    - use it to correct theoretical distributions
    - or compare detector effects removed expt distributions

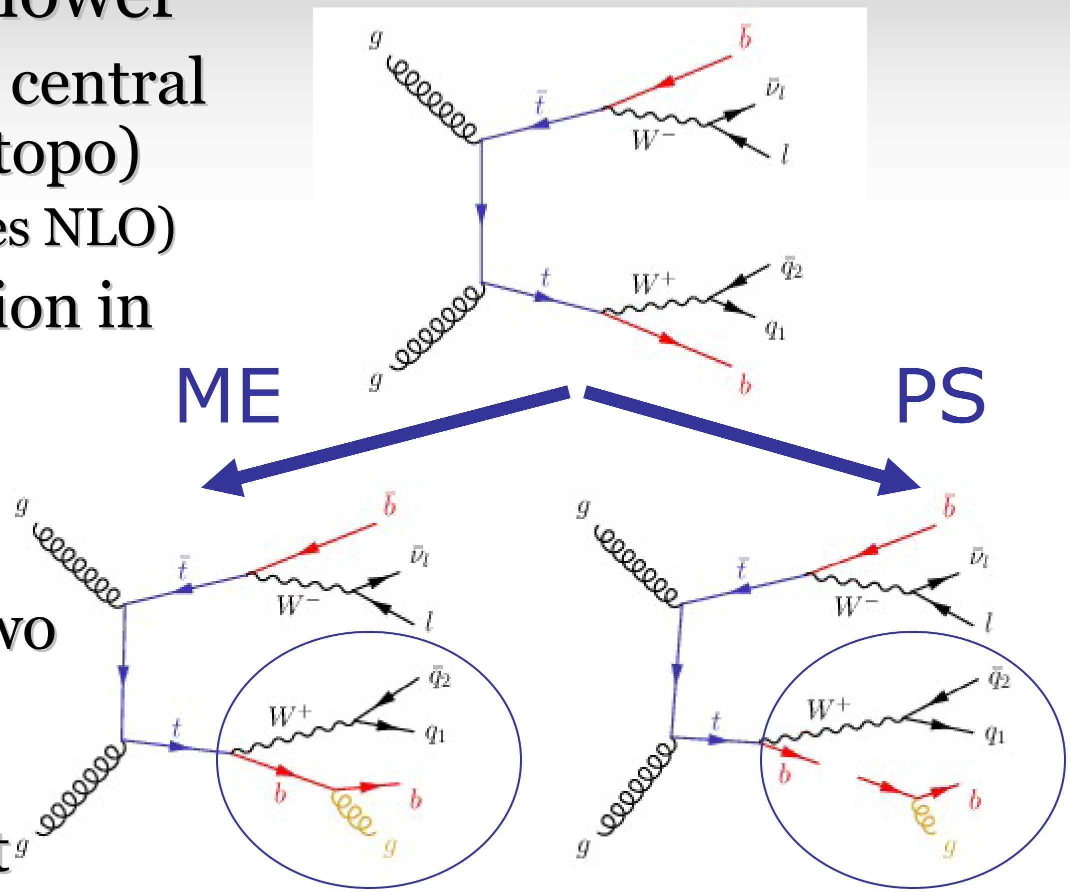
$$\frac{1}{\sigma}\frac{d\sigma}{dP_T^2} \cong \frac{1}{P_T^2} A_1 \alpha_s \ln\frac{M^2}{P_T^2} + A_2 \alpha_s^{\,2} \ln^3\frac{M^2}{P_T^2} + A_3 \alpha_s^{\,3} \ln^{2n-1}\frac{M^2}{P_T^2} + \ldots$$

