



Event generator physics for the LHC

Mike Seymour
University of Manchester

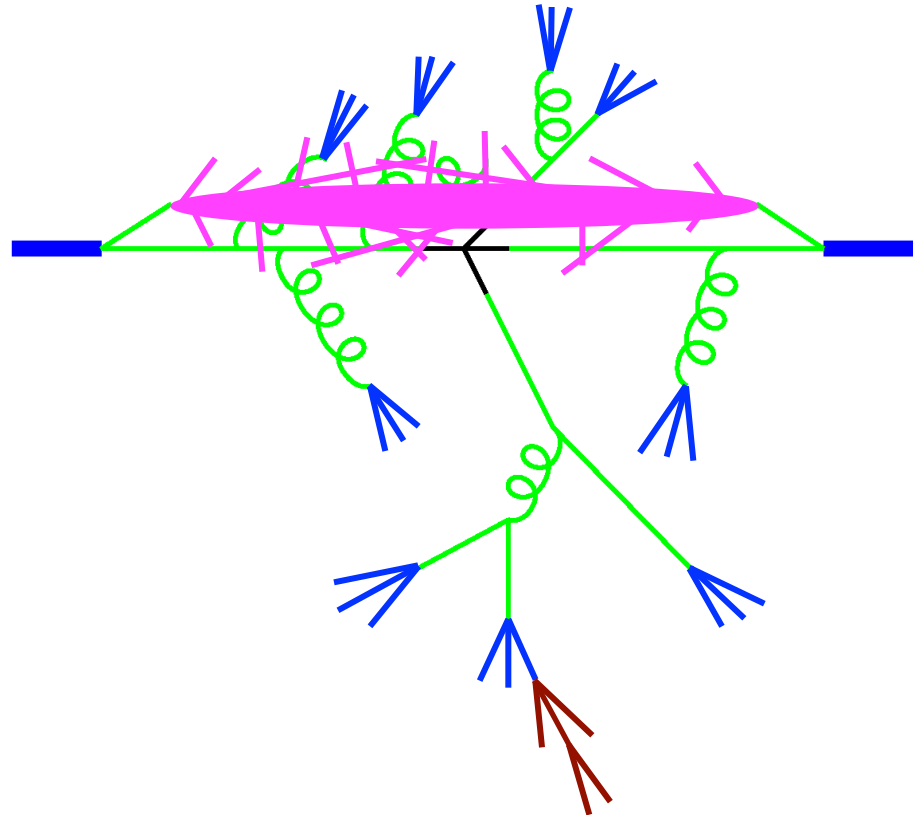
LPCC Summer Institute on LHC Physics
10th August 2011, CERN

Event generator physics for the LHC

1. Event generator overview
2. Progress in underlying event/soft inclusive physics
3. Progress in parton showers/colour evolution

Structure of LHC Events

1. Hard process
2. Parton shower
3. Hadronization
4. Underlying event
5. Unstable particle decays



Event Generators

- “Current” general purpose event generators:
 - Pythia8
 - Herwig++
 - Sherpa
- “Legacy” support for previous generation:
 - Pythia6
 - HERWIG(+Jimmy)
- Many specialized codes
 - MC@NLO, Powheg
 - VINCIA, Ariadne, Cascade, PhoJet, ...

Related programs

- Matrix element tools
 - Madgraph, ALPGEN, HELAC, CompHEP, ...
 - SanC, Grace, ...
 - MCFM, NLOJET++, BlackHat, Rocket, ...
 - aMC@NLO, PowHEG Box, ...
- Secondary decay packages
 - TAUOLA, PHOTOS, EvtGen, ...
- Validation/tuning/visualization tools
 - Rivet, Professor, mcplots

Menu

- [Front Page](#)
- [Update History](#)
- [Test4Theory](#)
- [Generators and Versions](#)

Beam: pp/ppbar ee

Jets : Di-jet $\Delta\phi$

Generator Group: Main [Herwig++](#) [Pythia 6](#) [Pythia 8](#) [Vincia](#)
Generator Subgroup:

pp @ 7000 GeV

Jets

- [Transverse Minor](#)
- [Transverse Thrust](#)
- [Di-jet \$\chi\$](#)
- [Di-jet \$\Delta\phi\$](#)
- [Di-jet mass](#)
- [Jet Fragmentation](#)
- [Differential shape](#)
- [Integral shape](#)
- [d \$\sigma\$ \(jet\)/dpT](#)

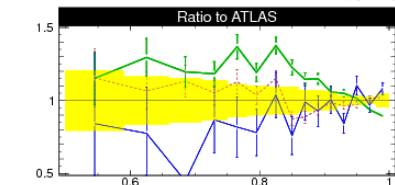
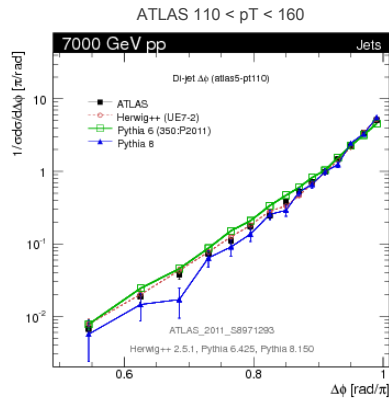
Underlying Event

- [<pT> vs Nch \(AWAY\)](#)
- [<pT> vs Nch \(TRNS\)](#)
- [<pT> vs Nch \(TWRD\)](#)
- [<pT> vs pT1 \(AWAY\)](#)
- [<pT> vs pT1 \(TRNS\)](#)
- [<pT> vs pT1 \(TWRD\)](#)
- [<Nch> vs \$\Delta\phi\$](#)
- [<Nch> vs \$\eta\$](#)
- [<Nch> vs pT1 \(AWAY\)](#)
- [<Nch> vs pT1 \(TRNS\)](#)
- [<Nch> vs pT1 \(TWRD\)](#)
- [dNch/dpT \(TRNS\)](#)
- [<pT> vs \$\Delta\phi\$](#)
- [\$\sigma\$ \(Nch\) vs pT1 \(TRNS\)](#)
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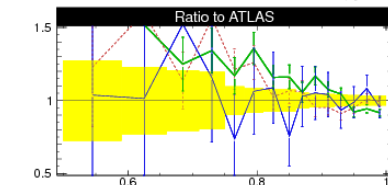
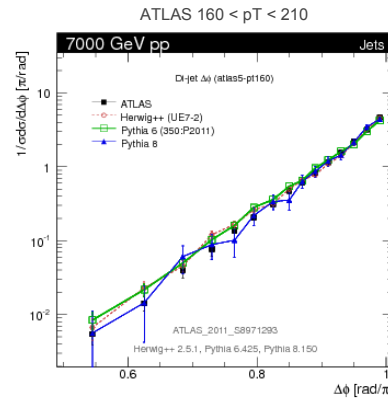
Minimum Bias

- [<pT> vs Nch](#)
- [\$\eta\$ Distributions](#)
- [Multiplicity Distributions](#)
- [pT Distributions](#)
- [\$\Sigma\$ \(ET\)](#)
- [\$\Sigma\$ \(ET\) vs Nch](#)
- [FB Correlations](#)
- [Identified Particles : pT](#)
- [Identified Particles : Ratios](#)

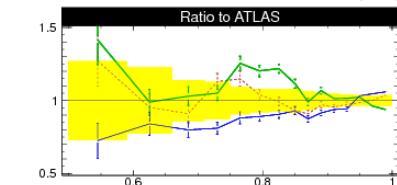
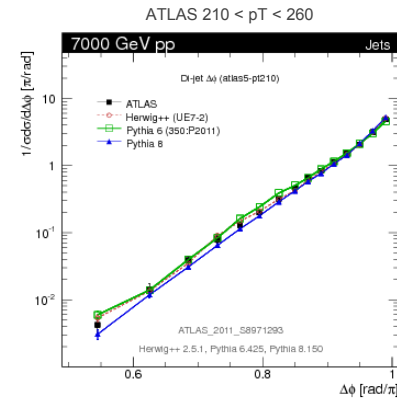
Z (Drell-Yan)



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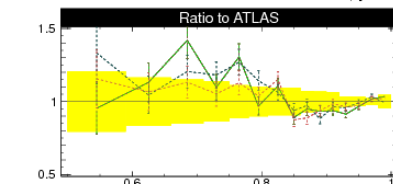
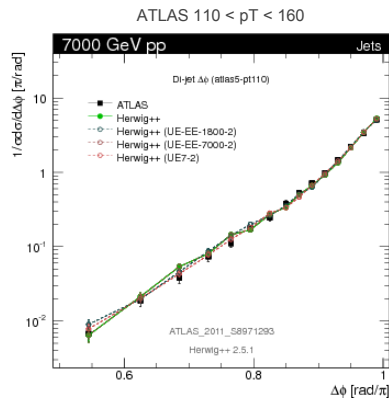
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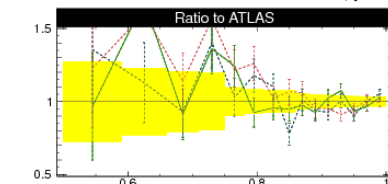
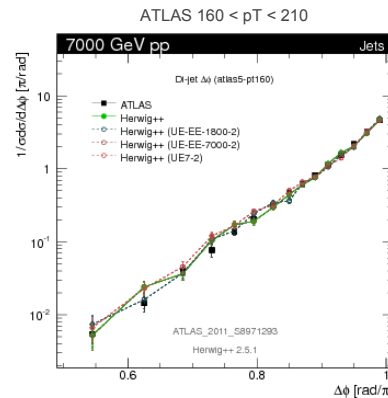
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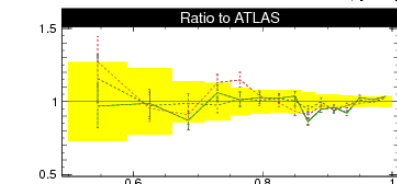
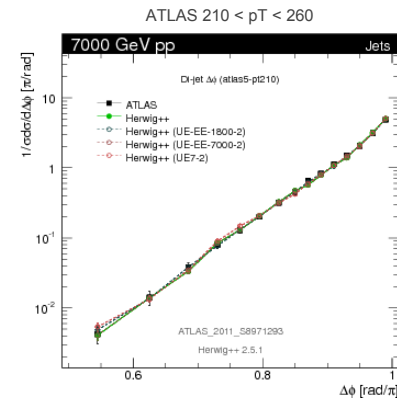
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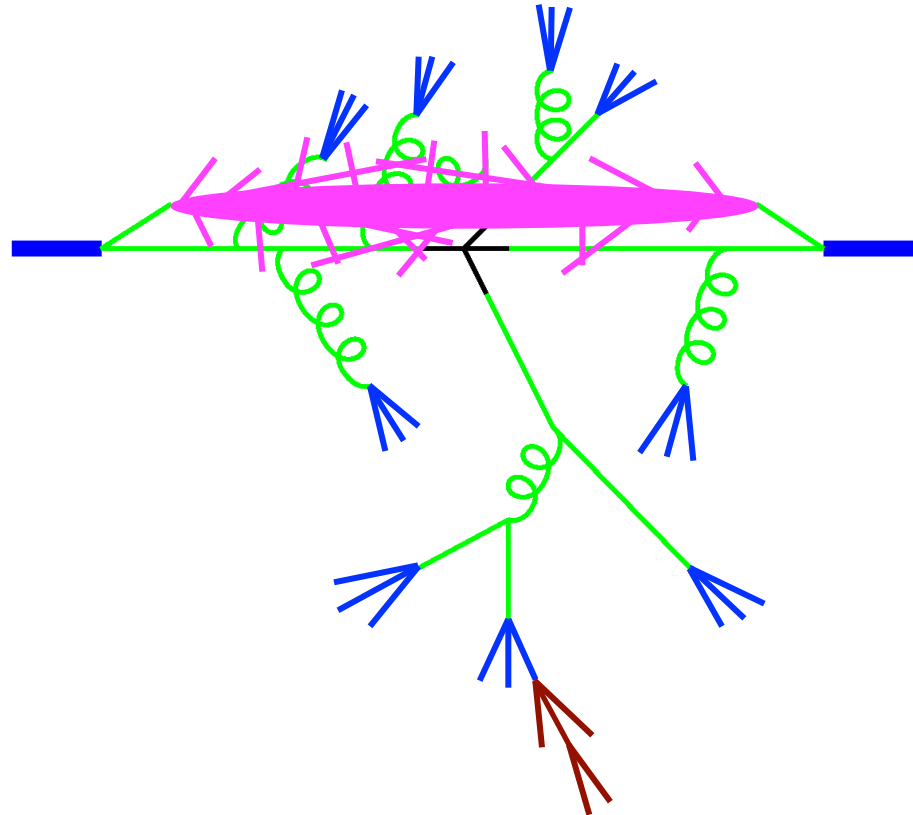
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Structure of LHC Events

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Hard process generation

- Tree-level matrix element automation: a solved problem
 - But efficiency improvements and generalizations always being made
 - Matching to parton showers without double-counting
 - MLM built in to Madgraph, Alpgen
 - CKKW-L automated in Sherpa, Herwig++
 - Crucial role of colour structure
 - Large N_c description good enough for precision physics?

