Progress on the PYTHIA 8 event generator

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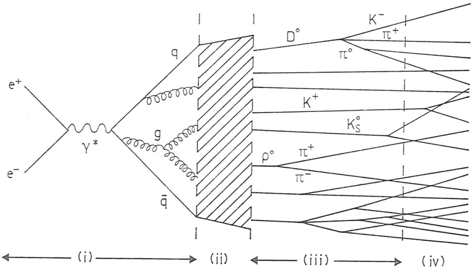
Introduction – 1

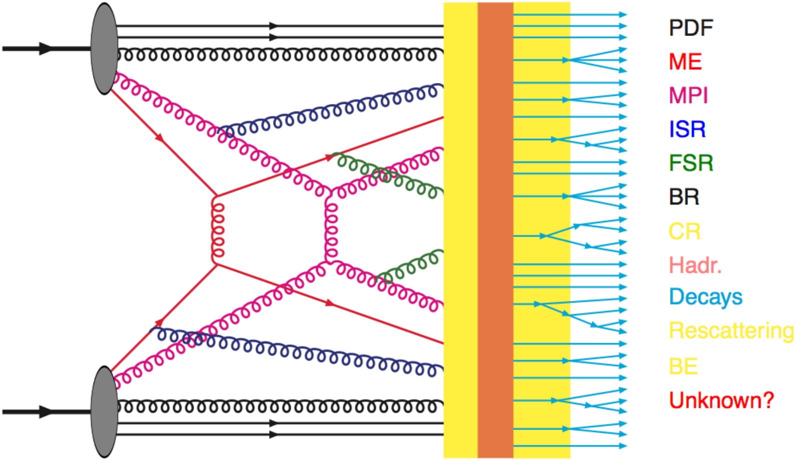
Modern event generators were born at DESY,
for the PETRA $\mathrm{e}^+\mathrm{e}^-$ collider! (1978 – 86, 13 – 46 GeV)

- Combine perturbative picture of hard processes, involving electroweak and strong interactions, with nonperturbative picture of hadronization.
- Provide "complete" events, with parameters to be tuned to data, and used to study and understand different kinds of physics.



JETSET (PYTHIA predecessor): ~1,000 lines of Fortran code in 1980

Events more messy at the LHC (even when simplified):



General-purpose event generators: PYTHIA, HERWIG, SHERPA
PYTHIA size: ∼80,000 lines (Fortran in PYTHIA 6, C++ in PYTHIA 8)

Event Generator Reasons

- Structure of LHC events impossible to “solve” from first principles.
- Several competing mechanisms contribute, both perturbative and nonperturbative.
- Even if calculable somehow, need 1000-body expressions and phase space sampling.
- Immense variability, with “typical events” and “rare corners”.

An event generator is intended to simulate various event kinds, with random numbers providing quantum mechanical variability.

It can be used to

- predict event rates and topologies ⇒ estimate feasibility
- simulate possible backgrounds ⇒ devise analysis strategies
- study detector requirements ⇒ optimize design and trigger
- study detector imperfections ⇒ evaluate acceptance

PYTHIA 8 development overview

Ambition (relative to PYTHIA 6)

- Meet experimental request for C++ code.
- Housecleaning ⇒ more homogeneous.
- More user-friendly (e.g. settings names).
- Better match to software frameworks (e.g. card files).
- More space for growth.
- Better interfaces to external standards.

Reality

- Work begun autumn 2004.
- 3 years at CERN ⇒ good progress.
- First release autumn 2007.
- Since then: slower progress, but gradually things get done.
- Usage is taking off, at long last.

Team members

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Stephen Mrenna
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Former members

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Contributors

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Philip Ilten
Tomas Kasemets
Mikhail Kirsanov
...

Key differences between PYTHIA 6.4 and 8.1

Old features definitely removed include, among others:

- independent fragmentation (always non-default option)
- mass-ordered showers (original ones)

Features omitted so far include, among others:

- ep, γp and $\gamma\gamma$ beam configurations
- several processes, especially Technicolor, partly SUSY

New features, not found in 6.4, include:

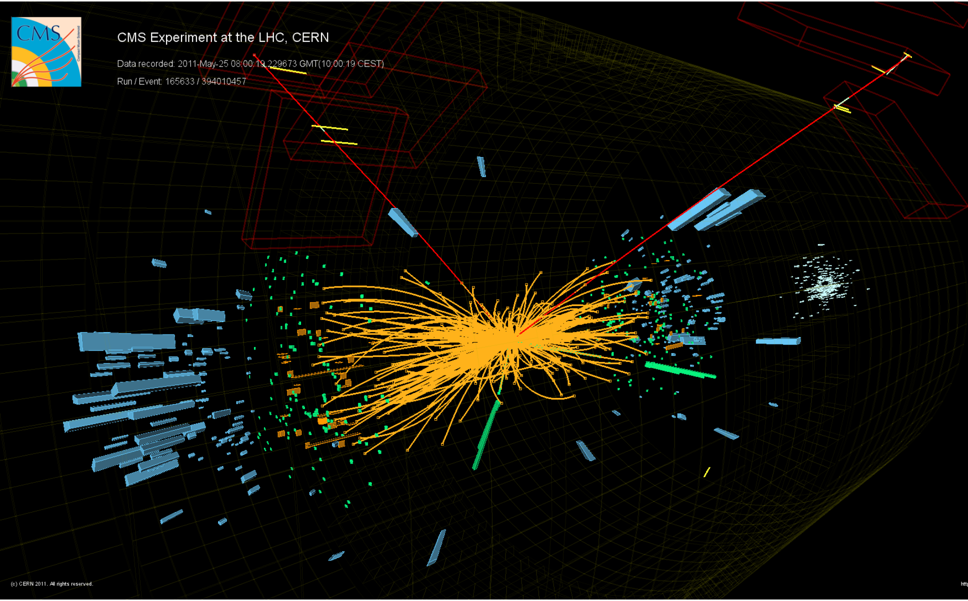
⋆ CKKW-L and MLM merging, support POWHEG, more coming
⋆ fully interleaved $p_{\perp}$-ordered MPI + ISR + FSR evolution
⋆ richer mix of underlying-event processes (γ, J/ψ, DY, . . .)
⋆ allow rescattering and x-dependent proton size in MPI framework
⋆ full hadron–hadron collision machinery for diffractive systems
⋆ several new processes, within and beyond SM
⋆ τ lepton polarization in production and decay
⋆ updated decay data and LO PDF sets
⋆ · · ·

Interfaces

PYTHIA intended to describe the complete structure of an event, but nobody can do everything – need to be open to the World.