Analytic Resummation



Matrix Elements vs. Parton Shower

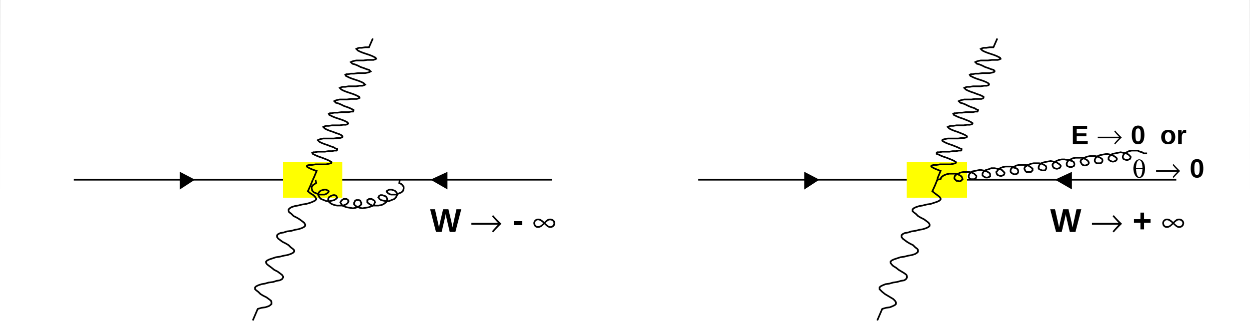
- ttj production: Matrix element vs. parton shower
  - ME: correct for hard, central emissions (exclusive topo)
    - (soft, collinear requires NLO)
  - PS: good approximation in soft, collinear regime (inclusive topo)
- WARNING:
  - you can't add these two simulations together.
  - Classic mistake = pp→W + pp → W+jet



figures from B. Kersevan

Challenges in combining NLO M.E. with the showering approach

1. Negative Weights



- Distinct final states need to be summed to avoid divergences
- regularization scheme → events frequently have negative weight
  - **implies: weighted events only**
    →but unweighted event needed for genuine simulation of expt data
  - **high statistics needed to effect the cancellations**
    →makes CPU intensive hadronization & detector simulation difficult

Challenges in combining NLO M.E. with the showering approach

1. Negative Weights

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Initial state radiation in simulations of vector boson production at hadron colliders

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Abstract

The production of vector bosons at present and future hadron colliders will provide a crucial test for QCD and Standard Model physics. In this paper we improve parton shower simulations of

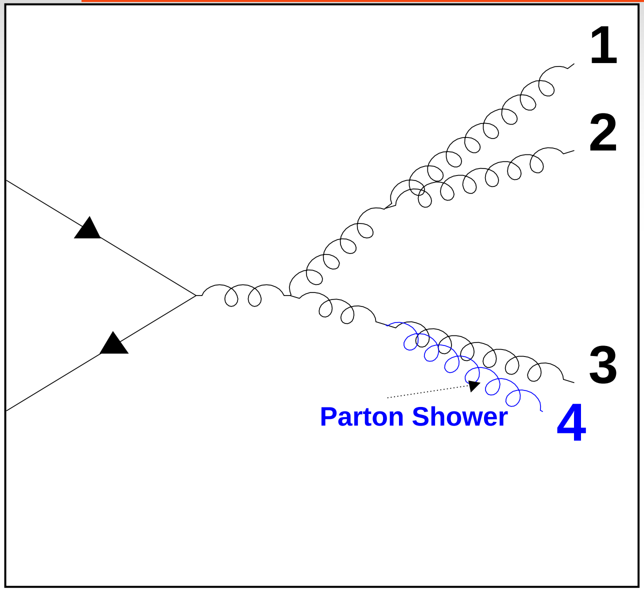
It is worth recalling that at present no Monte Carlo program including the full next-to-leading order (NLO) results exists, as it is not known how to set up a full NLO calculation in a probabilistic way. When providing parton showers with matrix-element corrections we still only get the leading-order normalization, because in the initial-state cascade we only include leading logs and not the full one-loop virtual contributions.

1\.

The production of vector bosons $W^{\pm}$, Z^0 and γ^* [1–3] in high energy hadronic collisions is one of the most important processes that should be investigated in order to

Challenges in combining NLO M.E. with the showering approach

2. Double Counting



Consider QCD 2→3 with a parton shower

Consistent when $E_1, E_2, E_3 > E_4^{PS}$

but, i.e. when $E_4^{PS} > E_2$ then E_4^{PS} should have been used in the matrix element to calculate the event weight

- **The NLO calculation yields *two* classes of events**

  (those with and those without an emission)

