# Rivet

## and (my) prospects for ALICE

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# outline

trying to **bridge between technical and physics aspects**

- Monte Carlo (QCD) event generators
- Rivet framework and analyses
- examples of relevant analyses
  (biased to scope of ALICE)
- parameters and tuning
- particularities of heavy-ion analyses

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there will be code snippets to **illustrate concepts**,

but this is **NOT meant to be a Rivet tutorial**!

# setting the stage

- **data**: measurements at hadron colliders
- **goal**: test QCD and/or QCD-inspired models
- **involved analyses**
  with finite acceptance, trigger conditions, non-trivial cuts, ...
  (normally **corrected for detector effects**)
- **non-trivial algorithms** on measured final states
  to extract physics objects (e.g. jet finders)
- analyses published in paper,
  data values (often) published on HepData

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comparison to theory often requires full final state

$\rightsquigarrow$ **Monte Carlo event generators**

# Monte Carlo event generators

event generators serve various purposes:

- provide **explicit final state** (at least those used with Rivet), also with complex phase space
- test theory and models
- reproduce known/expected processes
  - detector performance studies
  - efficiency evaluation
  - background subtraction
  - ...
- some have lots of tuning freedom:
  good to reproduce data, limited theory insight
- some implement a well-constrained idea:
  good to test idea, limited possibility to adapt to data

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$\rightsquigarrow$ **Monte Carlo generators** with different focus/goal

# Monte Carlo modelling

consider **pp collisions at LHC**:

- assuming factorisation
  $\rightsquigarrow$ decoupling of short/long-range processes
- hard interaction (hard scattering, hard ISR/FSR)
  - hard scale $\rightsquigarrow$ pQCD description
  - multi-parton interactions
- parton shower/cascade
  - sequential branchings (DGLAP evolution)
  - initial/final state radiation
  - parameters: $\alpha_{\mathrm{s}}$, intrinsic $k_{\mathrm{t}}$, $Q_0^2$ cut off for initial/final state radiation
- hadronisation
  - below cut-off scale:
    phenomenological hadronisation model
- underlying event (everything but hard interaction)

# general purpose generators (pp)

- PYTHIA 6/8 [hep-ph/0603175, 1410.3012]
  - fixed implementation of hard processes
  - multi-parton interactions (controlled by shape and $p_{\mathrm{T},0}$)
  - $p_{\perp}$-ordered parton shower (earlier virtuality-ordered)
  - Lund string hadronisation
- Herwig(++) [hep-ph/0011363, hep-ph/0210213, 0803.0883]
  - automatic generation of hard processes
  - multi-parton interactions
  - angular-ordered parton shower
  - cluster hadronisation
- Sherpa [0811.4622]
  - modular matrix element generation
  - multi-parton interaction similar to PYTHIA
  - dipole shower
  - cluster hadronisation

# further generators

- POWHEG BOX [hep-ph/0409146, 0709.2092, 1002.2581]
  - matching of NLO calculations with parton showers by implementation of POWHEG method (Positive Weight Hardest Emission Generator)
  - relevant for cross sections at NLO precision
- DIPSY [http://home.thep.lu.se/DIPSY/]
  - generator based on ThePEG framework (Dipoles in Impact Parameter Space and rapidity (Y))
  - rope hadronization
- Alpgen, MadGraph, MC@NLO, ...

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large variety of Monte Carlo generators + tunes

$\rightsquigarrow$ need for **reliable comparison to data**

can be **difficult to reproduce analysis purely from paper**

# history

- pre-LHC solution: **HZTool**
  analysis library, focussed on H1 and ZEUS
  [http://hztool.hepforge.org]
- preparations for **physics at LHC**
- emergence of **FastJet**
  as "standard" tool for jet finding
  [http://fastjet.fr]
- efforts of the phenomenology community led to **Rivet**
  [http://rivet.hepforge.org]

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$\rightsquigarrow$ **Rivet**

tools to calculate observables
and library of analyses

# Rivet

# Rivet

Robust Independent Validation of Experiment and Theory:

- **generator-agnostic analysis framework**,
  co-evolved with fastjet
- reads input from Monte Carlo generator
  (from file/FIFO)
- runs one (or more) analyses on the input data
- produces plots corresponding to available measurements
  with comparison MC/data
- distributed with (validated) analyses and corresponding data

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in the following: **focus on concepts**

detailed documentation:
Rivet user manual, tutorials

# HepMC

need **interface between generator and analysis**:

- **HepMC**: standardized event record
  contains final state particles
  (with Monte Carlo information)
- direct output of (most) modern generators,
  for others: interface software (e.g. Agile)

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de-facto standard for generator output
(still evolving, e.g. for heavy-ion)

[http://lcgapp.cern.ch/project/simu/HepMC/]