• FeynRules
• Towards automated loop calculation

NLO hard process generation

- How to combine NLO calculation with parton shower without double-counting real emission?
- Solved by MC@NLO method:
 - Carefully extract analytical expression for parton shower emission
 - Use it as subtraction term for NLO calculation
 - Gives finite (but not positive definite) weights for “real” and “virtual” phase space points

MC@NLO

- Available for a wide variety of processes and very successfully used
- But...
 - Negative weights
 - Tied to a specific event generator algorithm
 - Inclusively corrects *an* emission to the next-order tree level matrix element (not necessarily hardest)
 - Is not able to correct major deficiencies in hard emission distribution of parton shower

MC@NLO

- Is not able to correct major deficiencies in hard emission distribution of parton shower

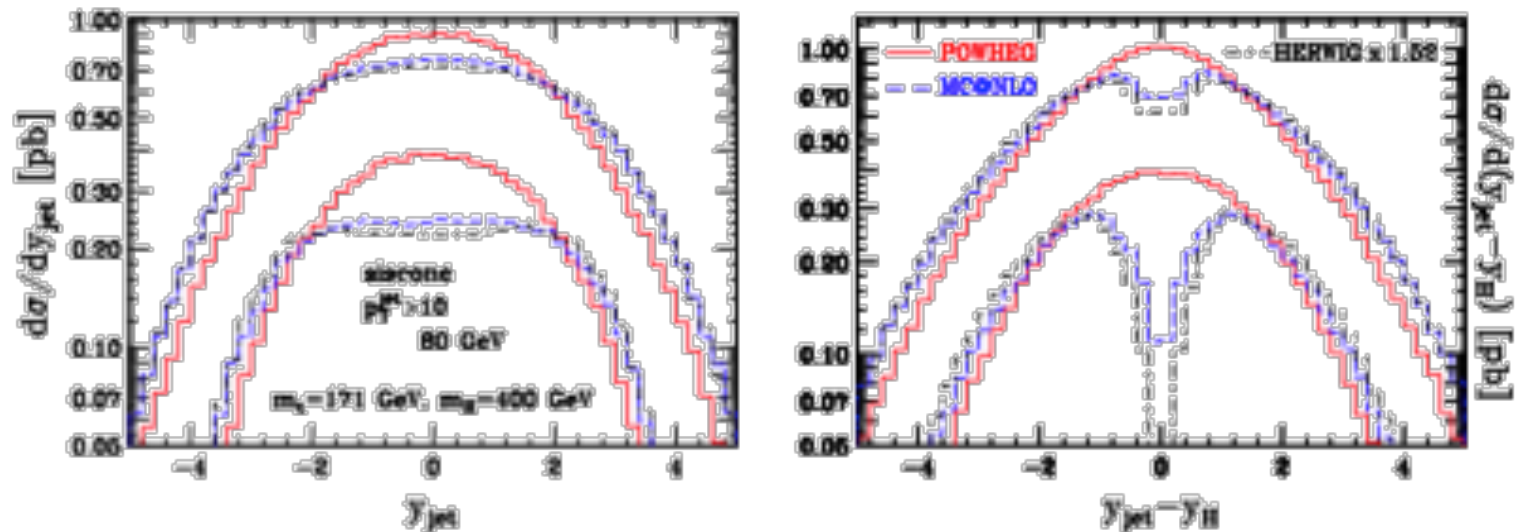


Figure 9: Comparison of POWHEG, MC@NLO and HERWIG (without matrix-element corrections), for the rapidity of the leading jet and the rapidity difference of the Higgs boson and the leading jet, defined according to the SISCONE algorithm, with different jet cuts.

Alioli, Nason, Oleari & Re, $gg \rightarrow H$, JHEP 0904(2009)002

MC@NLO

- Is guaranteed to reproduce next-order tree-level matrix element

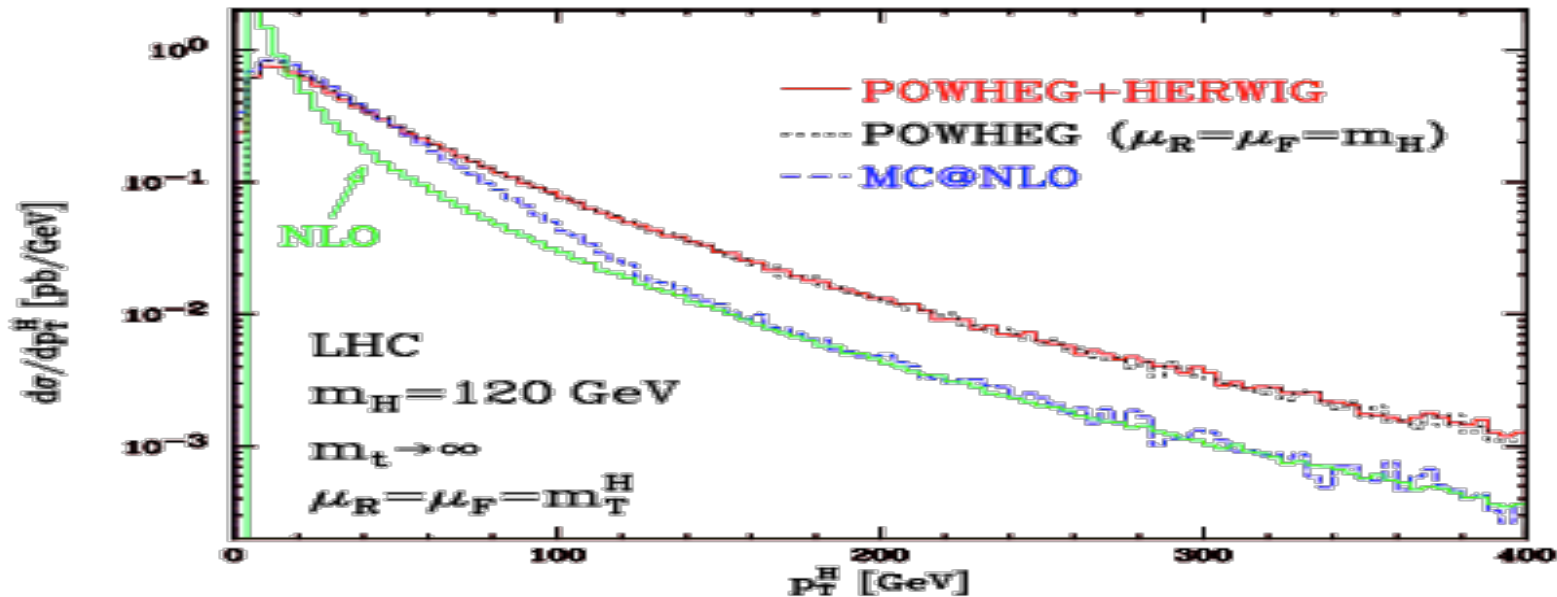


Figure 17: Comparison between POWHEG, MC@NLO and the NLO calculation, for $m_H = 120$ GeV at the LHC. All calculations are performed in the $m_t \rightarrow \infty$ approximation. Shower and hadronization are included in the MC results. The POWHEG result is also presented without shower and hadronization, and with a fixed-scale choice.

Alioli, Nason, Oleari & Re, $gg \rightarrow H$, JHEP 0904(2009)002

MC@NLO

- Is guaranteed to reproduce next-order tree-level matrix element

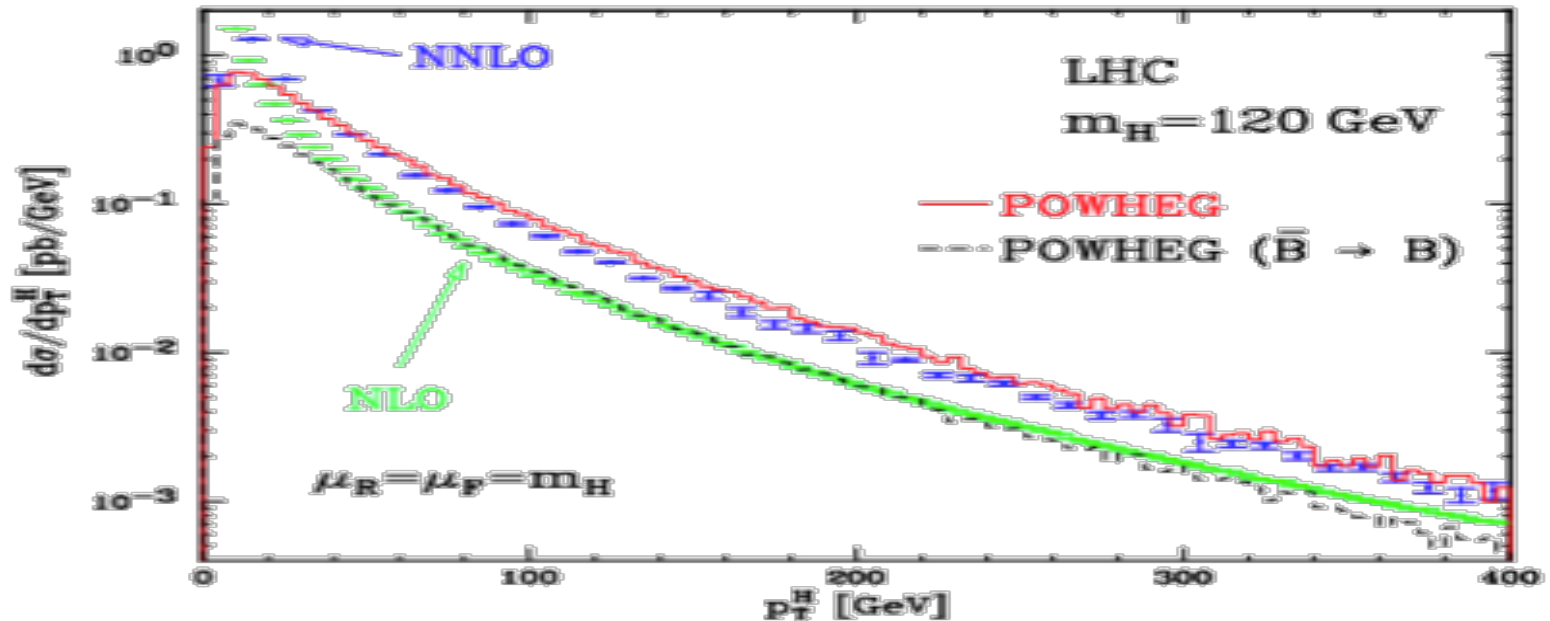


Figure 18: Comparison between POWHEG and fixed NLO and NNLO distributions for the transverse-momentum of the Higgs boson. Plots are done for $m_H = 120$ GeV at the LHC.

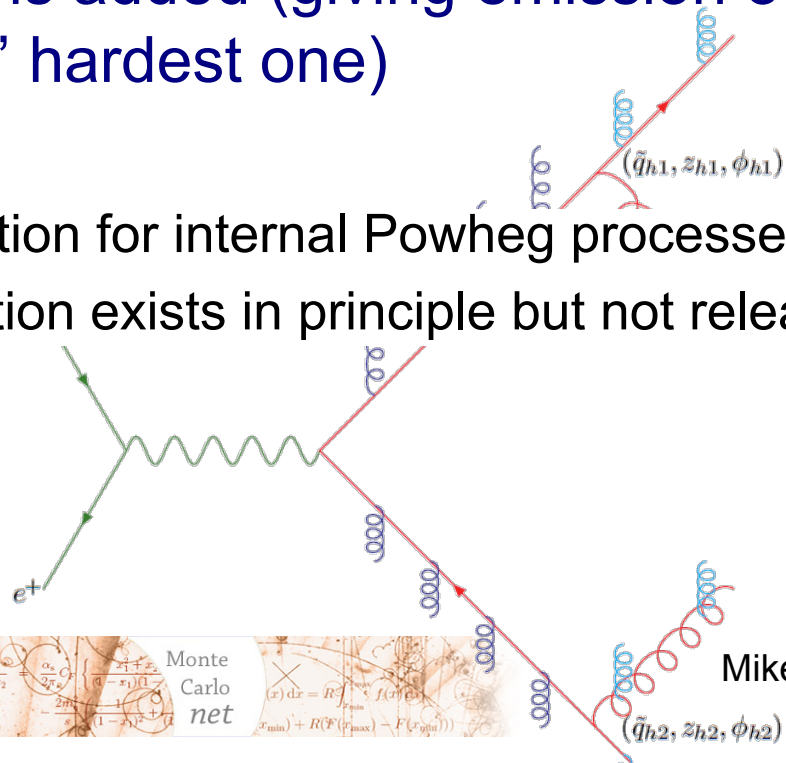
Alioli, Nason, Oleari & Re, $gg \rightarrow H$, JHEP 0904(2009)002

POWHEG

- Nason, JHEP 0411 (2004) 040
- Born configurations with NLO weight
- Hardest emission: exponentiated tree level ME
 - (Almost always) positive weight
 - Independent of shower algorithm
 - Hardest emission always given by ME
 - times inclusive K factor

Truncated shower

- Self-consistent implementation requires either
 - shower is k_t ordered (so POWHEG emission would have been first anyway)
 - or truncated shower is added (giving emission off internal lines 'before' hardest one)
 - Herwig++ status:
 - Working implementation for internal Powheg processes
 - General implementation exists in principle but not released

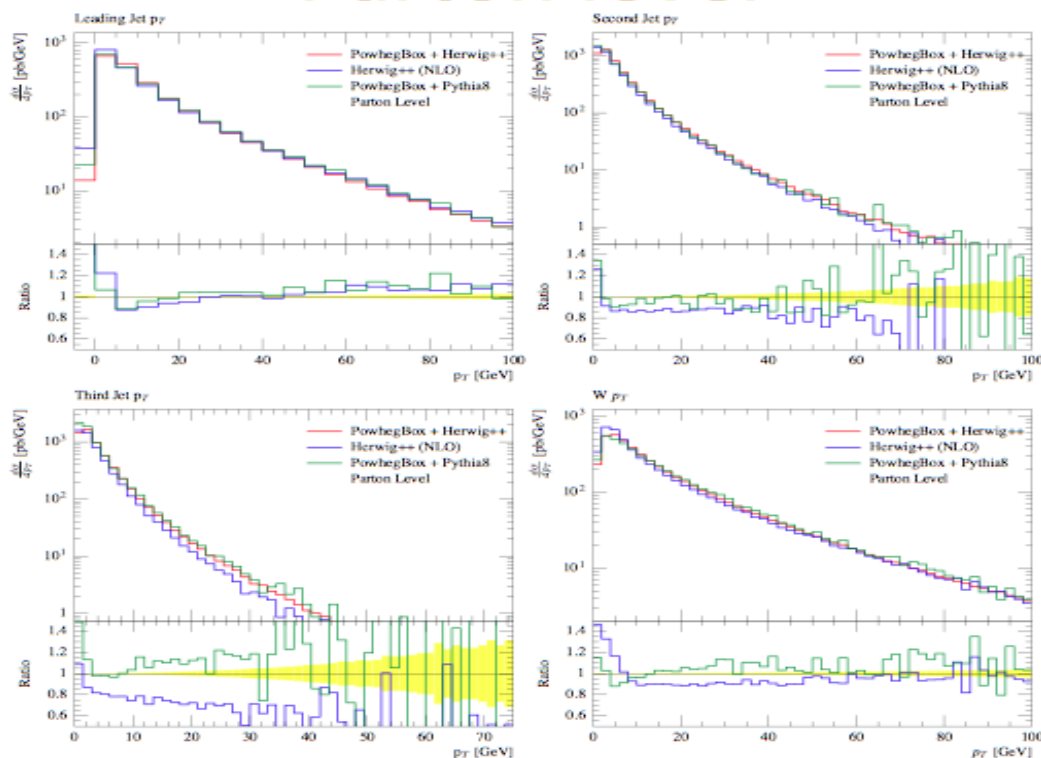


POWHEGs

- POWHEG method has become the method of choice for Sherpa and Herwig collaborations
 - $pp \rightarrow \gamma/W/Z/H/WH/ZH/WW/WZ/ZZ$
 - DIS, $pp \rightarrow VBF \rightarrow Hjj$
- POWHEG BOX (<http://powhegbox.mib.infn.it/>, Alioli, Hamilton, Nason, Oleari and Re) is a standalone implementation for even more processes, incl.
 - $pp \rightarrow$ dijets, $t\bar{t}b\bar{a}r$