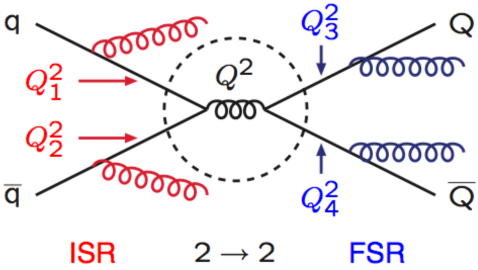
- Les Houches Event Files or runtime LHA interface
- LHAPDF or other external PDF libraries
- SUSY LHA input
- External random number generator
- External beam momentum and vertex spread
- Semi-internal matrix elements or resonance widths (MadGraph 5 can generate code for inclusion in PYTHIA)
- External parton showers (e.g. VINCIA)
- External decay of selected particles (EvtGen?)
- User hooks: step into generation process, e.g. to veto
- Particle/resonance gun (e.g. decay Higgs in isolation)
- HepMC output
- Combine with RIVET analyses

PYTHIA physics progress in recent years



The Parton-Shower Approach

$2 \to n \;=\; (2 \to 2) \oplus \text{ISR} \oplus \text{FSR}$



Iterative structure of emissions, with simple DGLAP splitting kernels

FSR = Final-State Radiation = timelike shower
$Q_i^2 \sim m^2 > 0$ decreasing

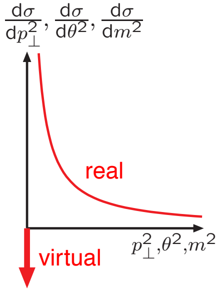
ISR = Initial-State Radiation = spacelike showers
$Q_i^2 \sim -m^2 > 0$ increasing

Showers are unitary: do not (explicitly) change cross sections; emission probabilities do not exceed unity — Sudakov factor.

Matrix Elements vs. Parton Showers

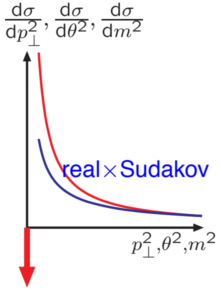
ME : Matrix Elements

- \+ systematic expansion in α_{s} ('*exact*')
- \+ powerful for multiparton Born level
- \+ flexible phase space cuts
- − loop calculations very tough
- − negative cross section in collinear regions
  $\Rightarrow$ unpredictive jet/event structure
- − *no easy match to hadronization*



PS : Parton Showers

- − approximate, to LL (or NLL)
- − main topology not predetermined
  $\Rightarrow$ inefficient for exclusive states
- \+ process-generic $\Rightarrow$ simple multiparton
- \+ Sudakov form factors/resummation
  $\Rightarrow$ sensible jet/event structure
- \+ *easy to match to hadronization*



Matrix Elements and Parton Showers

Recall complementary strengths:
- ME's good for well separated jets
- PS's good for structure inside jets

Marriage desirable! But how?

Very active field of research; requires a lecture of its own

- Reweight first PS emission by ratio ME/PS (simple POWHEG)
- Combine several LO MEs, using showers for Sudakov weights
  - CKKW: analytic Sudakov – not used any longer
  - CKKW-L: trial showers gives sophisticated Sudakovs
  - MLM: match of final partonic jets to original ones
- Match to NLO precision of basic process
  - MC@NLO: additive ⇒ LO normalization at high $p_{\perp}$
  - POWHEG: multiplicative ⇒ NLO normalization at high $p_{\perp}$
- Combine several orders, as many as possible at NLO
  - MENLOPS
  - UNLOPS (U = unitarized = preserve normalizations)

Matching/merging with PYTHIA

- Built-in NLO+PS for many resonance decays ($\gamma^*/Z^0, W^\pm, t, H^0$, SUSY, ...)
- Some few built-in +1 matching ($\gamma^*/Z^0/W^\pm + 1$ jet)
- Default max scale gives fairly good QCD jet rates, also for gauge boson pairs, top pairs (with damping), SUSY
- Accepts just about any valid Les Houches Event input (but matching at an ill–defined "scale")
- POWHEG interface extends on "scale" matching to showers
- no MC@NLO interface, but Frixione et al working on it
- MLM matching code for ALPGEN input recently introduced, coming for MadGraph5
- CKKW-L LO matching (tested for MadGraph5 input)
- UNLOPS NLO matching coming
- VINCIA: alternative antenna shower package, with ME matching on the way

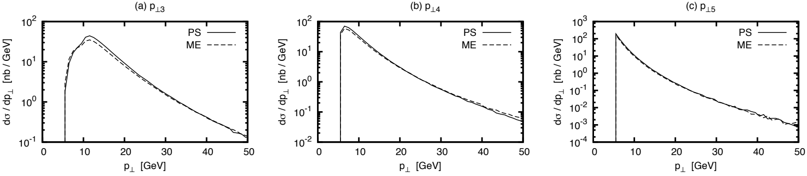
Power vs. wimpy showers – 1

Increased role of ME's at expense of PS's, but also

- desire for total increased precision
- PS's used for virtual corrections (Sudakovs)
- fast first estimate for new physics

Three main cases for starting scale of hard process (mainly ISR):

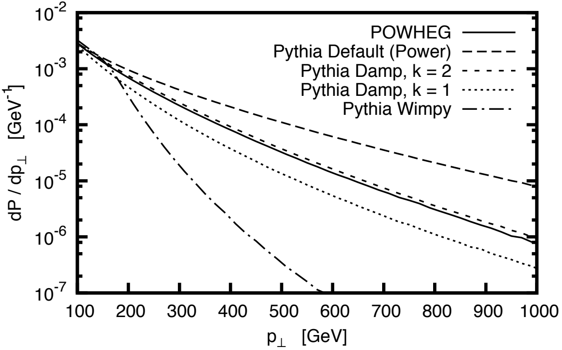
I. QCD jets: must avoid doublecounting,
shower starting scale $= p_\perp$ of hard $2 \to 2$ process.
Generally gives surprisingly good agreement, e.g. for $2 \to 3$:



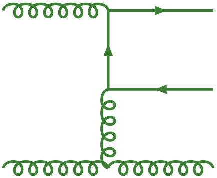
II. Production of colour singlets in final state:
no destructive interference ⇒ showers full blast ("power shower")

Power vs. wimpy showers – 2

III. Production of coloured partons in final state:
destructive interference between ISR and FSR ⇒ dampening



$t\bar{t}$ production

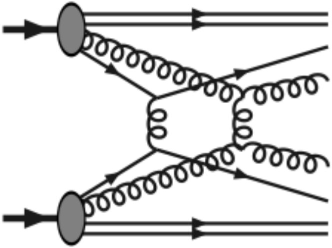


$$M^2 = m_{\perp t}^2 = m_t^2 + p_{\perp t}^2$$

Typically correct behaviour interpolates between "power" and "wimpy" (stop at scale of hard process):

$$\frac{\mathrm{d}P_{\mathrm{ISR}}}{\mathrm{d}p_\perp^2} \propto \frac{1}{p_\perp^2}\,\frac{k^2 M^2}{k^2 M^2 + p_\perp^2}$$

Multiparton interactions (MPI's)



Many parton-parton interactions per pp event: MPI.