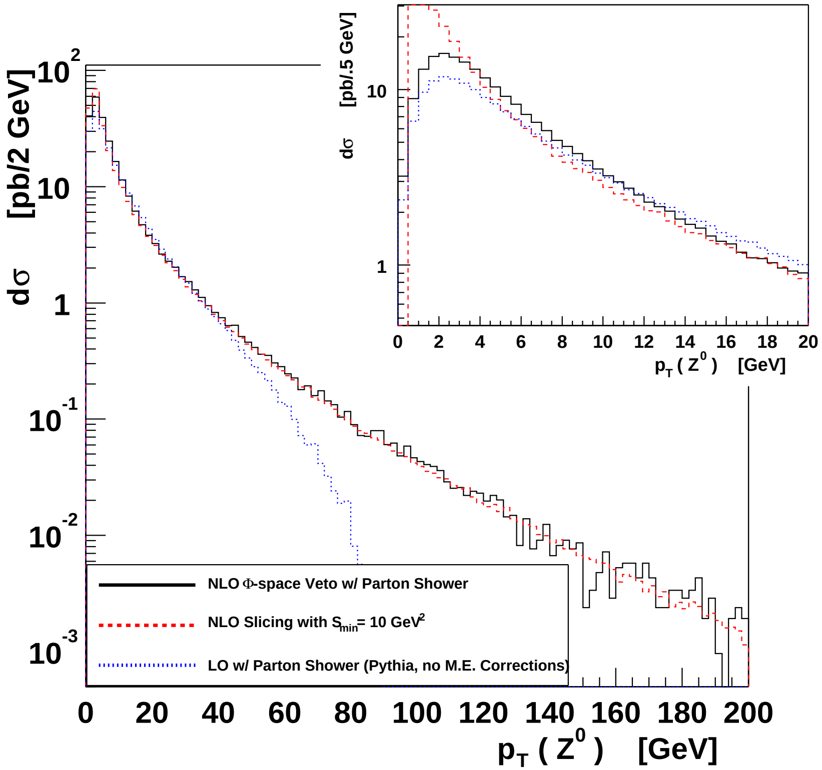
- **The parton shower can violate the boundary,**

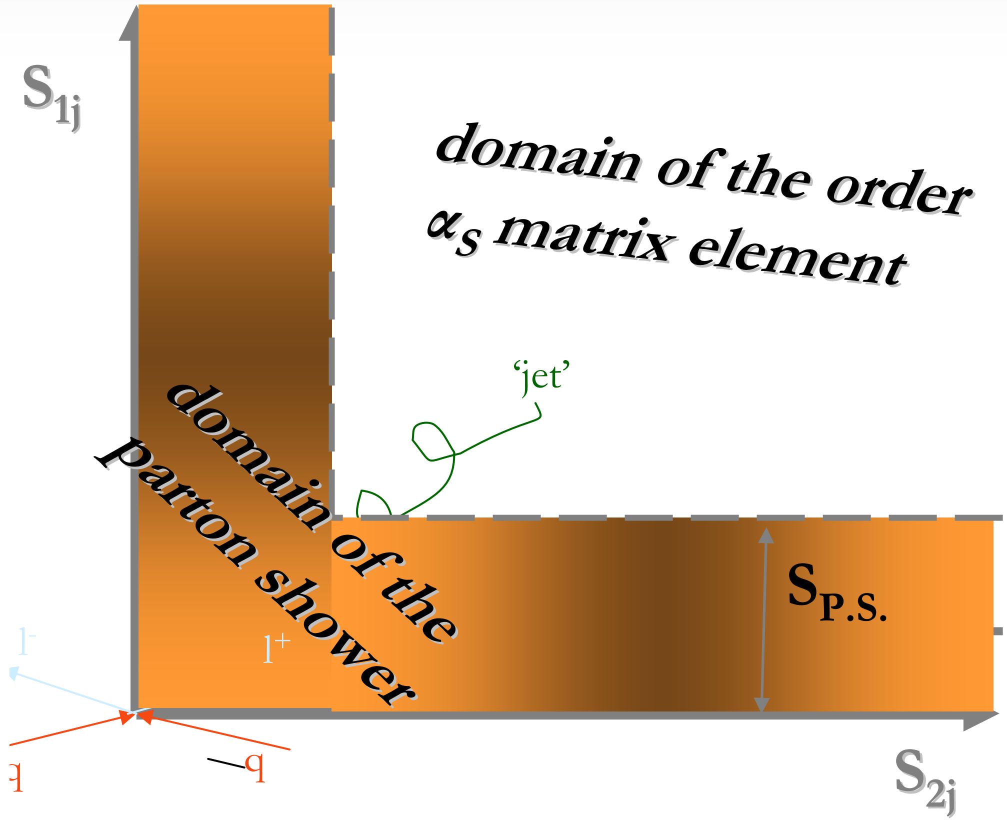
  producing an emission which should have been sampled by the matrix element.