Internal vs external Powhegs

Parton level



14/04/2011

Kiran Joshi

9

Internal vs external Powhegs

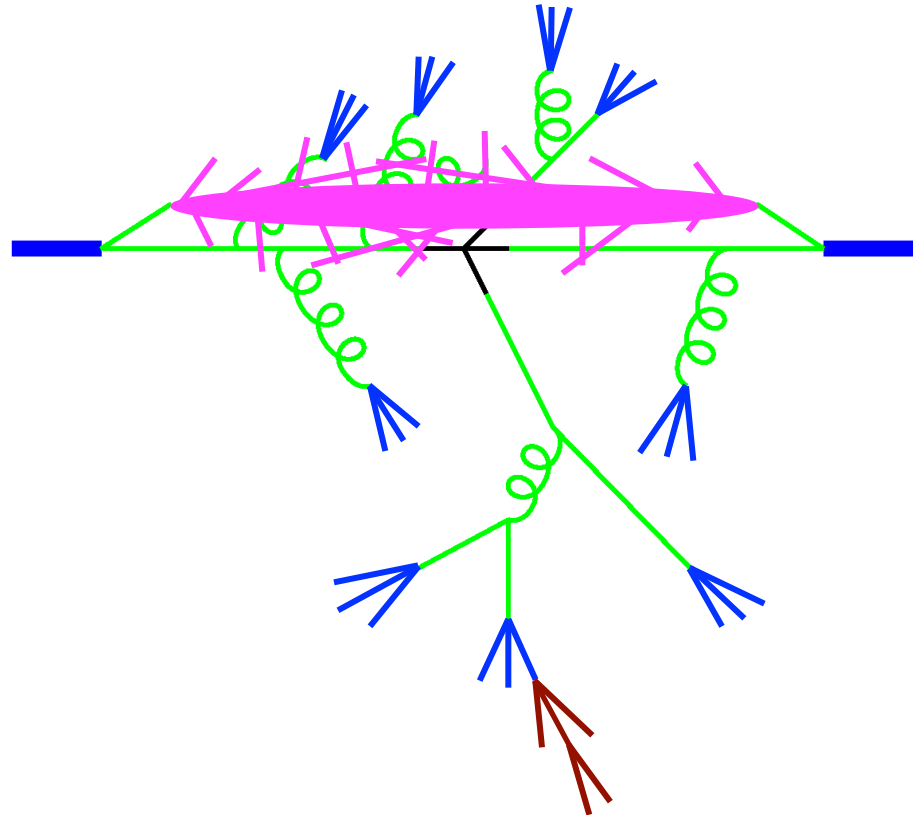
- Should agree exactly (up to corrections from truncated shower)
- Disagree by more than Pythia vs Herwig
- Not understood (not truncated shower)

MENLOPS

- Hamilton & Nason, JHEP 1006 (2010) 039
- Höche et al, JHEP 1104 (2011) 024
- Giele, Kosower & Skands, Vincia...
- Combines multi-jet matching with NLO matrix elements normalization from lowest-multiplicity cross section
- Step towards NLO multi-jet matching

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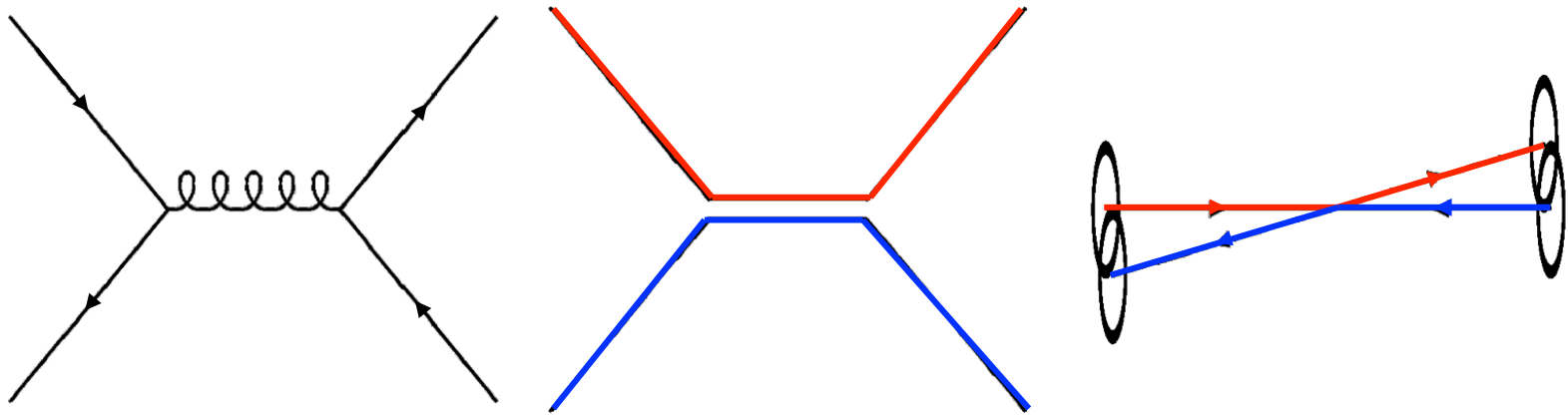
Parton showers

- Colour coherence long established as essential
 - angular-ordered parton showers (Herwig++ default)
 - k_t -ordered dipole/antenna showers (Ariadne, Pythia6 default, Pythia8, Sherpa, Herwig++ experimental, ...)
 - Dokshitzer & Marchesini (JHEP 0903 (2009) 117) cast some doubt on the validity of dipole showers
 - Nagy & Soper, JHEP 0905 (2009) 088
 - Skands & Weinzierl, Phys. Rev. D79 (2009) 074021
 - Plätzer & Gieseke, JHEP 1101 (2011) 024
 - Giele, Kosower & Skands, arXiv:1102.2126

conclude that problem was E-ordering, not dipoles

Parton showers

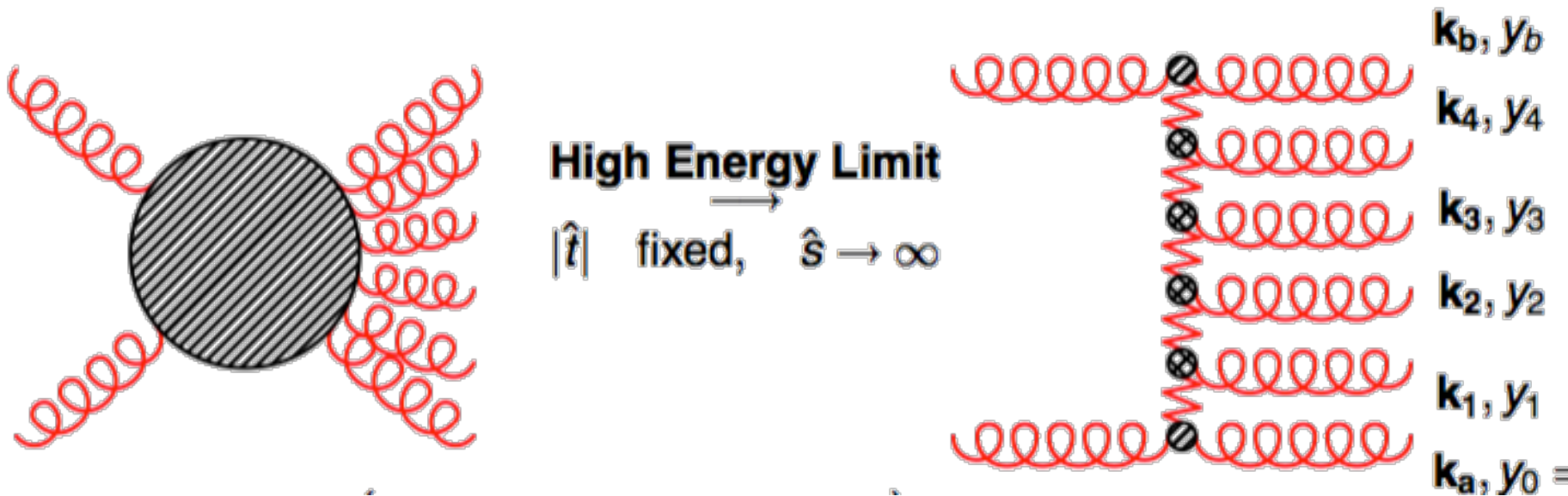
- Crucial role of colour structure of hard process
 - e.g. $qq \rightarrow qq$



- Corrections suppressed by $\sim 1/N_c^2$ interjet region
 - shouldn't we worry about them too?

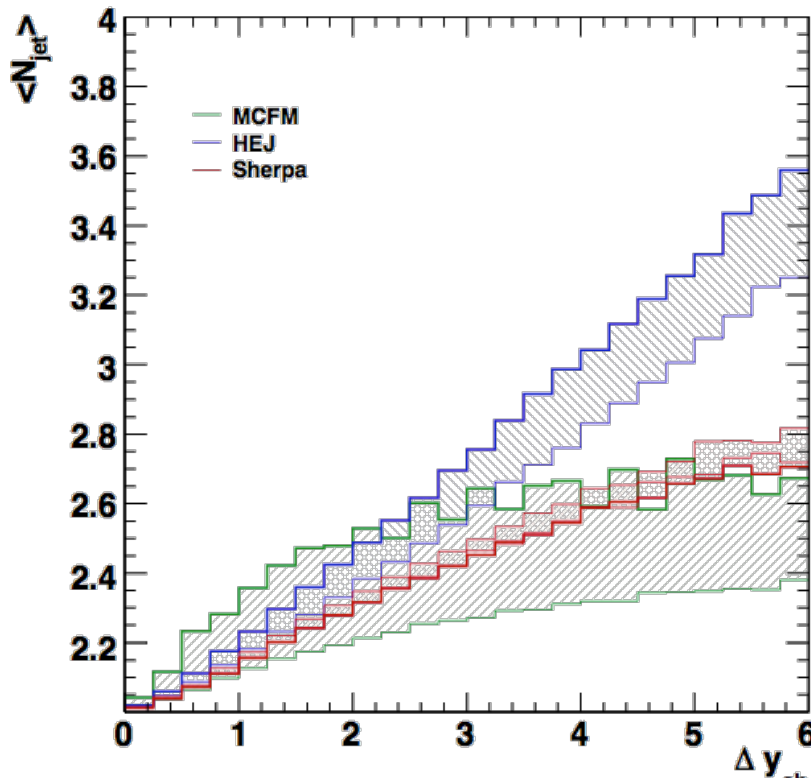
New approaches

- HEJ (Andersson & Smillie) resums rapidity-enhanced (i.e. small- x) terms
- Can be combined with dipole shower (+Lönnblad)



New approaches

- HEJ (Andersson & Smillie) resums rapidity-enhanced (i.e. small- x) terms



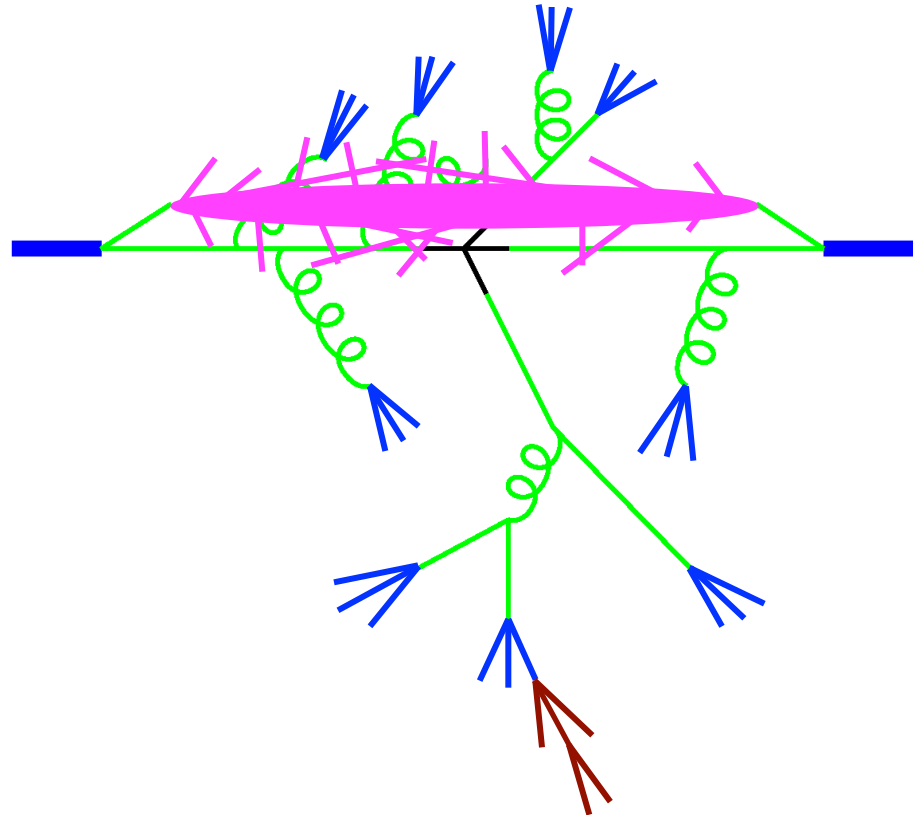
- important for Higgs production [Andersen, Campbell & Höche, arXiv:1003.1241]
- mean no. of jets as a function of rapidity distribution between most forward and most backward
 - c.f. VBF cuts/rapidity veto

New approaches

- Kusina, Jadach, Skrzypek & Slawinska: proof of principle of exclusive parton evolution with NLO kernels
- Ward: Herwiri: Herwig(++) evolution with IR-resummed kernels
- Nagy & Soper, Sjödaahl: off-diagonal colour evolution – exact in colour

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Hadronization

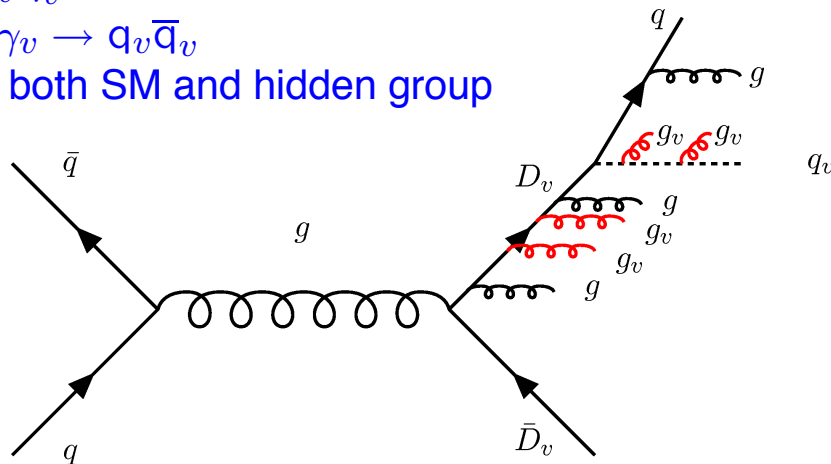
- Basic string and cluster models ~ unchanged in 25 years
 - Many small improvements motivated by deeper understanding/better data
 - e.g. baryon production models
- Pythia 8: BSM hadronization scenarios
 - R -hadrons (confined long-lived spartons)
 - Hidden sector hadronization

BSM Physics 3: Hidden Valley (Secluded Sector)

What if new gauge groups at low energy scales, hidden by potential barrier or weak couplings? (M. Strassler & K. Zurek, ...)