Most have small $p_\perp, \sim 2$ GeV
$\Rightarrow$ not visible as separate jets,
but contribute to event activity.

Solid evidence that MPIs play central role for event structure.

Problem:

$$\sigma_{\mathrm{int}} = \iiint \mathrm{d}x_1\,\mathrm{d}x_2\,\mathrm{d}p_\perp^2\, f_1(x_1, p_\perp^2)\, f_2(x_2, p_\perp^2)\, \frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}p_\perp^2} = \infty$$

since $\int \mathrm{d}x\, f(x, p_\perp^2) = \infty$ and $\mathrm{d}\hat{\sigma}/\mathrm{d}p_\perp^2 \approx 1/p_\perp^4 \to \infty$ for $p_\perp \to 0$.
Requires empirical dampening at small $p_\perp$,
owing to colour screening (proton finite size).

Many aspects beyond pure theory $\Rightarrow$ model building.

Multiparton interactions modelling

Regularise cross section with $p_{\perp 0}$ as free parameter

$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}p_{\perp}^2} \propto \frac{\alpha_s^2(p_{\perp}^2)}{p_{\perp}^4} \to \frac{\alpha_s^2(p_{\perp 0}^2 + p_{\perp}^2)}{(p_{\perp 0}^2 + p_{\perp}^2)^2}$$

with energy dependence

$$p_{\perp 0}(E_{\mathrm{CM}}) = p_{\perp 0}^{\mathrm{ref}} \times \left(\frac{E_{\mathrm{CM}}}{E_{\mathrm{CM}}^{\mathrm{ref}}} \right)^{\epsilon}$$

Matter profile in impact-parameter space
gives time-integrated overlap which determines level of activity:
simple Gaussian or more peaked variants

ISR and MPI compete for beam momentum $\to$ PDF rescaling
$+$ flavour effects (valence, $\mathrm{q\overline{q}}$ pair companions, ...)
$+$ correlated primordial $k_{\perp}$ and colour in beam remnant

Many partons produced close in space–time
$\Rightarrow$ colour rearrangement; reduction of total string length
$\Rightarrow$ steeper $\langle p_{\perp} \rangle (n_{\mathrm{ch}})$

Interleaved evolution

- Transverse-momentum-ordered parton showers for ISR and FSR
- MPI also ordered in $p_\perp$

$\Rightarrow$ Allows interleaved evolution for ISR, FSR and MPI:

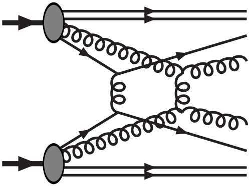
$$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}p_\perp} = \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MPI}}}{\mathrm{d}p_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{FSR}}}{\mathrm{d}p_\perp} \right) \times \exp\left(- \int_{p_\perp}^{p_{\perp\mathrm{max}}} \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MPI}}}{\mathrm{d}p'_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p'_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{FSR}}}{\mathrm{d}p'_\perp} \right) \mathrm{d}p'_\perp \right)$$

Ordered in decreasing $p_\perp$ using "Sudakov" trick.
Corresponds to increasing "resolution":
smaller $p_\perp$ fill in details of basic picture set at larger $p_\perp$.

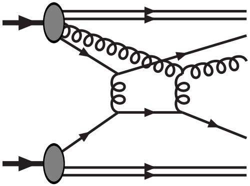
- Start from fixed hard interaction $\Rightarrow$ underlying event
- No separate hard interaction $\Rightarrow$ minbias events
- Possible to choose two hard interactions, e.g. $\mathrm{W}^-\mathrm{W}^-$

Rescattering

Often assume that MPI =



. . . but should also include



Same order in α_s, $\sim$ same propagators, but

- one PDF weight less $\Rightarrow$ smaller σ
- one jet less $\Rightarrow$ QCD radiation background $2 \to 3$ larger than $2 \to 4$

$\Rightarrow$ will be tough to find direct evidence.

Rescattering grows with number of "previous" scatterings:

	Tevatron		LHC	
	Min Bias	QCD Jets	Min Bias	QCD Jets
Normal scattering	2.81	5.09	5.19	12.19
Single rescatterings	0.41	1.32	1.03	4.10
Double rescatterings	0.01	0.04	0.03	0.15

An x-dependent proton size – 1

Normally assume that PDFs factorize in longitudinal and transverse space:

$$f(x, r) = f(x)\, \rho(r)$$

In contradiction with

- intuitive picture of partons spreading out by cascade to lower x
- Mueller's dipole cascade
- formally BFKL, Balitsky-JIMWLK, Colour Glass Condensate, ...
- Froissart-Martin $\sigma_{\mathrm{tot}} \propto \ln^2 s$

by Gribov theory related to $r_{\mathrm{p}} \propto \ln(1/x)$

- generalized parton distributions, ...

For now address inelastic nondiffrative events with ansatz:

$$\rho(r, x) \propto \frac{1}{a^3(x)} \exp\left(-\frac{r^2}{a^2(x)}\right) \quad \text{with} \quad a(x) = a_0 \left(1 + a_1 \ln \frac{1}{x}\right)$$

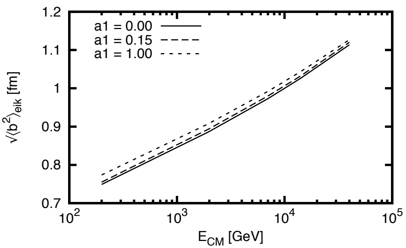
$a_1 \approx 0.15$ tuned to **rise** of σ_{ND}

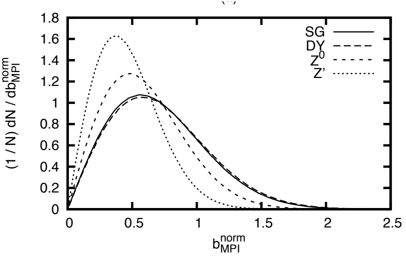
a_0 tuned to **value** of σ_{ND}, given PDF, $p_{\perp 0}$, ...]