Phase Space Veto Method

- our description of the hard central region is dominated by the NLO matrix elements
- ideally, we want the small P_T region to be the domain of the Parton Shower

Dobbs, Phys RevD64, 0904011, 2002.



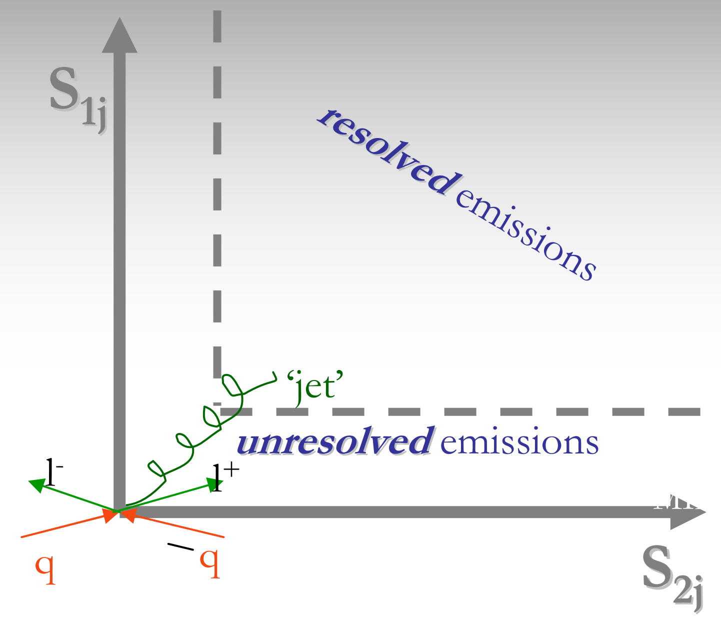


NLO 'event integrators' $pp \rightarrow Z+X \rightarrow l^+l^-+X$

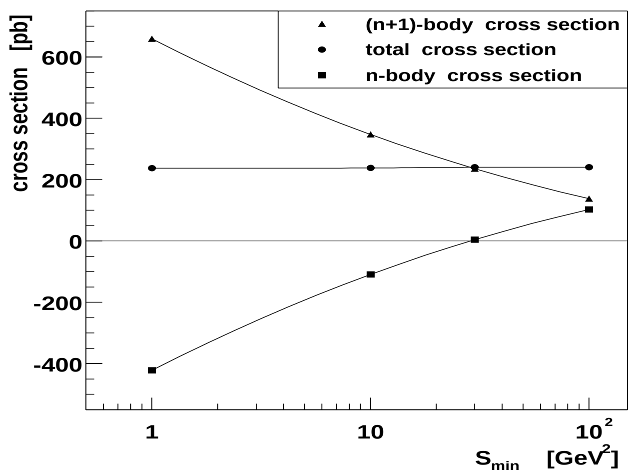
Regularization scheme example:

Phase Space Slicing

("S_{MIN} slicing")



- partition phase space:
  - **resolved** region: integrated numerically
  - **unresolved** region: integrated analytically
- programmed as two separate generators
- cross section is independent of our S_{MIN} choice



$$\sigma^n(S_{MIN}) + \int_{s_{ik}>S_{MIN}} \sigma^{n+1}(\Phi_{+1})\, d\Phi_{+1} = \text{Const}$$

→ **can choose (almost) any S_{MIN} we like.**

MC@NLO

(Frixione & Webber)