Complete framework implemented in PYTHIA:

- ★ New gauge group either Abelian $U(1)$ or non-Abelian $SU(N)$
 - ★ 3 alternative production mechanisms
 - 1) massive Z' : $q\bar{q} \rightarrow Z' \rightarrow q_v\bar{q}_v$
 - 2) kinetic mixing: $q\bar{q} \rightarrow \gamma \rightarrow \gamma_v \rightarrow q_v\bar{q}_v$
 - 3) massive F_v charged under both SM and hidden group
 - ★ Interleaved shower in QCD, QED and HV sectors:
 add $q_v \rightarrow q_v\gamma_v$ (and F_v)
 or $q_v \rightarrow q_v g_v$, $g_v \rightarrow g_v g_v$,
 which gives recoil effects also in visible sector
-



L. Carloni & TS, JHEP 09 (2010) 105;

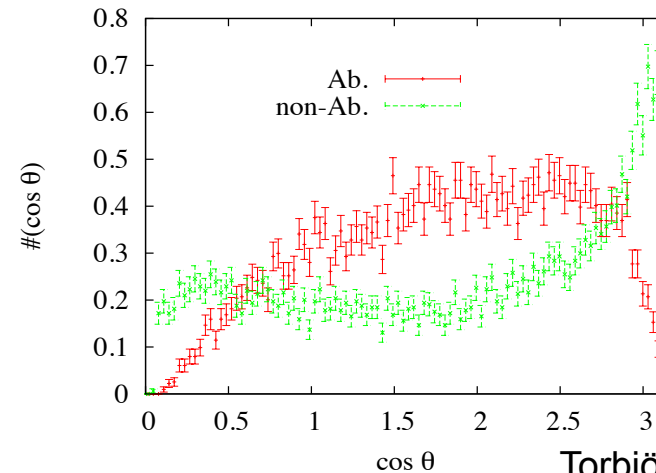
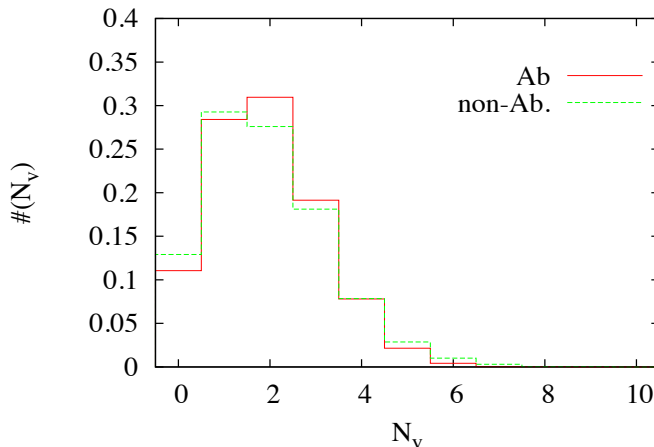
L. Carloni, J. Rathsmann & TS, JHEP 04 (2011) 091

Torbjörn Sjöstrand

Mike Seymour

- ★ Hidden Valley particles may remain invisible, or ...
- ★ Broken $U(1)$: γ_v acquire mass, radiated γ_v s decay back
 $\gamma_v \rightarrow \gamma \rightarrow f\bar{f}$ with BRs as photon (\Rightarrow lepton pairs!)
- ★ $SU(N)$: hadronization in hidden sector, with full string fragmentation, permitting up to 8 different q_v flavours and 64 $q_v\bar{q}_v$ mesons, but for now assumed degenerate in mass, so only distinguish
 - off-diagonal, flavour-charged, stable & invisible
 - diagonal, can decay back $q_v\bar{q}_v \rightarrow f\bar{f}$

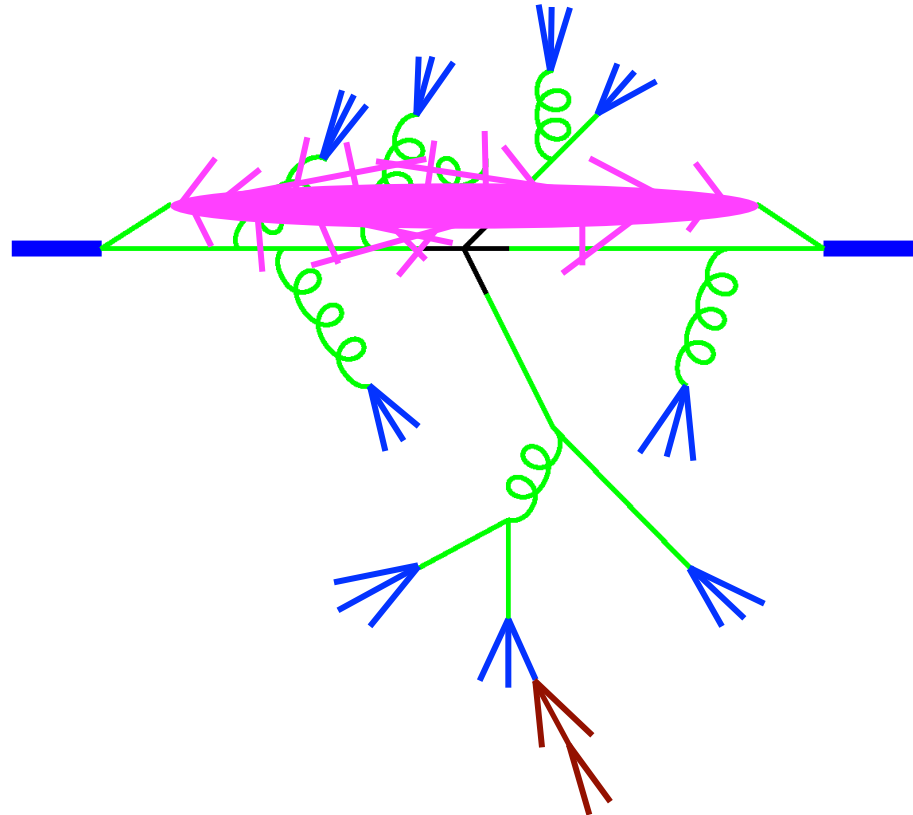
Even when tuned to same average activity, hope to separate $U(1)$ and $SU(N)$:



Torbjörn Sjöstrand

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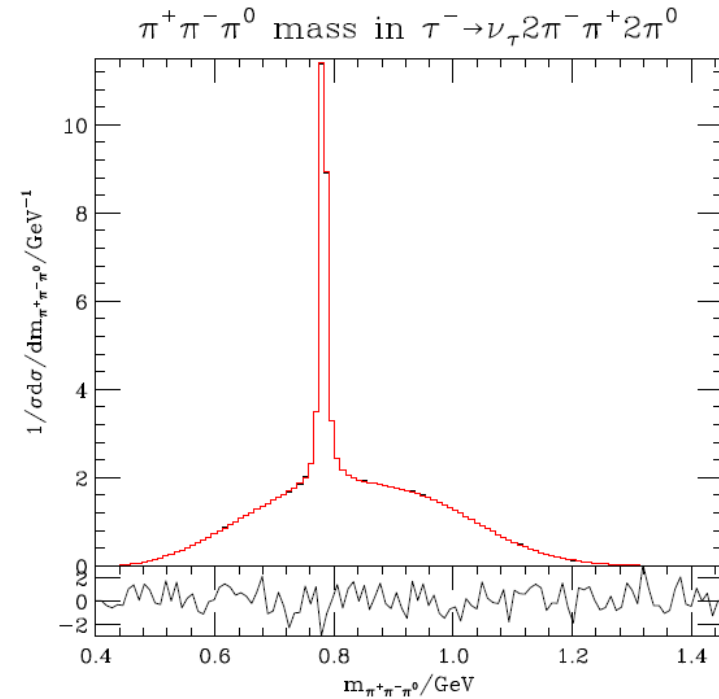
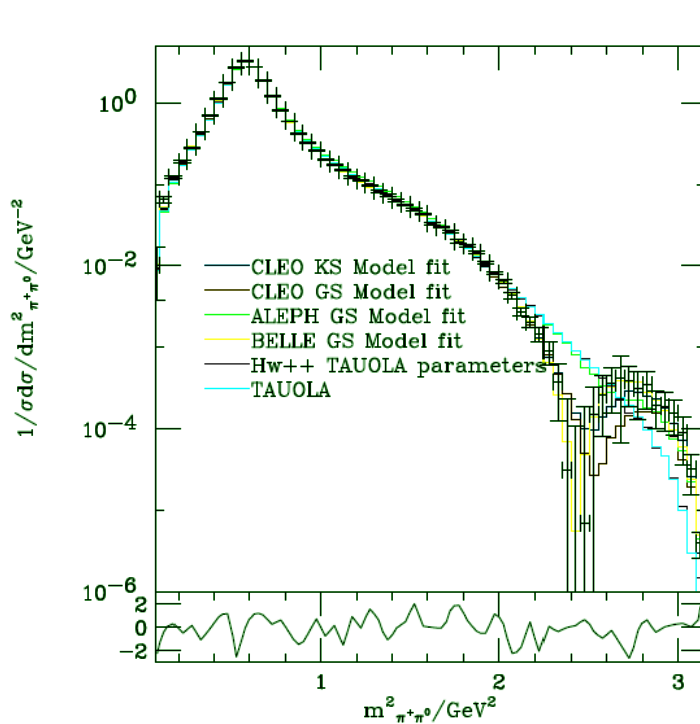
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Secondary particle decays

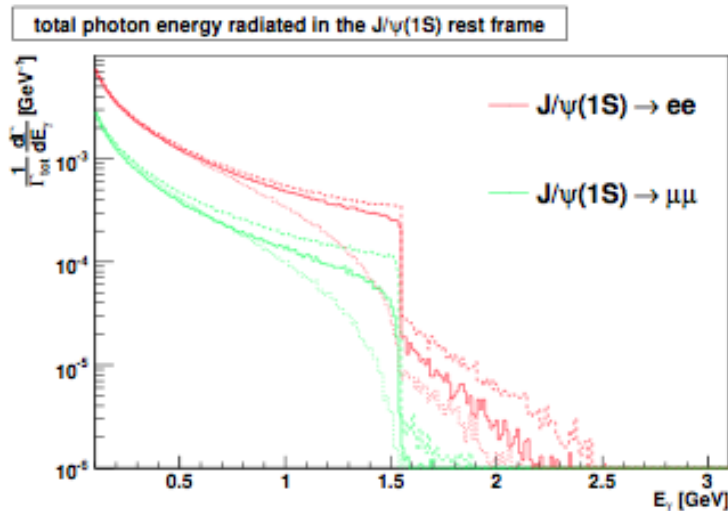
- Previous generations typically used external packages, e.g. TAUOLA, PHOTOS, EVTGEN
- Sherpa & Herwig++ contain at least as complete a description in all areas...
- without interfacing issues (c.f. τ spin)

Tau Decays

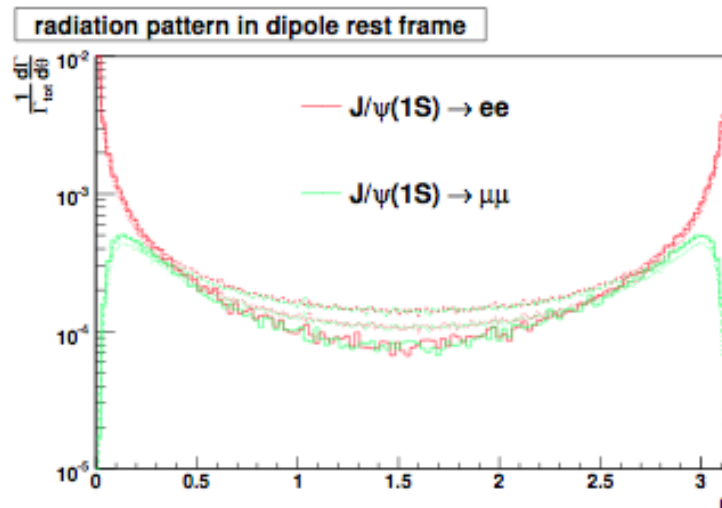


Mass spectrum of $\pi\pi$ in $\tau \rightarrow \pi\pi\nu_\tau$ for various models and example of mass distribution in $\tau \rightarrow 5\pi\nu_\tau$ comparing Herwig++ and TAUOLA.