An x-dependent proton size – 2

Convolution of two incoming protons gives impact parameter shape

$$\tilde{\mathcal{O}}(b; x_1, x_2) = \frac{1}{\pi} \frac{1}{a^2(x_1) + a^2(x_2)} \exp\left(-\frac{b^2}{a^2(x_1) + a^2(x_2)}\right)$$

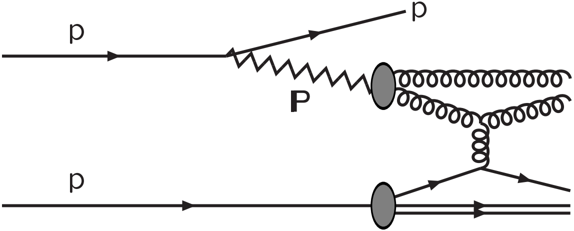




Consequence: collisions at large x will have to happen at small b, and hence further large-to-medium-x MPIs are enhanced, while low-x partons are so spread out that it plays less role.

Diffraction – 1

Ingelman-Schlein: Pomeron as hadron with partonic content
Diffractive event = (Pomeron flux) × ($\mathbb{P}$p collision)



Used e.g. in
POMPYT
POMWIG
PHOJET

1) σ_{SD} and σ_{DD} taken from existing parametrization or set by user.

2) $f_{\mathbb{P}/\mathrm{p}}(x_{\mathbb{P}}, t) \Rightarrow$ diffractive mass spectrum, $p_{\perp}$ of proton out.

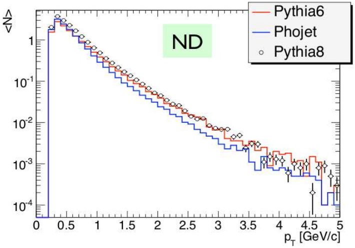
3) Smooth transition from simple model at low masses to $\mathbb{P}$p with full pp machinery: multiple interactions, parton showers, etc.

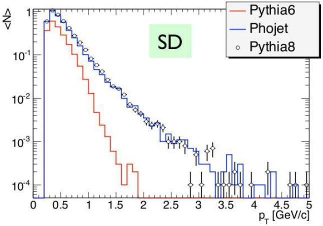
4) Choice between 5 Pomeron PDFs.

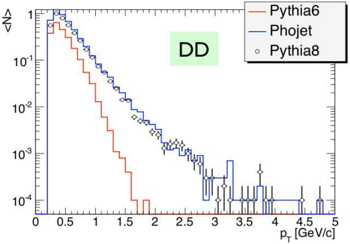
5) Free parameter $\sigma_{\mathbb{P}\mathrm{p}}$ needed to fix $\langle n_{\mathrm{interactions}} \rangle = \sigma_{\mathrm{jet}} / \sigma_{\mathbb{P}\mathrm{p}}$.

Diffraction – 2

p_T Distributions ($\sqrt{s}$=0.9 TeV)







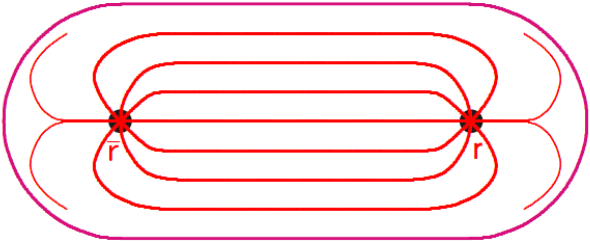
- Softer p_T spectrum in **Pythia6** due to lack of high mass diffraction
- **Pythia8** and **Phojet** agree quite well

10

Beate Heinemann, MB/UE Working Group (also Sparsh Navin)

The Lund String Model

In QCD, for large charge separation, field lines seem to be compressed to tubelike region(s) $\Rightarrow$ **string(s)**



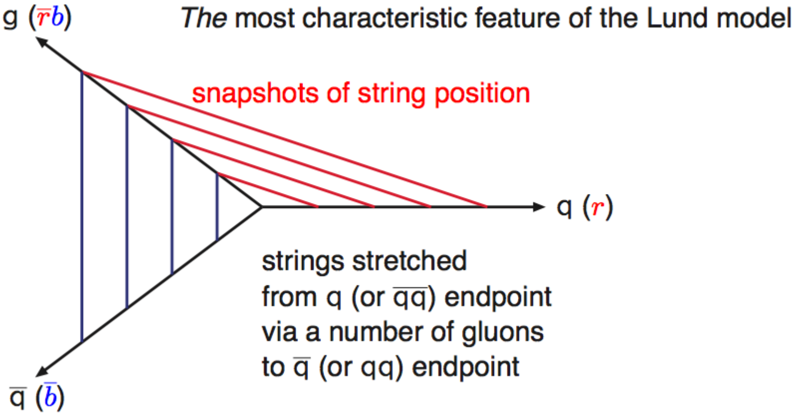
by self-interactions among soft gluons in the "vacuum".

Gives linear confinement with string tension:

$F(r) \approx \mathrm{const} = \kappa \approx 1\ \mathrm{GeV/fm} \quad \Longleftrightarrow \quad V(r) \approx \kappa r$

String breaks into hadrons along its length,
with roughly uniform probability in rapidity,
by formation of new $\mathrm{q}\overline{\mathrm{q}}$ pairs that screen endpoint colours.