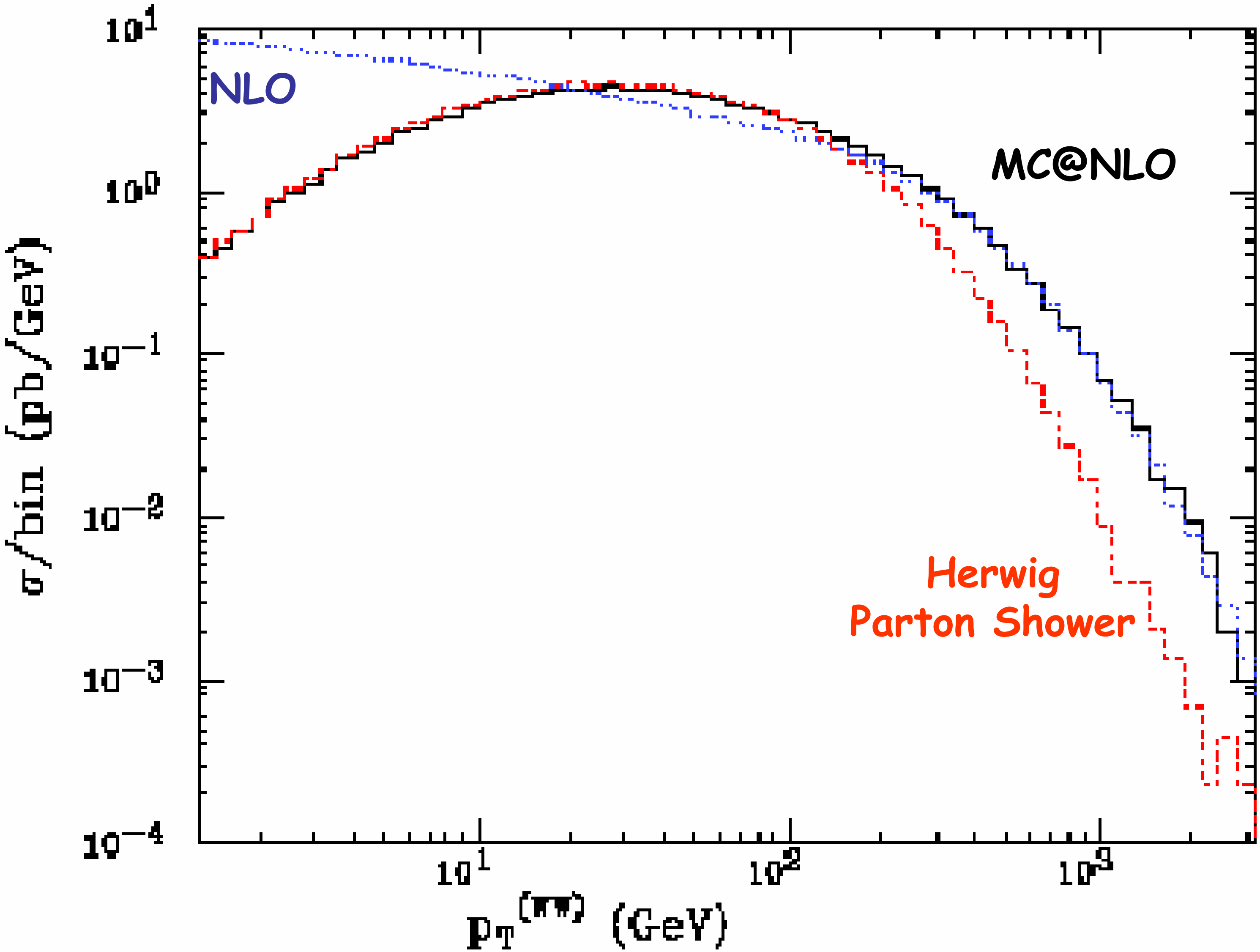
- Full NLO included in the hard subprocess
  - WARNING: event weights can be +1 (~85%) or -1 (~15%).
    - can be problematic when dealing with small numbers of events and detector simulation.
  - uses a modified subtraction technique.

- The first emission of the parton shower is corrected, such that it is exactly NLO.
  - additional emissions are ordered, such that no double counting occurs.
  - This means that the matrix elements “know” about the shower and vice versa (i.e. you cannot plug in a pythia shower).

  → result is a prediction which is everywhere >= NLO and parton shower accuracy for soft/collinear emissions.

- pp→ WW WZ ZZ, bb, tt, H, W, Z, γ
  - WARNING: no decay correlations for VV or tt products.

MC@NLO pp→WW



Outlook

- The MC world is complicated, and nothing can be treated reliably as a black box.
  - it's the experimenter's responsibility to know her tools.
- Our measurements rely crucially on MC generators.
- Huge amount of progress in MC generators in last several years
  - mostly accomplished by a few authors on a shoestring
- most notable developments:
  - automatic matrix element generators
  - combined NLO + showering programs.

Quiz

- T or F: LL is better than LO ?
- T of F: NLO ≡ NLL ?
- Elliot says, "I've assessed the PDF error by reweighting my pythia events with a different PDF."
  - What cross check should he do?
- Joanne says, "My backgrounds have a contribution of 300 W events and 500 W+jet events, as estimated from Pythia"
  - what do you tell her?
- Joe says, "I've got the NLO code for pp → WW+X, I just need to put it in pythia for the shower."
  - what do you tell him?