Leptonic hadron decays: $J/\psi \rightarrow \ell\bar{\ell}$



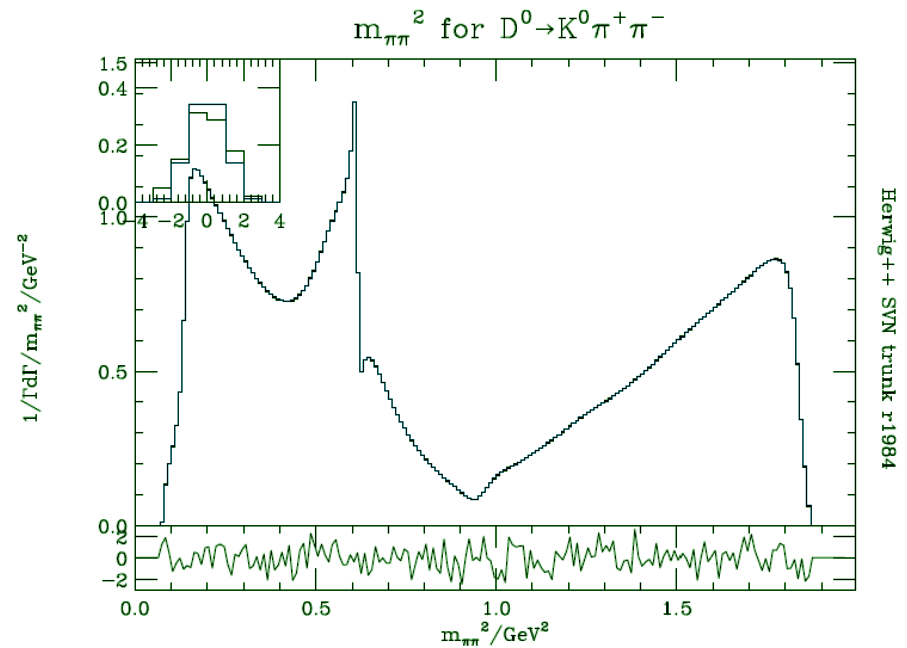
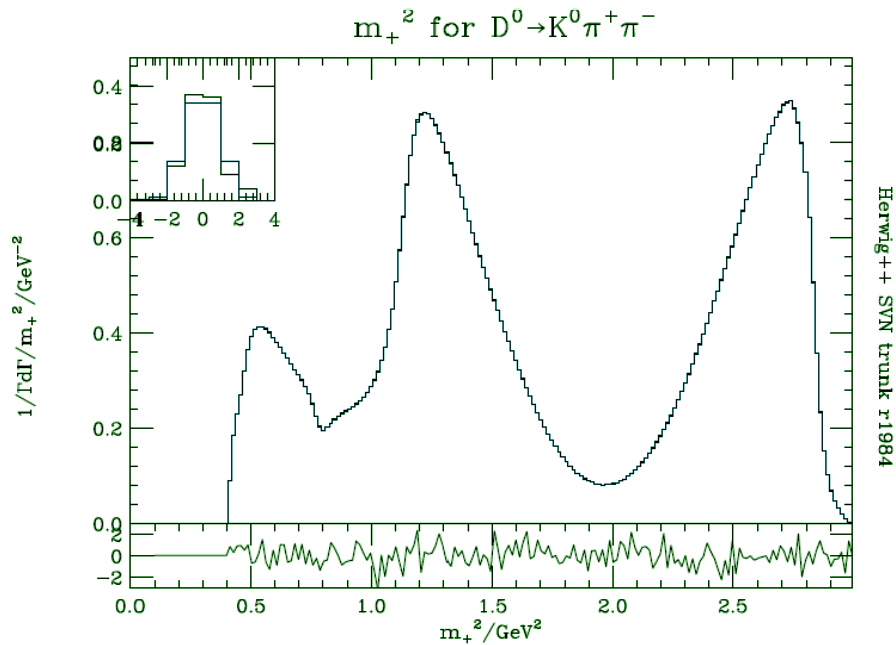
total radiated energy in the J/ψ rest frame



angular spectrum in the rest frame of the dipole

- soft only (dotted)
- collinear approximated ME (dashed)
- exact ME (solid)

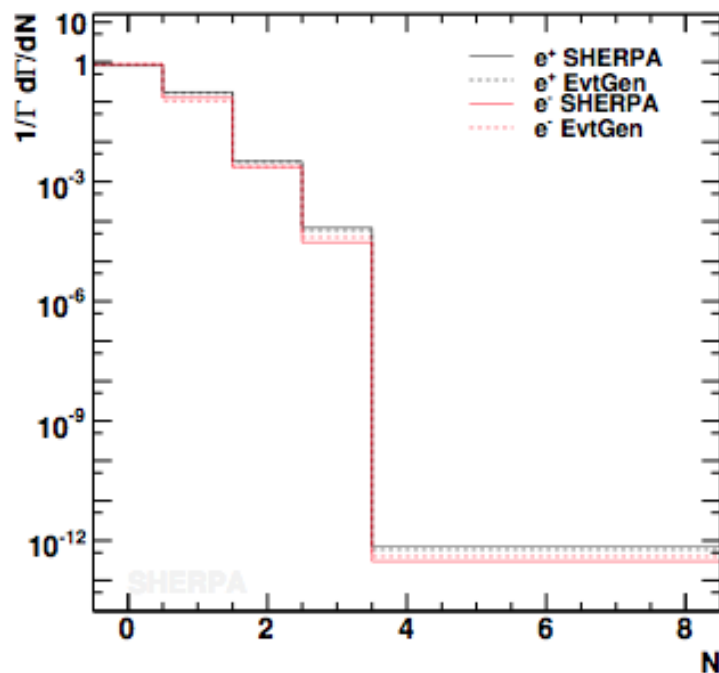
$D \rightarrow K \pi \pi$



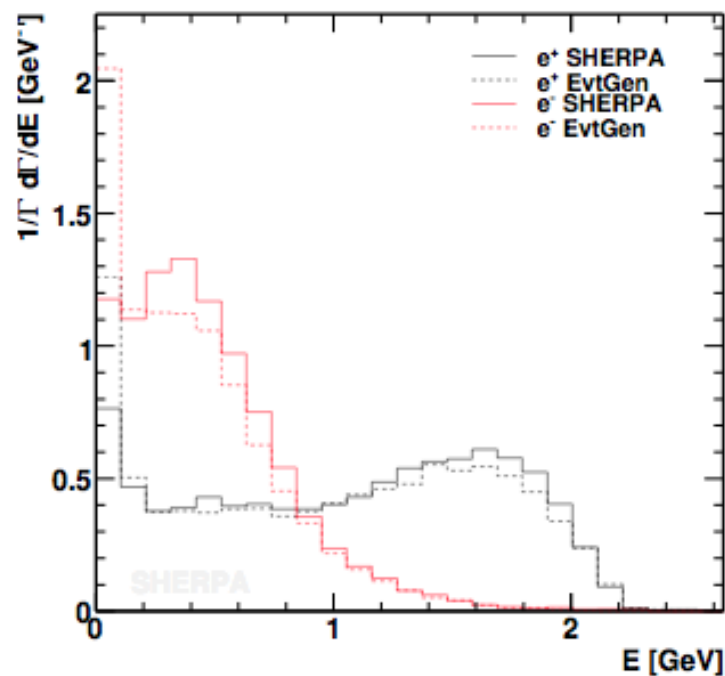
Comparison of Herwig++ and EvtGen implementations of the fit of Phys. Rev. D63 (2001) 092001 (CLEO).

Inclusive observables for B^+ decay

Electron multiplicity

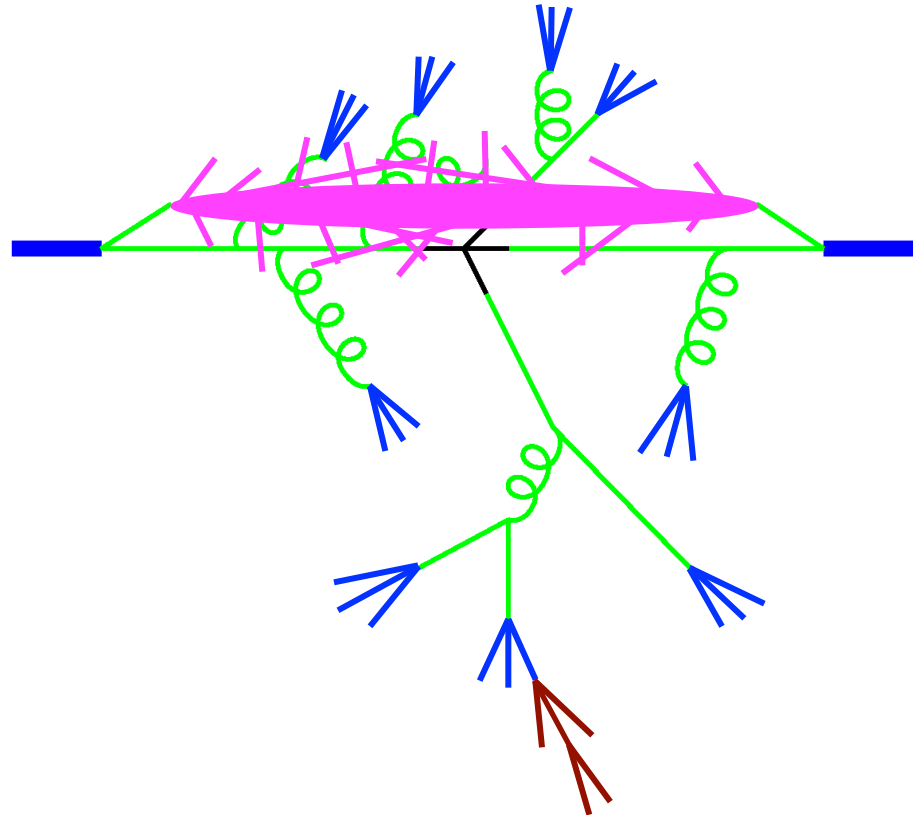


Electron energy spectrum



Structure of LHC Events

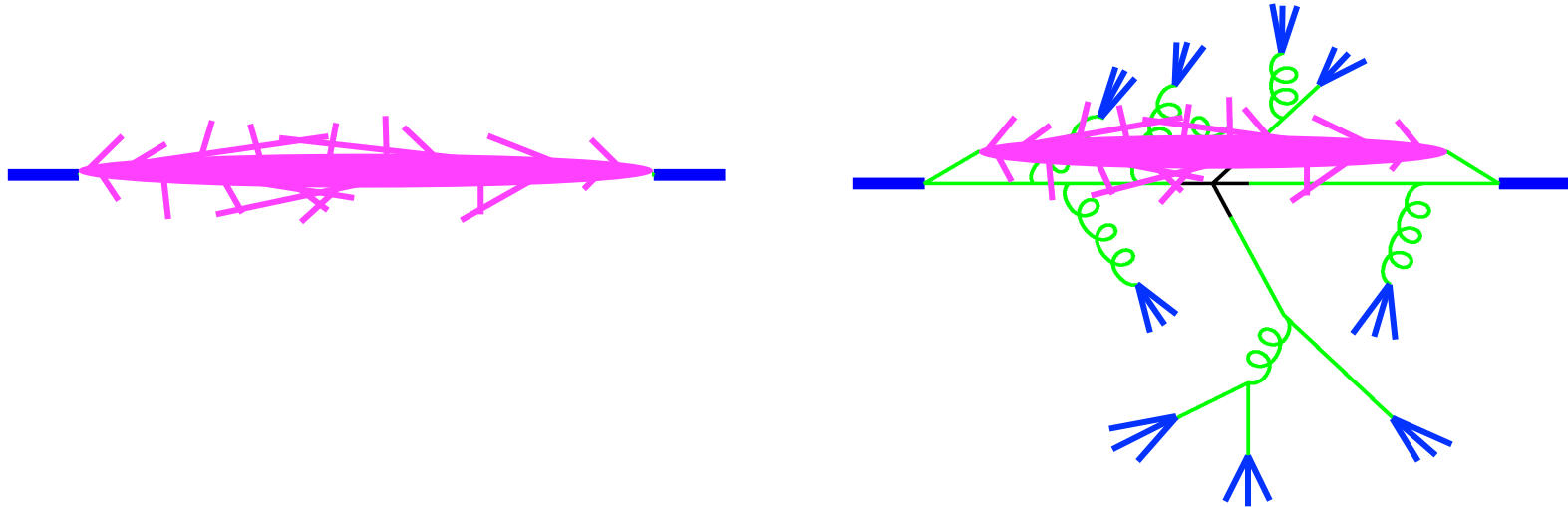
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2. Progress in underlying event/soft inclusive physics

The Basics: event classes

‘Minimum bias’ collision and underlying event



Minimum bias = experimental statement

Models = zero bias? i.e. inclusive sample of all inelastic (non-diffractive?) events

General-purpose event generators for LHC physics

Andy Buckley^a, Jonathan Butterworth^b, Stefan Gieseke^c,
David Grellscheid^d, Stefan Höche^e, Hendrik Hoeth^d, Frank Krauss^d,
Leif Lönnblad^{f,g}, Emily Nurse^b, Peter Richardson^d, Steffen Schumann^b,
Michael H. Seymour^d, Torbjörn Sjöstrand^f, Peter Skands^g, Bryan Webber^j

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^h*Institute for Theoretical Physics, University of Heidelberg, 69120 Heidelberg, Germany*

ⁱ*School of Physics and Astronomy, University of Manchester, M13 9PL, UK*

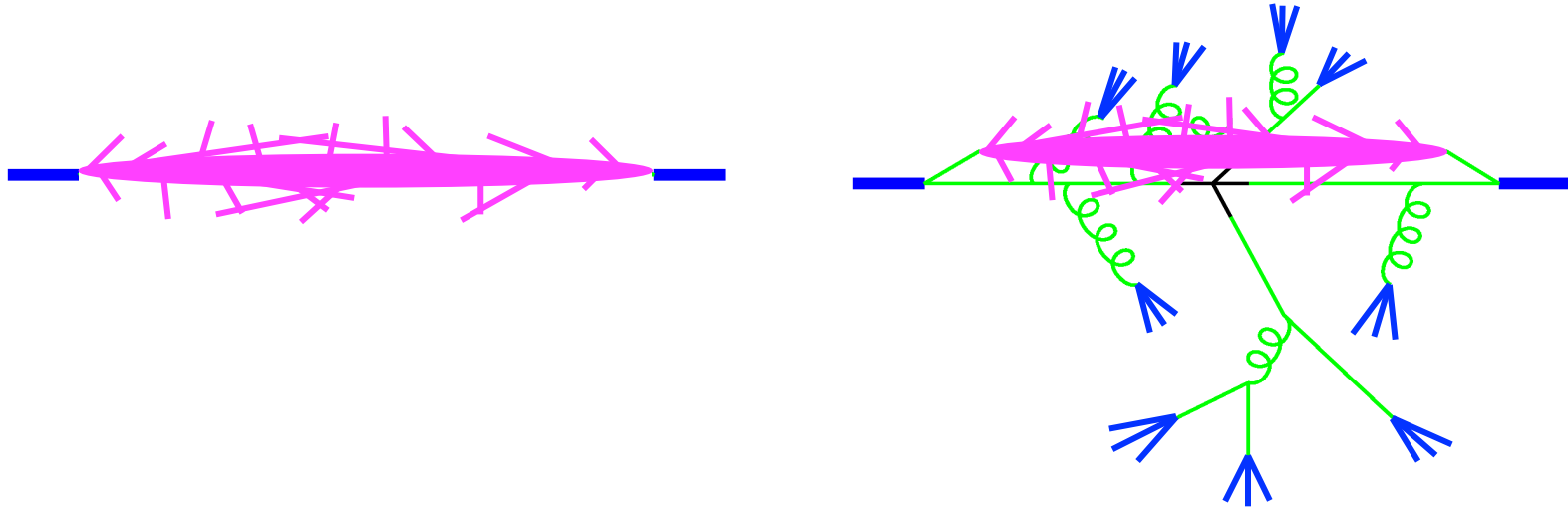
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Abstract

We review the physics basis, main features and use of general-purpose Monte Carlo event generators for the simulation of proton-proton collisions at the Large Hadron Collider. Topics included are: the generation of hard-scattering matrix elements for processes of interest, at both leading and next-to-leading QCD perturbative order; their matching to approximate treatments of higher orders based on the showering approximation; the parton and dipole shower formulations; parton distribution functions for event generators; non-perturbative aspects such as soft QCD collisions, the underlying event and diffractive processes; the string and cluster models for hadron formation; the treatment of hadron and tau decays; the inclusion of QED radiation and beyond-Standard-Model processes. We describe the principal features of the ARIADNE, Herwig++, PYTHIA 8 and SHERPA generators, together with the Rivet and Professor validation and tuning tools, and discuss the physics philosophy behind the proper use of these generators and tools. This review is aimed at phenomenologists wishing to understand better how parton-level predictions are translated into hadron-level events as well as experimentalists wanting a deeper insight into the tools available for signal and background simulation at the LHC.