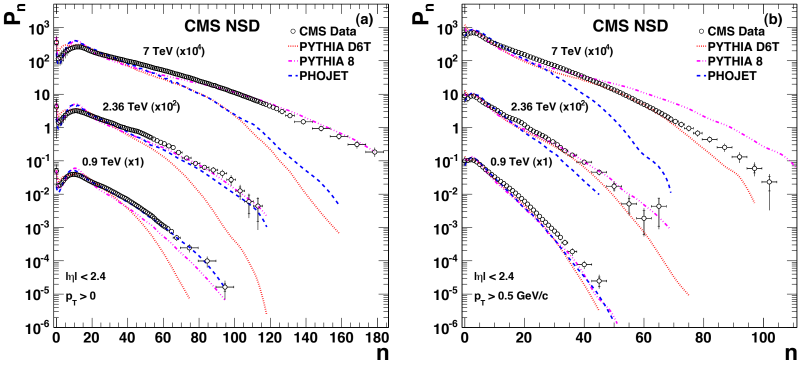
The Lund Gluon Picture



Gluon = kink on string

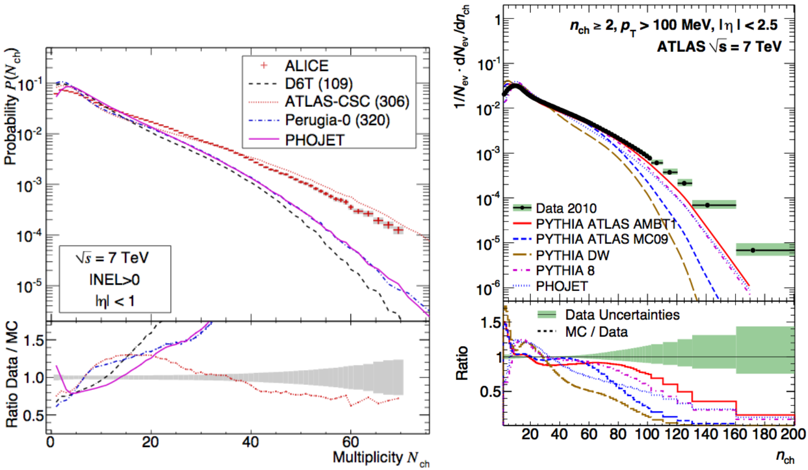
Force ratio gluon/ quark = 2,
cf. QCD $N_C/C_F = 9/4, \rightarrow 2$ for $N_C \rightarrow \infty$
No new parameters introduced for gluon jets!

Charged Multiplicity Distribution – 1



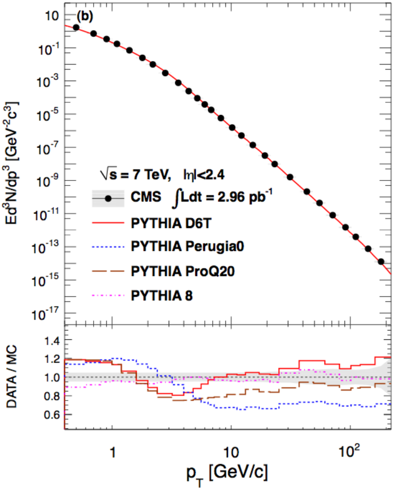
- We need to understand both average and spread.
- "Ankle": transition from one to ≥ 2 interactions?
- High multiplicity tail driven by abundant MPI rate.
- Broad spectrum of tunes even within given model.

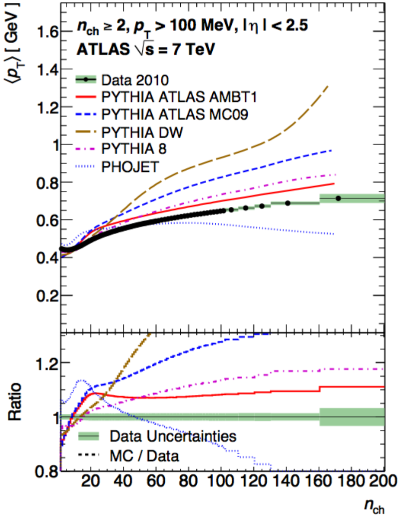
Charged Multiplicity Distribution – 2



"Ankle" also present in ALICE and ATLAS data.
Benchmark comparisons ALICE/ATLAS/CMS generally successful.

Charged Transverse Momentum Distribution





$\langle p_{\perp} \rangle$ sensitive to colour correlations between MPIs!

Some in-house tunes: “handmade”

Parameter	2C	2M	4C	4Cx
`SigmaProcess:alphaSvalue`	0.135	0.1265	0.135	0.135
`SpaceShower:rapidityOrder`	on	on	on	on
`SpaceShower:alphaSvalue`	0.137	0.130	0.137	0.137
`SpaceShower:pT0Ref`	2.0	2.0	2.0	2.0
`MultipartonInteractions:alphaSvalue`	0.135	0.127	0.135	0.135
`MultipartonInteractions:pT0Ref`	2.320	2.455	2.085	2.15
`MultipartonInteractions:ecmPow`	0.21	0.26	0.19	0.19
`MultipartonInteractions:bProfile`	3	3	3	4
`MultipartonInteractions:expPow`	1.60	1.15	2.00	N/A
`MultipartonInteractions:a1`	N/A	N/A	N/A	0.15
`BeamRemnants:reconnectRange`	3.0	3.0	1.5	1.5
`SigmaDiffractive:dampen`	off	off	on	on
`SigmaDiffractive:maxXB`	N/A	N/A	65	65
`SigmaDiffractive:maxAX`	N/A	N/A	65	65
`SigmaDiffractive:maxXX`	N/A	N/A	65	65

R. Corke & TS, JHEP 03 (2011) 032, JHEP 05 (2011) 009

Systematic tuning

RIVET: collection of experimental data, together with matching analysis routines. Can be applied to generator events for comparison with data.

PROFESSOR: parameter tuning in multidimensional parameter space.

- Generate large event samples at $\mathcal{O}(n^2)$ *random* points in (reasonable) parameter space. Slow!
- Analyze events and fill relevant histograms.
- For each bin of each histogram parametrize

$$X_{MC} = A_0 + \sum_{i=1}^{n} B_i p_i \sum_{i=1}^{n} C_i p_i^2 + \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} D_{ij} p_i p_j$$

- Do minimization of χ^2 to parametrized results. Fast!

Prepackaged tunes

`Tune:pp` selects prepackaged set of parameter changes.

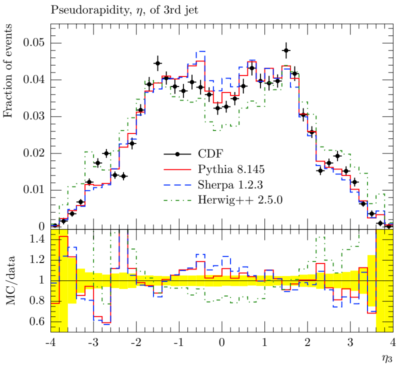
1	original values before any tunes
2	Tune 1
3	Tune 2C (CTEQ 6L1)
4	Tune 2M (MRST LO**)
5	Tune 4C
6	Tune 4Cx
7	ATLAS MB tune A2-CTEQ6L1
8	ATLAS MB tune A2-MSTW2008LO
9	ATLAS UE tune AU2-CTEQ6L1
10	ATLAS UE tune AU2-MSTW2008LO
11	ATLAS UE tune AU2-CT10
12	ATLAS UE tune AU2-MRST2007LO*
13	ATLAS UE tune AU2-MRST2007LO**

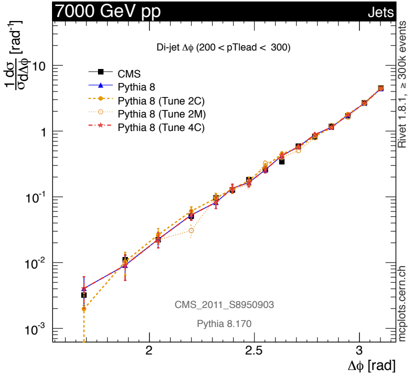
`Tune:ee` similar but less extensive for FSR and hadronization.