The Basics: event classes

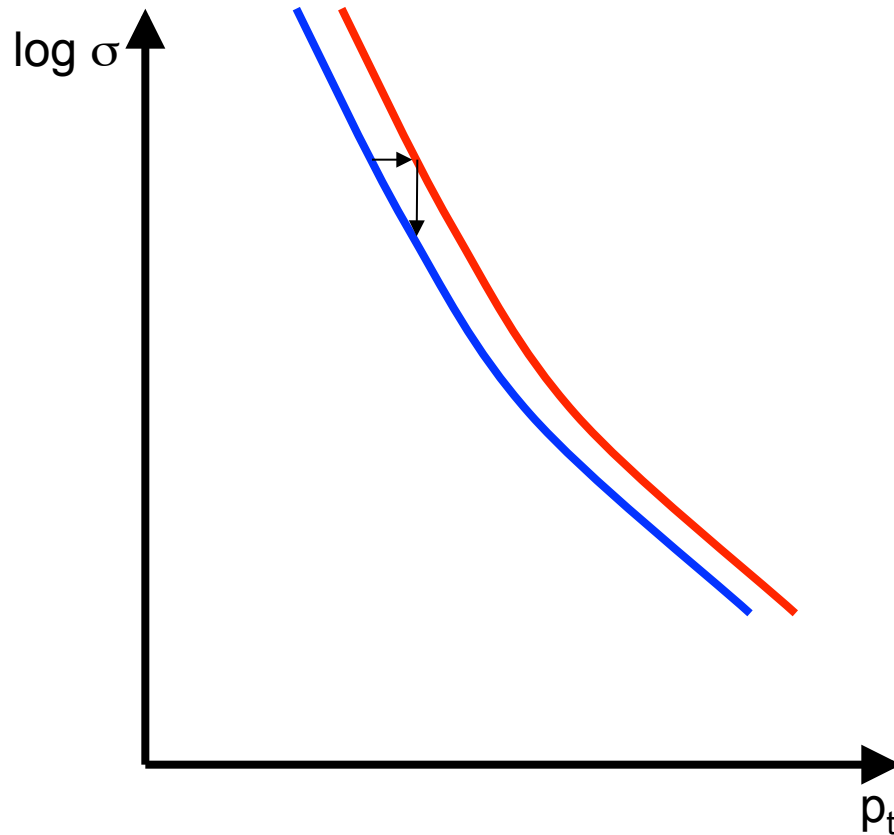
‘Soft inclusive’ events and the underlying event



How similar are they?

Fluctuations and correlations play crucial role

Fluctuations and correlations



Steep distribution \Rightarrow
small sideways shift =
large vertical

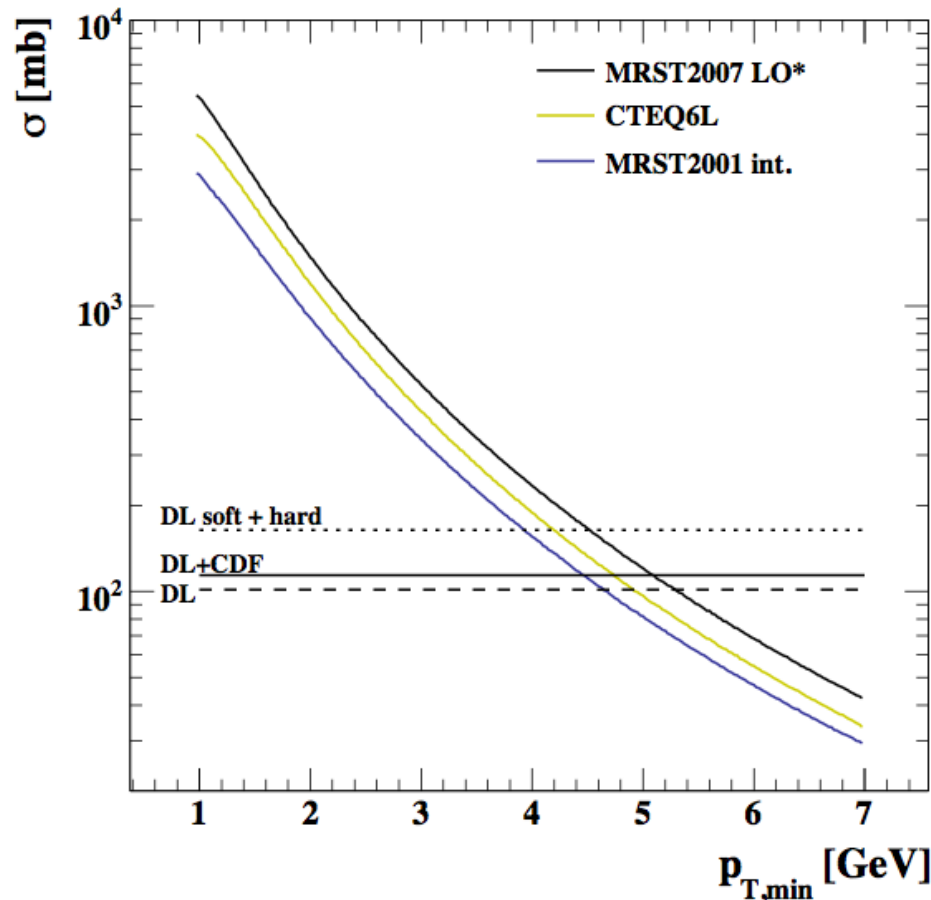
Rare fluctuations can
have a huge influence

$1/p_t^n \rightarrow n$ th moment

\Rightarrow corrections depend
on physics process

The Basics: Multiparton Interaction Model

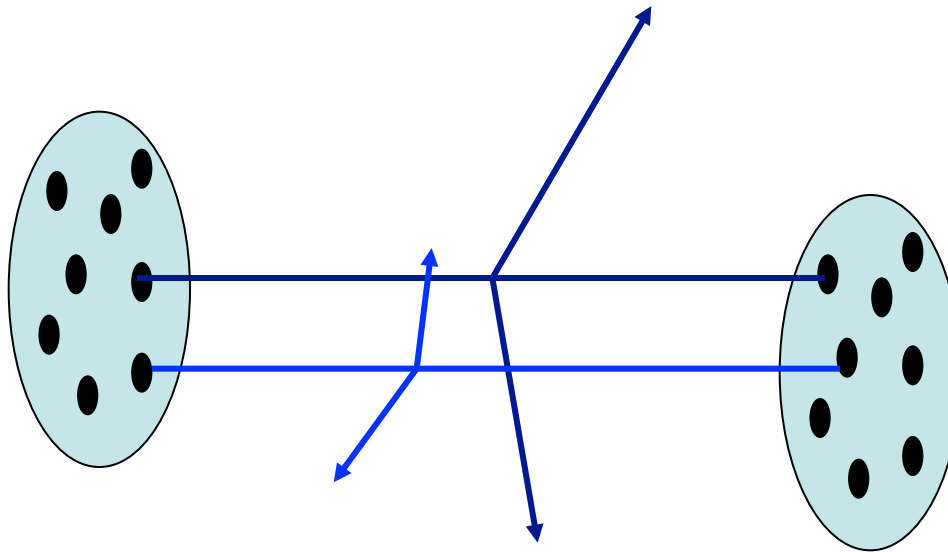
For small $p_{t\min}$ and high energy inclusive parton—parton cross section is larger than total proton—proton cross section.



The Basics: Multiparton Interaction Model

For small $p_{t\min}$ and high energy inclusive parton—parton cross section is larger than total proton—proton cross section.

→ More than one parton—parton scatter per proton—proton



Sjöstrand, van Zijl,
Phys. Rev. D36
(1987) 2019

Need a model of spatial distribution within proton

→ Perturbation theory gives you n-scatter distributions

Matter Distributions

- Usually assume x and b factorize (\rightarrow see later)

$$n_i(x, b; \mu^2, s) = f_i(x; \mu^2) G(b, s)$$

- and n -parton distributions are independent (\rightarrow see soon)

$$n_{i,j}(x_i, x_j, b_i, b_j) = n_i(x_i, b_i) n_j(x_j, b_j)$$

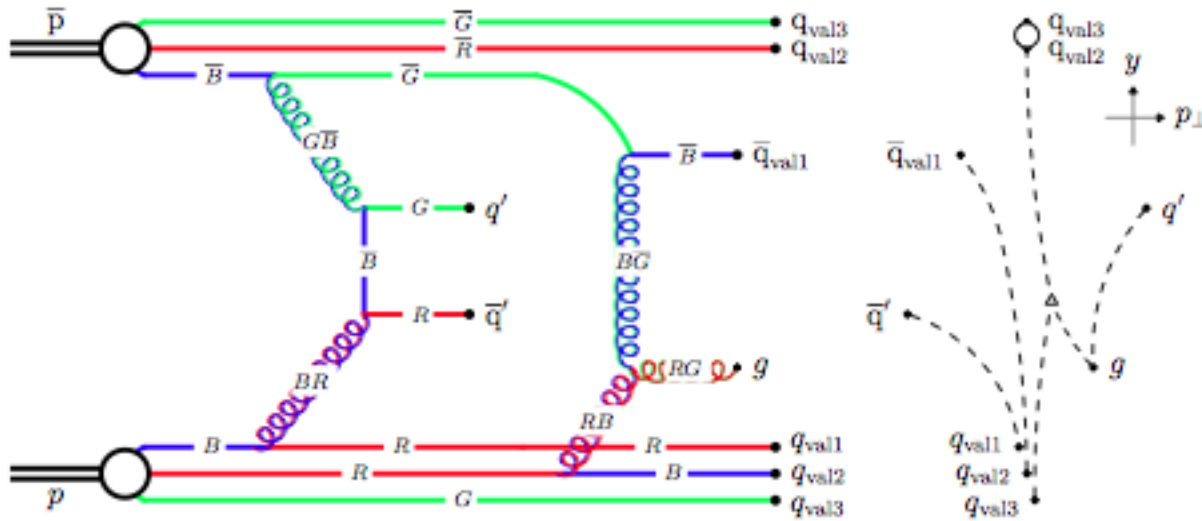
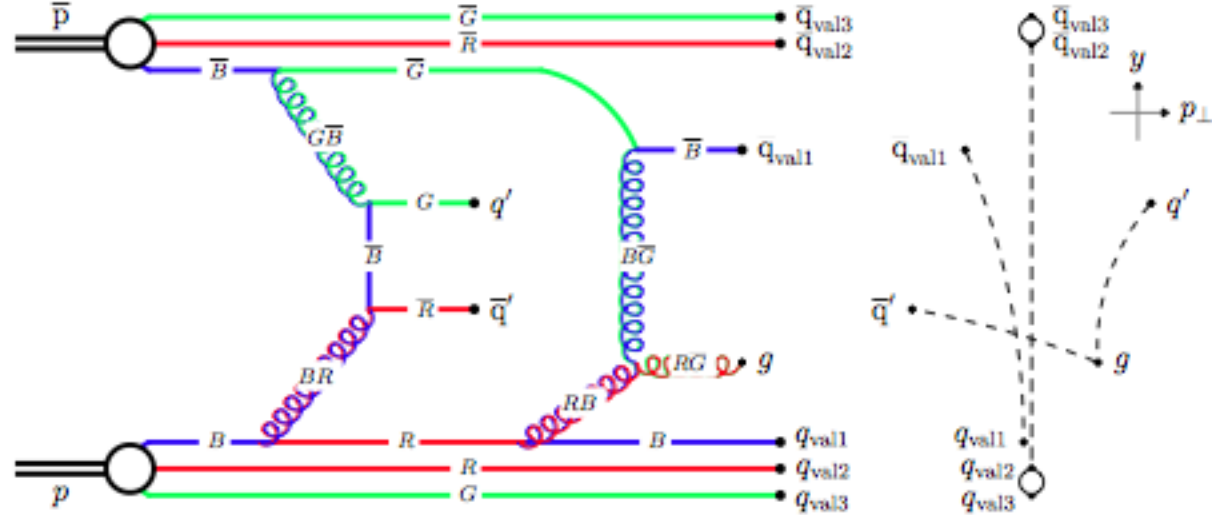
\Rightarrow scatters Poissonian at fixed impact parameter

$$\sigma_n = \int d^2b \frac{(A(b)\sigma^{inc})^n}{n!} \exp(-A(b)\sigma^{inc})$$

$$A(b) = \int d^2b_1 G(b_1) d^2b_2 G(b_2) \delta(b - b_1 + b_2)$$

Colour correlations

Can have a big influence on final states



→ see later

The Herwig++ Model (formerly known as Jimmy+Ivan)

- Take eikonal+partonic scattering seriously

$$\sigma_{tot} = 2 \int d^2b \left(1 - e^{-\frac{1}{2} A(b) \sigma_{inc}} \right)$$

$$B = \left[\frac{d}{dt} \left(\ln \frac{d\sigma_{el}}{dt} \right) \right]_{t=0} = \frac{1}{\sigma_{tot}} \int d^2b b^2 \left(1 - e^{-\frac{1}{2} A(b) \sigma_{inc}} \right)$$

- given form of matter distribution \Rightarrow size and σ_{inc}

Bähr, Butterworth & MHS, JHEP 0901:067, 2009

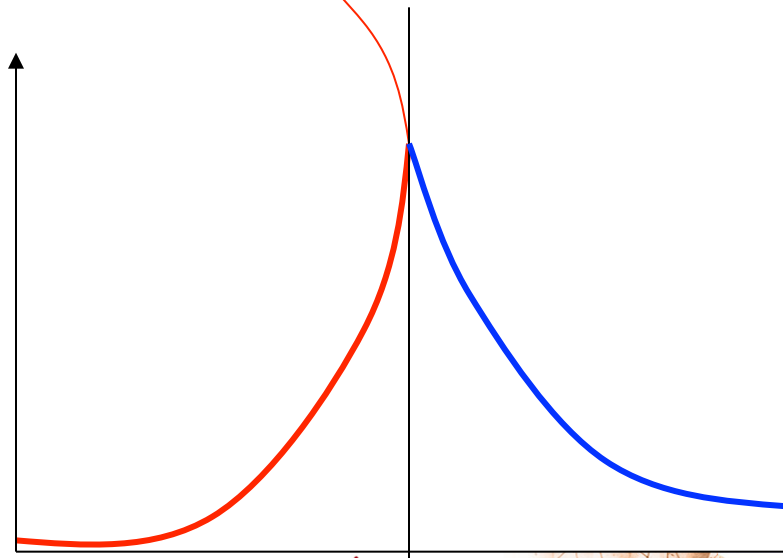
- too restrictive \Rightarrow

$$\sigma_{tot} = 2 \int d^2b \left(1 - e^{-\frac{1}{2} (A_{\text{soft}}(b) \sigma_{\text{soft,inc}} + A_{\text{hard}}(b) \sigma_{\text{hard,inc}})} \right)$$

- \Rightarrow two free parameters

Final state implementation

- Pure independent perturbative scatters above PT_{MIN}
- Gluonic scattering below PT_{MIN} with total $\sigma_{soft,inc}$ and Gaussian distribution in p_t
- $d\sigma/dp_t$ continuous at PT_{MIN}

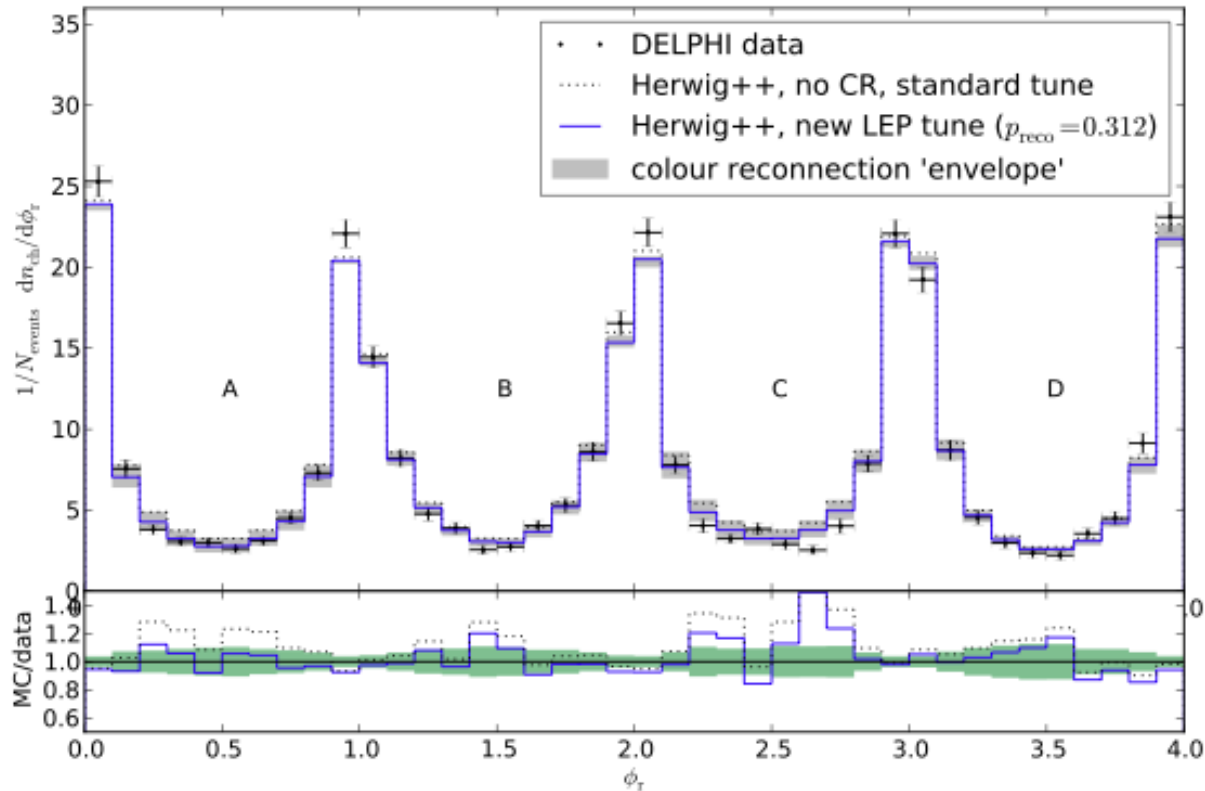


→ possibility that entire process could be described perturbatively?

Colour reconnection model

- Röhr, Siodmok and Gieseke have implemented a new model based on momentum structure
- Refit LEP-I and LEP-II data
- Conclusion: hadronization parameters correlated with reconnection probability, but good fit can be obtained for any value of p_{reco}

Retrospective: particle flow in $WW \rightarrow 4j$ at LEP



- ▶ small effects here
- ▶ marginal improvement (if at all)

data from [DELPHI Collaboration, Eur. Phys. J. C51 (2007) 249-269]

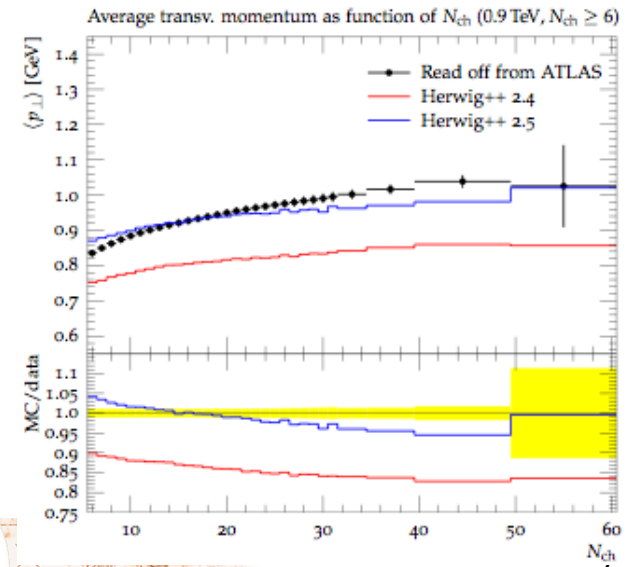
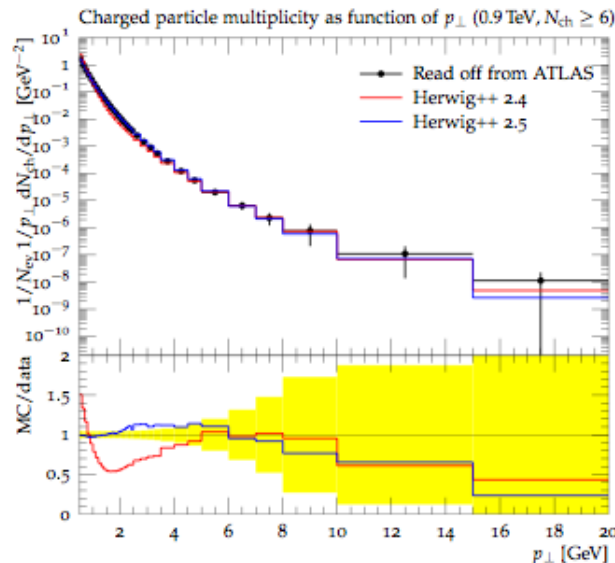
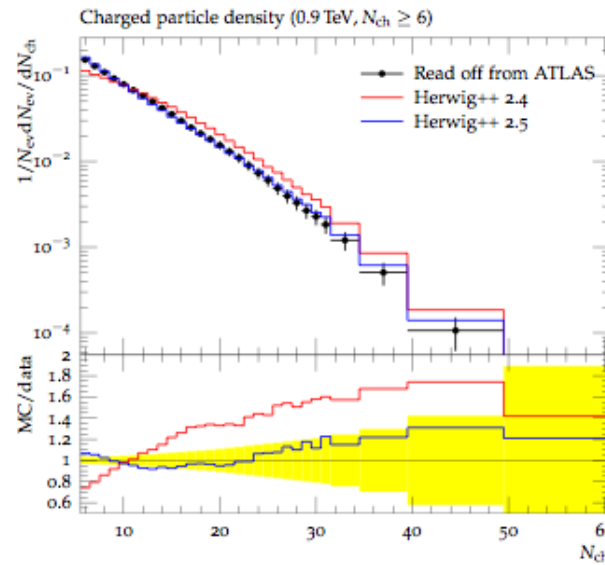
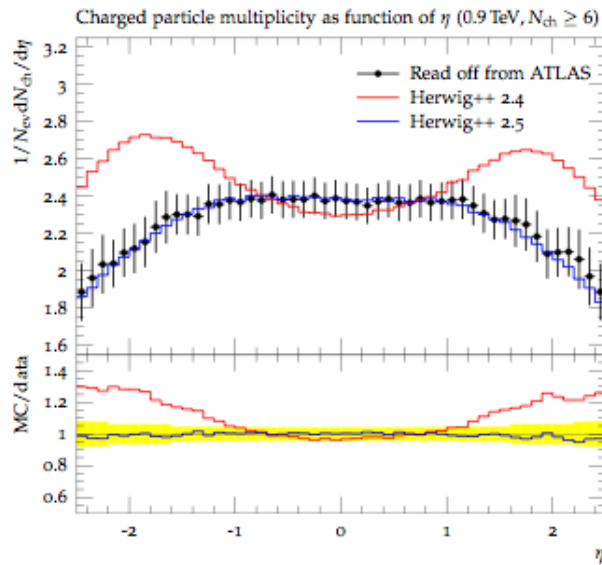
Colour Reconnection in Cluster Hadronisation, 8th MCnet Meeting, Cambridge, 22-24 Sept 2010

7 / 14

Parameter tuning

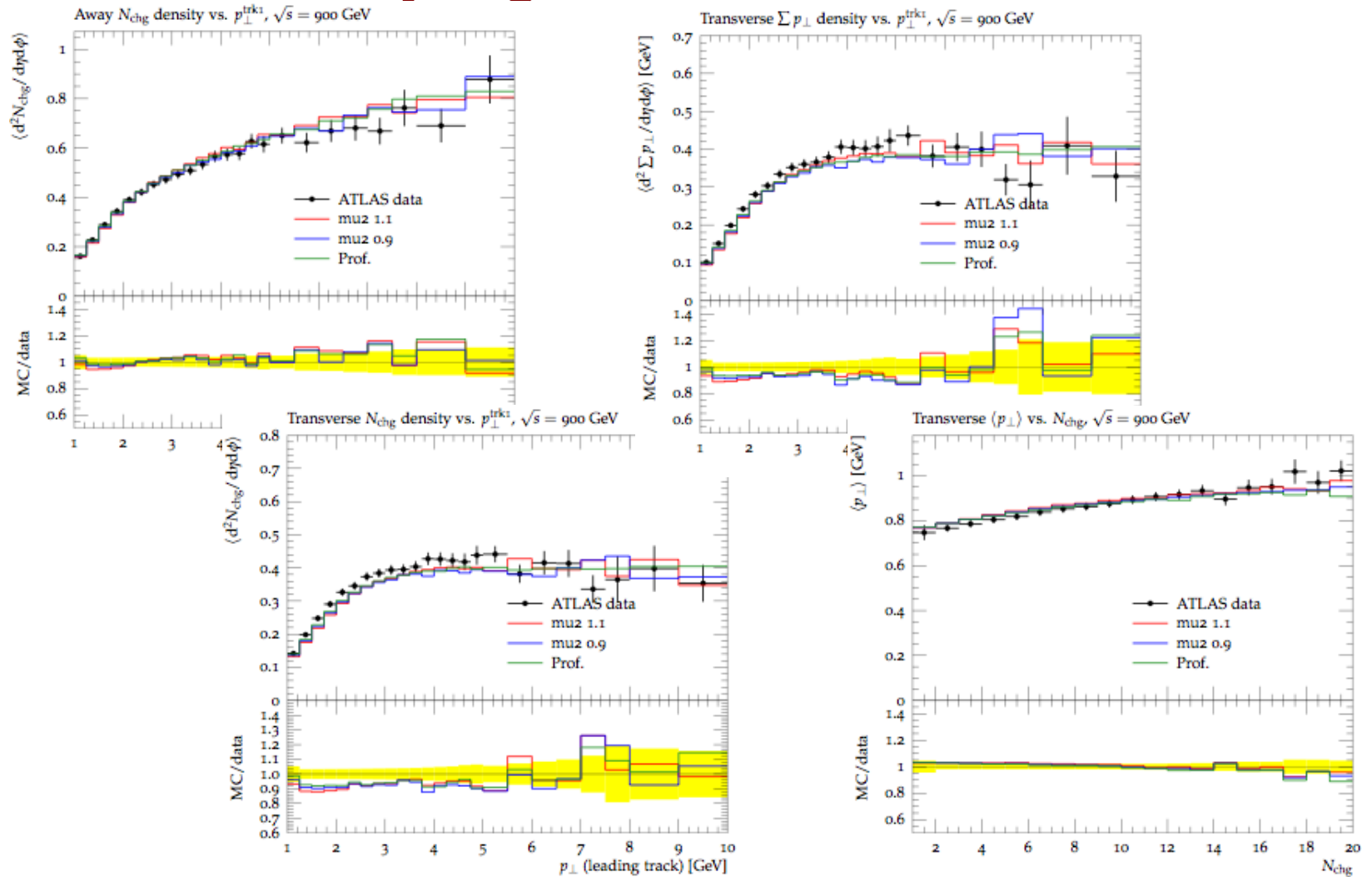
- Procedure:
 - fix parton shower and hadronization parameters to LEP data, as a function of colour reconnection p_{reco}
 - choose a total cross section and elastic slope parameter $\Rightarrow A_{\text{soft,inc}}(b)$ and $\sigma_{\text{tot,inc}}$
 - fit $A_{\text{hard,inc}}(b)$, $p_{\text{t,min}}$ ($\Rightarrow \sigma_{\text{hard,inc}}$ and $\sigma_{\text{soft,inc}}$) and p_{reco} to minimum bias and underlying event data