MCnet Marie Curie network 2007 – 2010 worked on generators and produced review

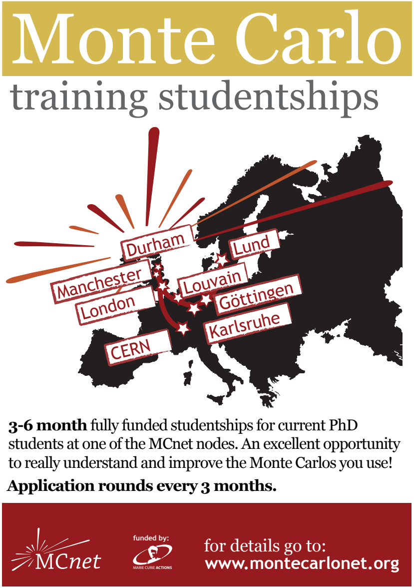
"General-purpose event generators for LHC physics", A. Buckley et al. (MCnet), Phys. Rep. 504 (2011) 145,

which compares PYTHIA 8.145 tune 4C, Herwig++, SHERPA:





MCnet – second round



MCnet funded 2013 – 2016

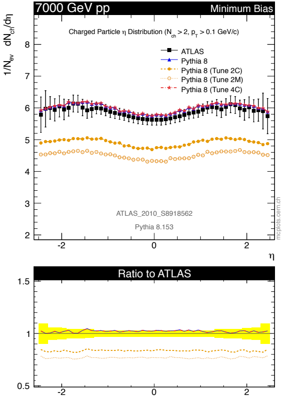
Projects:

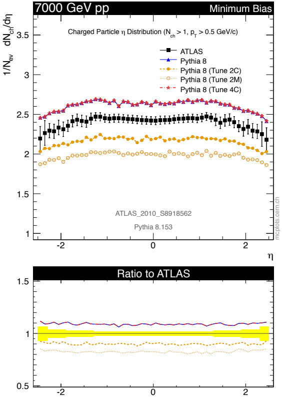
- PYTHIA (incl. VINCIA)
- Herwig
- Sherpa
- MadGraph
- Ariadne (incl. HEJ)
- CEDAR (Rivet, Professor)

MCPLOTS

Repository of comparisons between various tunes and data, mainly based on RIVET for data analysis, see `http://mcplots.cern.ch/`.
Part of the LHC@home 2.0 platform for home computer participation.

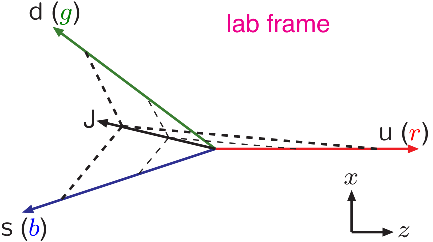
Generator	Version
alpgenherwigjimmy	
alpgenpythia6	
herwig++	
herwig++powheg	
pythia6	
pythia8	
sherpa	
vincia	

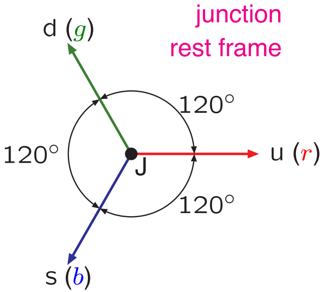


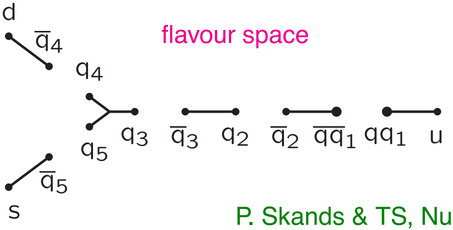


BSM physics 1: R-parity violation

Encountered in R-parity violating SUSY decays $\tilde{\chi}_1^0 \to$ uds, or when 2 valence quarks kicked out of proton beam







More complicated (but ≈solved) with gluon emission and massive quarks

P. Skands & TS, Nucl. Phys. B659 (2003) 243

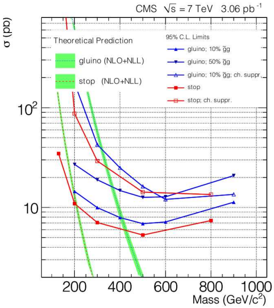
BSM physics 2: R-hadrons

What if coloured (SUSY) particle like $\tilde{g}$ or $\tilde{t}_1$ is long-lived?

- ⋆ Formation of R-hadrons

$\tilde{g}q\overline{q}$	$\tilde{t}_1\overline{q}$	"mesons"
$\tilde{g}qqq$	$\tilde{t}_1qq$	"baryons"
$\tilde{g}g$		"glueballs"

- ⋆ Conversion between R-hadrons
  by "low-energy" interactions with matter:
  $\tilde{g}u\overline{d} + p \rightarrow \tilde{g}uud + \pi^+$ irreversible
- ⋆ Displaced vertices if finite lifetime, or else
- ⋆ punch-through: $\sigma \approx \sigma_{\mathrm{had}}$ but
  $\Delta E \lesssim 1$ GeV $\ll E_{\mathrm{kin},R}$



CMS, arXiv:1101.1645

A.C. Kraan, Eur. Phys. J. C37 (2004) 91;
M. Fairbairn et al., Phys. Rep. 438 (2007) 1

Partly event generation, partly detector simulation.
Public add-on in PYTHIA 6, now integrated part of PYTHIA 8.
Can also be applied to non-SUSY long-lived "hadrons".

BSM physics 3: Hidden Valley (Secluded Sector) – 1

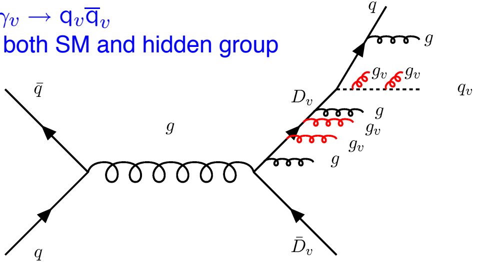
What if new gauge groups at low energy scales, hidden by potential barrier or weak couplings? (M. Strassler & K. Zurek, . . .)