Colour reconnection model/MPI tuning

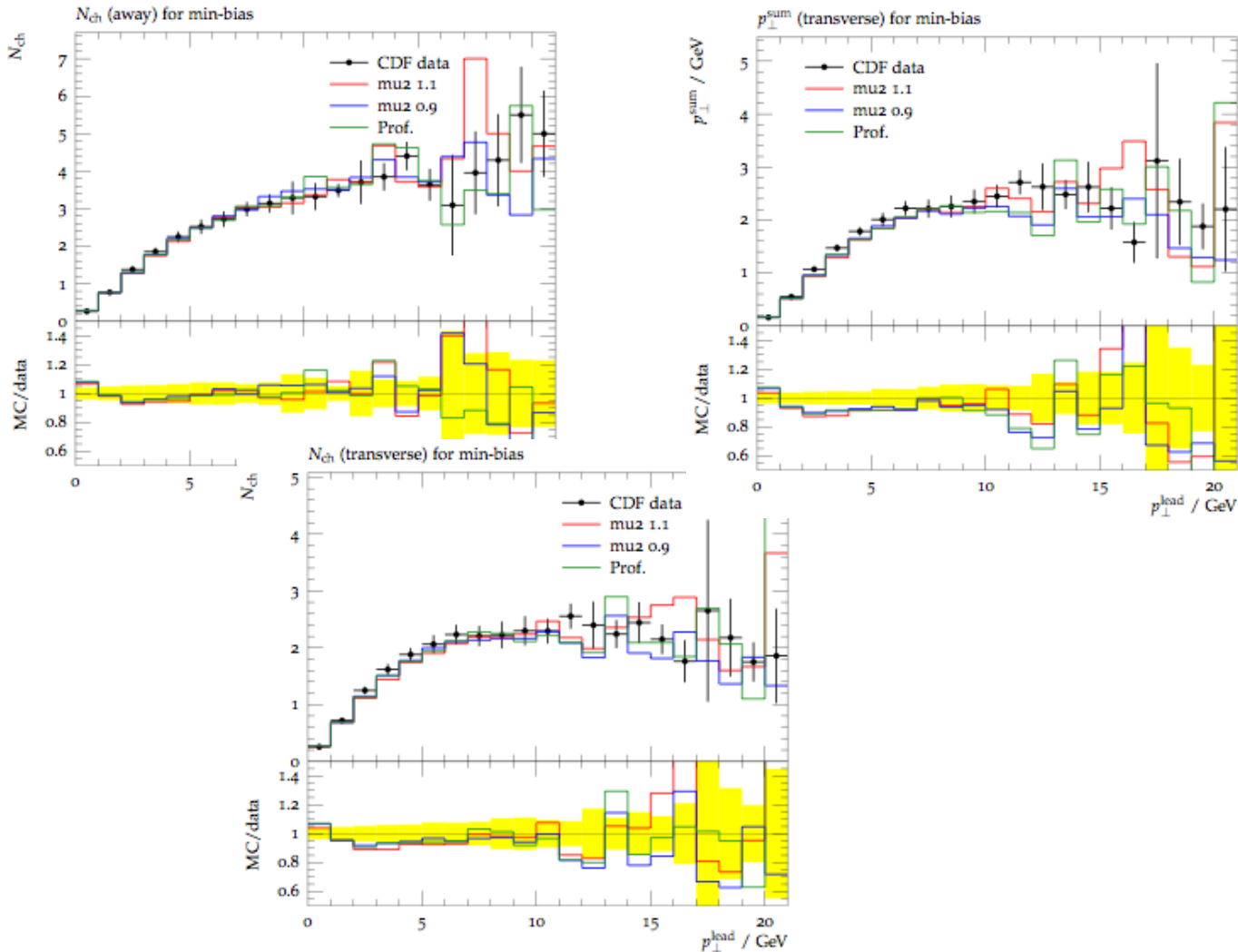


THLPCC11

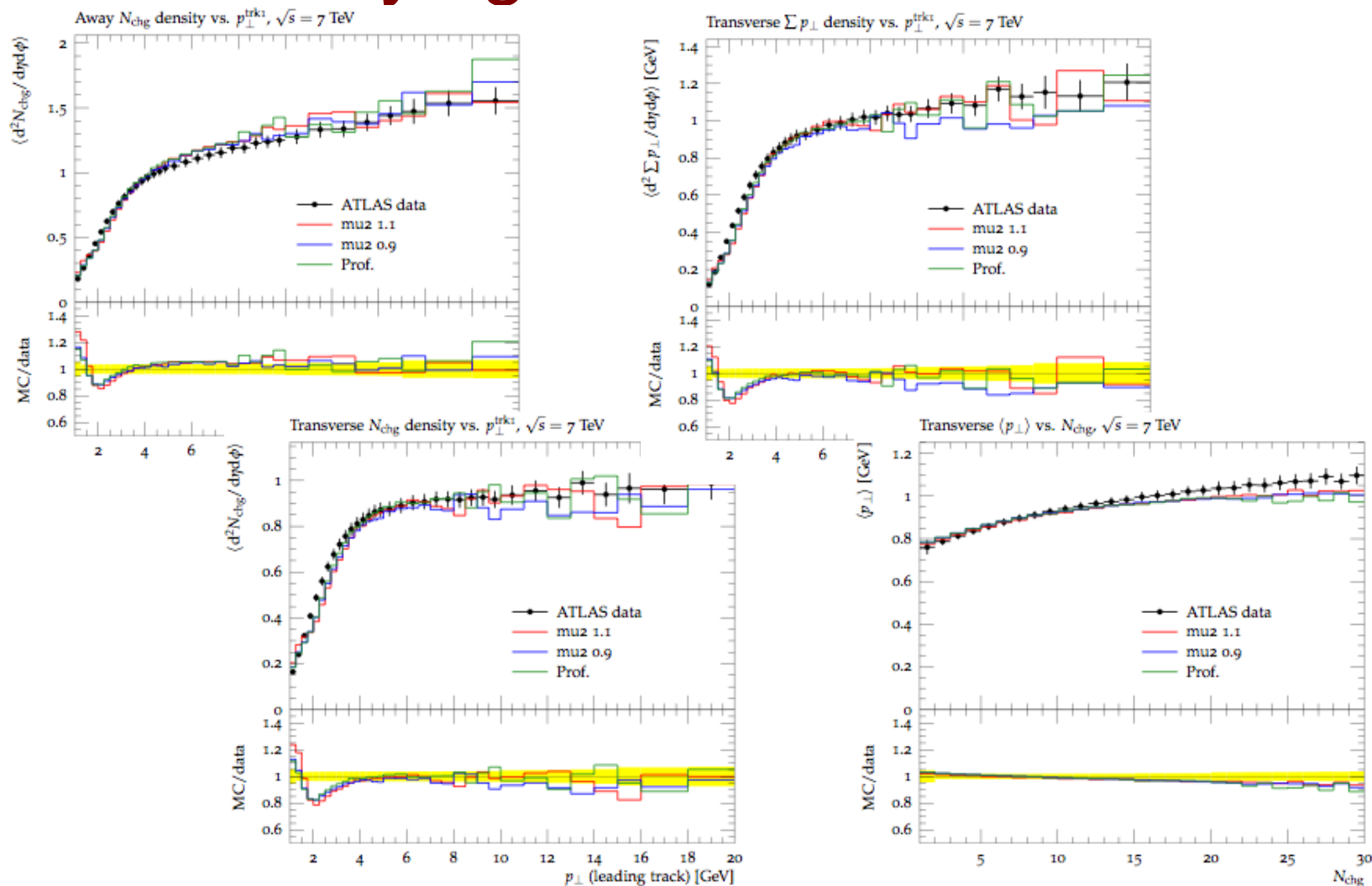
Underlying event at 900 GeV



Underlying event at 1800 GeV



Underlying event at 7000 GeV



x-dependent matter distributions

- Most existing models use factorization of x and b
 - or (Herwig++) crude separation into hard and soft components (simple hot-spot model)
- R.Corke and T.Sjöstrand, arXiv:1101.5953 consider Gaussian matter distribution with width

$$a(x) = a_0 \left(1 + a_1 \ln \frac{1}{x} \right)$$

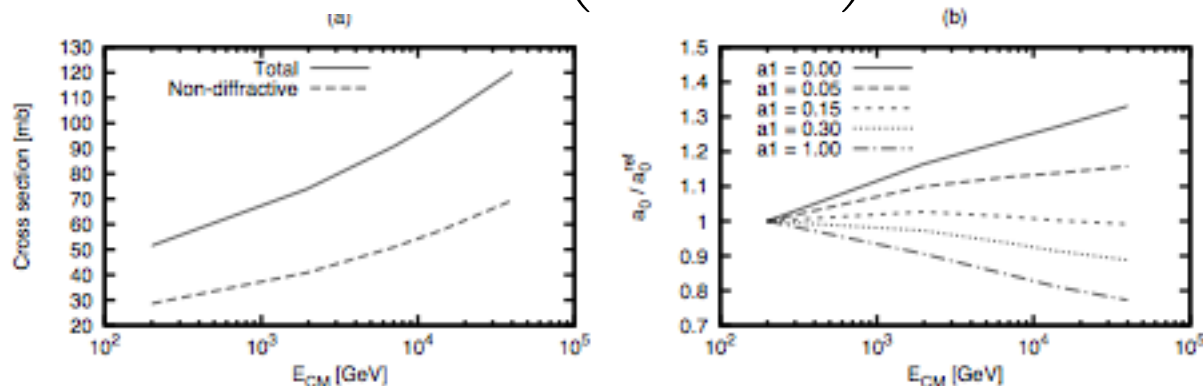


Figure 1: (a) The rise of the total and non-diffractive pp cross section with energy, and (b) the ratio $a_0(E_{CM})/a_0(200 \text{ GeV})$, over the same energy range, for a set of different a_1 values

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- for $a_1 \approx 0.15$, matter distribution can be E-indep

x-dependent matter distributions

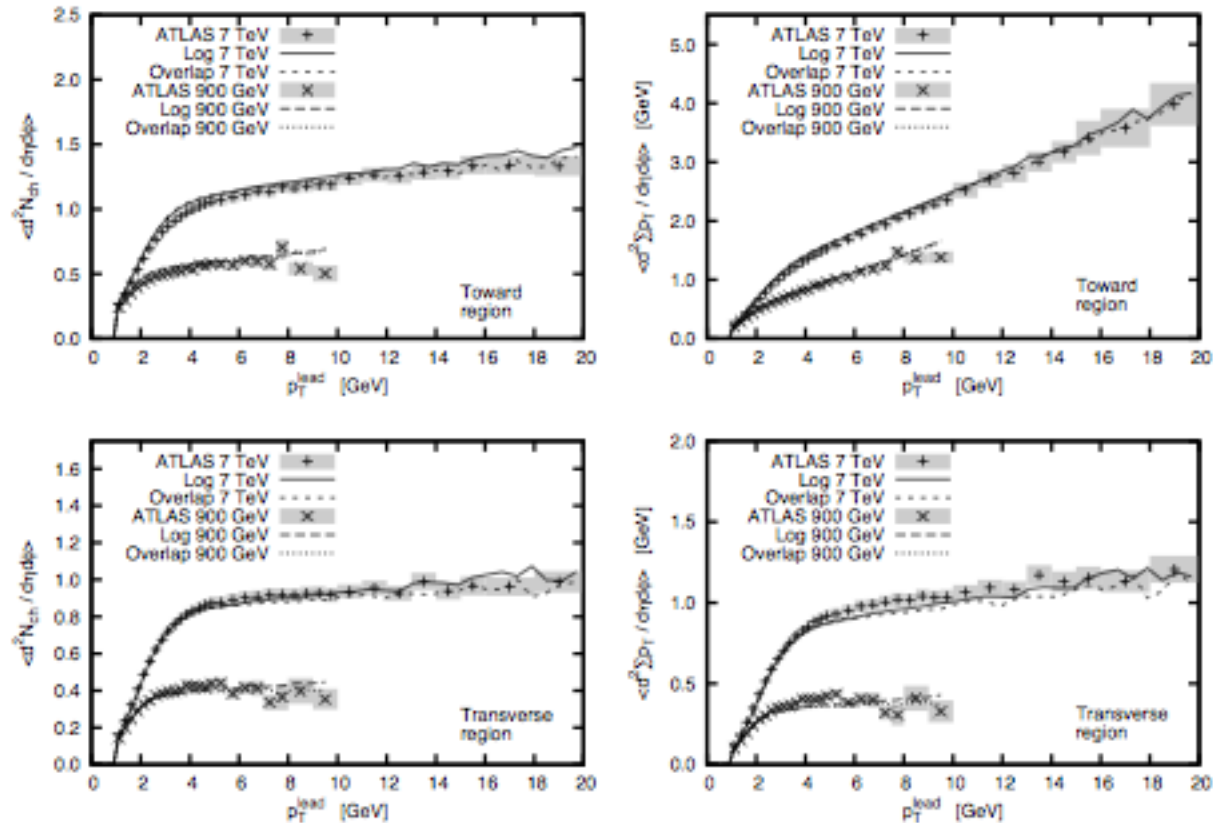


Figure 11: Tune 4C, using the log profile, and with a raised $p_{\perp 0}$ in the MPI framework, compared against an overlap profile with $p = 1.6$, also with a raised $p_{\perp 0}$, and LHC data

x-dependent matter distributions

- (My) conclusion: for soft inclusive and jet underlying event data compatible with data but not required, but sheds interesting light on energy dependence
- Interesting correlation with hardness of hard scatter, e.g. less underlying event in 1 TeV Z' events than in Z events

Conclusions on UE/MB

- Despite ~25 year history, multi-parton interaction models are still in their infancy
 - LHC experiments'
 - step up in energy
 - high efficiency, purity and phase space coverage
 - emphasis on physical definition of observables
- have given us a huge amount of *useful* data
- existing models describe data well with tuning
 - need more understanding of correlations/corners of phase space/relations between different model components

Conclusions on UE/MB

- don't forget that jet corrections depend on correlations and high moments of distributions and are physics-process dependent

Conclusions

- Modern event generators are extremely well developed and tested
- Step up to LHC opens up phase space enormously – lots of scope for multiple hard emission and lots of different logs
 - matrix element matching mandatory
- Multiple-interaction physics entering quantitative phase