Complete framework implemented in PYTHIA:

⋆ New gauge group either Abelian $U(1)$ or non-Abelian $SU(N)$

⋆ 3 alternative production mechanisms
   1) massive Z': $q\overline{q} \to Z' \to q_v\overline{q}_v$
   2) kinetic mixing: $q\overline{q} \to \gamma \to \gamma_v \to q_v\overline{q}_v$
   3) massive F_v charged under both SM and hidden group

⋆ Interleaved shower in QCD, QED and HV sectors: add $q_v \to q_v\gamma_v$ (and F_v) or $q_v \to q_v g_v$, $g_v \to g_v g_v$, which gives recoil effects also in visible sector



L. Carloni & TS, JHEP 09 (2010) 105;
L. Carloni, J. Rathsman & TS, JHEP 04 (2011) 091

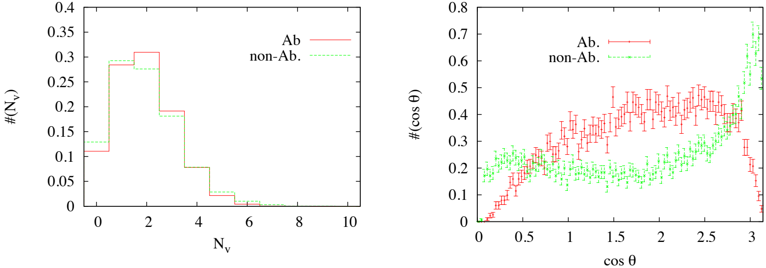
BSM physics 3: Hidden Valley (Secluded Sector) – 2

⋆ Hidden Valley particles may remain invisible, or . . .

⋆ Broken $U(1)$: γ_v acquire mass, radiated γ_vs decay back
$\gamma_v \to \gamma \to \mathrm{f}\bar{\mathrm{f}}$ with BRs as photon (⇒ lepton pairs!)

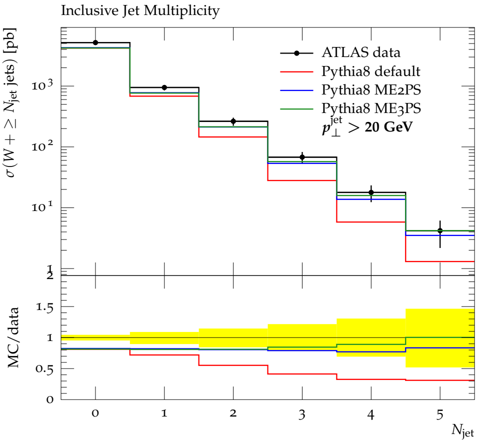
⋆ $SU(N)$: hadronization in hidden sector, with full string fragmentation, permitting up to 8 different q_v flavours and 64 $\mathrm{q}_v\bar{\mathrm{q}}_v$ mesons, but for now assumed degenerate in mass, so only distinguish
– off-diagonal, flavour-charged, stable & invisible
– diagonal, can decay back $\mathrm{q}_v\bar{\mathrm{q}}_v \to \mathrm{f}\bar{\mathrm{f}}$

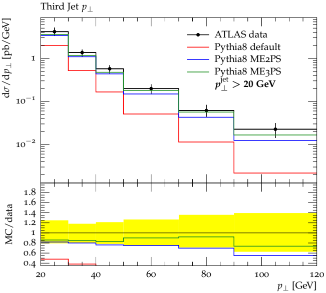
Even when tuned to same average activity, hope to separate $U(1)$ and $SU(N)$:

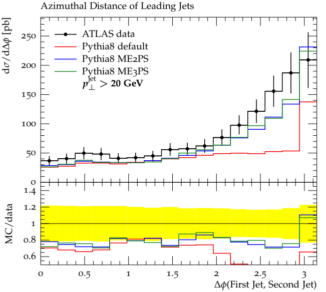


W/Z emission in showers: motivation – 1

While showers work for $W/Z + 1$ jet they fail for $W/Z + \geq 2$ jets:





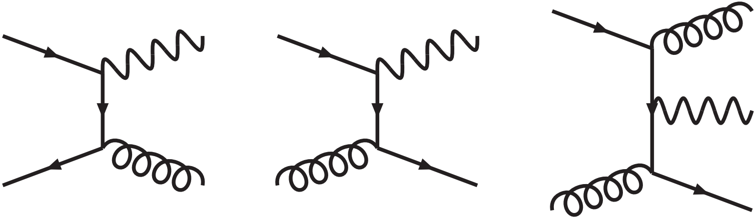


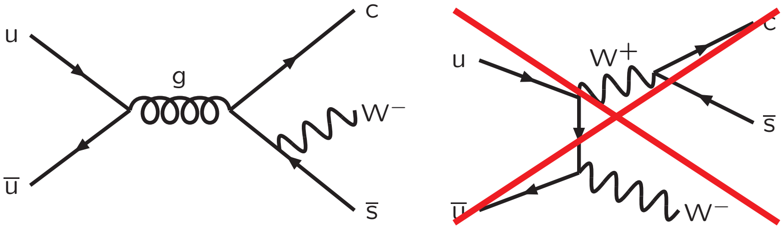
(CKKW-L merging by Stefan Prestel)

W/Z emission in showers: motivation – 2

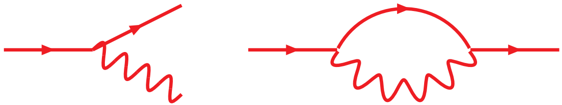
Q: So what is unique about $\mathrm{W/Z} + 2$ jets?

A: First order in which core “hard process” cannot be chosen as $\mathrm{W/Z}$ production!





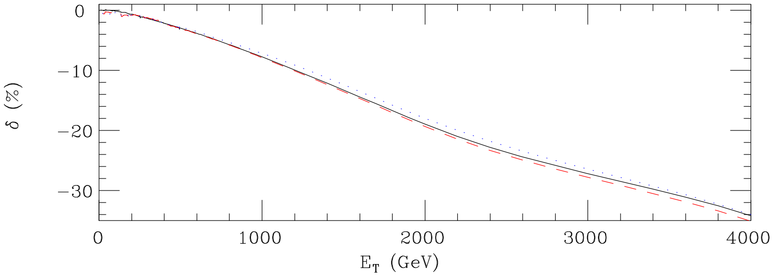
Leading electroweak corrections of type $\alpha_{\mathrm{w}} \ln^2(Q^2/M_{\mathrm{W}}^2)$:



Bloch-Nordsieck violation: real/virtual non-cancellation

W/Z in final state is another class of events

$\Rightarrow$ large negative correction to no-W/Z cross sections!



S. Moretti, M.R. Nolten and D.A. Ross, Nucl. Phys. B759 (2006) 50

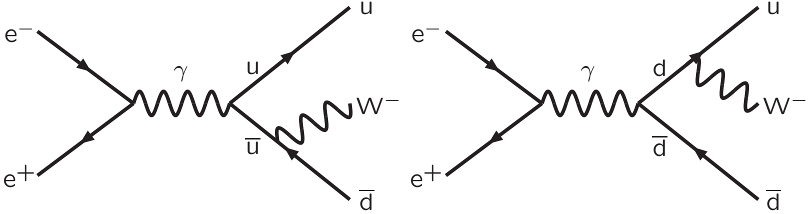
W/Z emission in showers: progress

Need to start from QCD 2 → 2 and add shower emission of $\mathrm{W/Z}$:
- FSR: final-state radiation $\mathrm{q} \to \mathrm{q}' \, \mathrm{W}^{\pm}$, $\mathrm{q} \to \mathrm{q} \, \mathrm{Z}^0$.
- ISR: partly already covered by $\mathrm{W/Z}$ production processes.

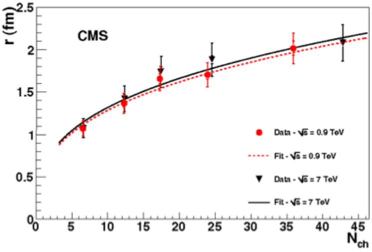
Project at a primitive stage; for now only $\mathrm{e}^+\mathrm{e}^-$ annihilation.

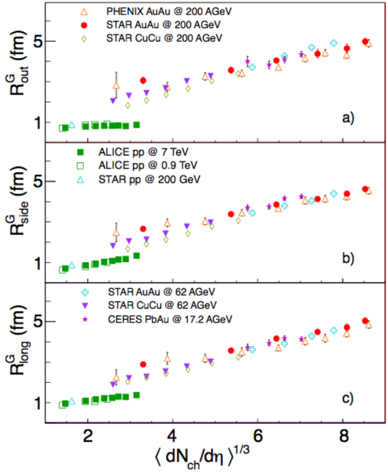
Formulated as dipole emission, *interleaved* with QCD emissions

For W emission interference between two dipole ends
is replaced by interference between two flavour topologies:



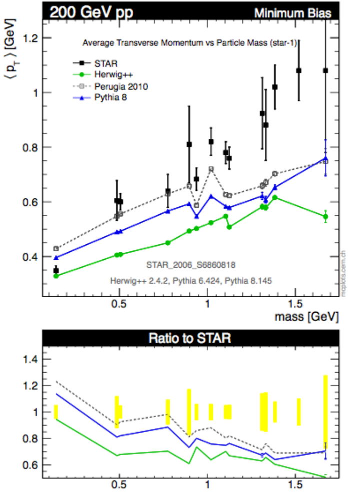
Bose-Einstein $r(N_{\mathrm{ch}}) \propto N_{\mathrm{ch}}^{1/3}$
cannot be accommodated
in PYTHIA effective description
that worked at LEP

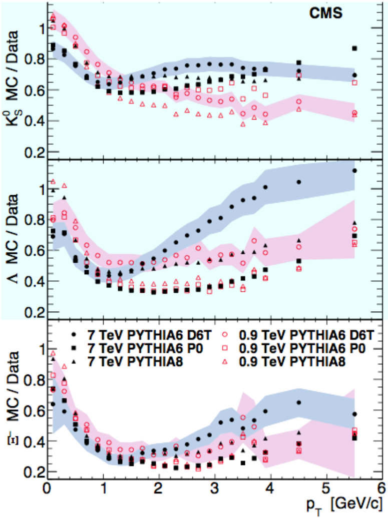




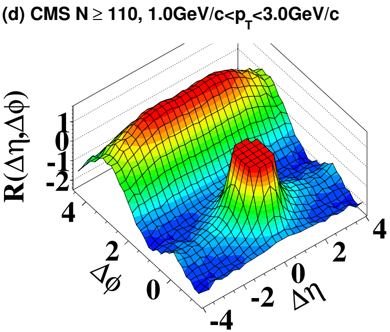
Multiple overlapping fragmenting strings ⇒ dense hadron gas!

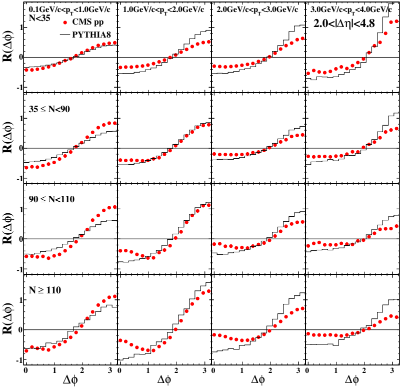
Need more $p_\perp$ for K, p, Λ, ..., relative to $\pi^{\pm}$:





Cloud #3: The Ridge





Geometry of colliding protons (non-symmetric shapes)?
Collective phenomena?

Strengths and weaknesses

(subjectively, absolute or compared with Herwig++ and Sherpa)

- $+$ fair selection og built-in processes ready to go
- $-$ no built-in ME generator (need e.g. MadGraph)
- $-$ matching/merging/NLO usually not automatic
- $\pm$ parton showers of comparable quality
- $+$ most sophisticated & robust MPI framework
- $+$ models for diffractive events
- $+$ most sophisticated & robust hadronization framework
- $-$ no QED in hadronic decays (need e.g. Photos)
- $+$ interfaces & many options $\Rightarrow$ flexible
- $+$ user-friendly, well documented, many examples
- $+$ generally comparing well with LHC data ...
- $-$ ... but known discrepancies, e.g. flavour composition

Summary and outlook

- PYTHIA 6 is winding down
  - currently supported but not developed
  - *not* supported after long shutdown 2013–14
- PYTHIA 8 is the natural successor
  - is (sadly!) not yet quite up to speed in *all* respects
  - but for most physics clearly better than PYTHIA 6
- Advise/plea to experimentalists
  - gradually step up PYTHIA 8 usage to gain experience
  - if you want new features then be prepared to use PYTHIA 8
  - provide feedback, both what works and what does not
  - make relevant data available in RIVET
  - do your own tunes to data and tell outcome

News list:

`http://www.hepforge.org/lists/listinfo/pythia8-announce`

The work is never done!