# Rivet architecture

- **framework**
  - loading and steering of analysis
  - input/output of data and results
  - analysis tools, including interface to fastjet
  - plotting (now based on YODA, previously AIDA)
- **library of analysis plugins**
  - about 300 distributed with Rivet (as of version 2.3.0)
  - new ones can be added locally
    or contributed (once mature enough)

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user interaction with Rivet through executables:

- rivet
- rivet-mkhtml, rivet-mkanalysis
- rivet-cmphistos
- make-plots

# Rivet analysis

Rivet analysis comprises

- ID `<experiment>_<year of publication>_I<inspire ID>`
- title
- description:
  short summary of the analysis content
  collision system and energies
  reference to paper
  status: preliminary, unvalidated, validated, obsolete, ...
- algorithm:
  code to reproduce the analysis on Monte Carlo output
- data:
  measured data points and uncertainties

e.g. look at:

```
rivet --show-analysis ALICE_2011_S8945144
```

# Rivet implementation

- user can easily provide additional analyses by implementing C++ class inheriting from Rivet::Analysis
- one can start from a template

```
rivet-mkanalysis MC_MY_ANALYSIS
```

- requires implementation of
  - init
    definition of projections (final states), booking of histograms, ...
  - analyze
    per-event analysis (whatever it may be), histogram filling, ...
  - finalize
    typically normalisation to cross section, ...
- analysis built by

```
rivet-buildplugin MC_MY_ANALYSIS.cc
```

- analyses loaded from library and run by

```
rivet -a MC_MY_ANALYSIS output.hepmc
```

# projections

abstraction of common physical entities $\rightsquigarrow$ projections
(avoid repetition of computing-intense calculations)

- charged particles

```
const ChargedFinalState cfs(-3.2, 3.2);
addProjection(cfs, "CFS");
```

- charged jets

```
FastJets fj(cfs, FastJets::ANTIKT, 0.4);
addProjection(fj, "Jets");
```

analysis typically iterates on such projections:

```
const FinalState &cfs =
  applyProjection <FinalState> (evt, "CFS");
foreach (const Particle &p, cfs.particles()) {
  // fill histogram
}
```

# histograms

- histogramming based on external package (YODA)
- book histogram manually:

```
_hist = bookHisto1D("pt_h", 10, 0., 20.,
                    "ch. part.",
                    "$p_\\perp$", "counts");
```

- book histogram according to reference histogram:

```
_hist = bookHisto1D("d01-x01-y01")
```

name corresponding to the one from HepData

- fill histograms with event weight:

```
const double weight = event.weight();
_hist->fill(phi, weight);
```

for proper uncertainties (and merging)

# HepData interaction

- for published analyses:
  values can usually be obtained from HepData
- **natural integration with HepData**
  useful for retrieval of experimental data
- for published analysis (e.g. ALICE UE):
  `rivet-mkanalysis ALICE_2011_I1080735`
  creates template and downloads data files
- for unpublished analysis:
  reference data must be fed manually

# example

```
namespace Rivet {
  class MC_MY_ANALYSIS : public Analysis {
    public:
    MC_MY_ANALYSIS() : Analysis("MC_MY_ANALYSIS") { }

    void init() {
      const ChargedFinalState cfs(-.9, .9);
      addProjection(cfs, "CFS");

      const FinalState fs_jet(-1., 1.);
      addProjection(fs_jet, "FS_JET");
      FastJets fj02(fs_jet, FastJets::ANTIKT, .2);
      addProjection(fj02, "Jets02");

      _h_pt_jet02 = bookHisto1D("pt_jet", 20, 0., 100.);
    }
    ...
```

# example (cont'd)

```
    void analyze(const Event& event) {
      Jets alljets = applyProjection<FastJets>(event, "Jets02").
        jetsByPt(0., 200., -.8, .8);
      foreach (const Jet &jet, alljets)
        _h_pt_jet02->fill(jet.momentum().pT(), event.weight());
    }

    void finalize() {
      const double fac =
        crossSection() / (millibarn * sumOfWeights() * 2 * pi);
      scale(_h_pt_jet02, fac);
    }

    private:
    Histo1DPtr _h_pt_jet02;
    DECLARE_RIVET_PLUGIN(MC_MY_ANALYSIS);
  }
}
```

# mcplots

- availability of Rivet analyses allows for **automatized creation of comparison plots**
- large number of generators and tunes
- **mcplots** project hosted at CERN
  - generate events using voluntary computing (Test4Theory, LHC@home)
  - run analyses
  - provide interface to plot comparison of selected generators/tunes to data
- **good overview** of quality of description by MC generators

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$\rightsquigarrow$ extensive source of comparison plots:

`https://mcplots.cern.ch`

[http://arxiv.org/abs/1306.3436]

# pp physics

# applications for physics

simultaneous comparison to many observables,
some interesting ones are:

- jets (spectra, fragmentation, shapes, . . . )
- identified particle spectra
- multiplicity distributions
- underlying event
- . . .

many of these plots are available from mcplots

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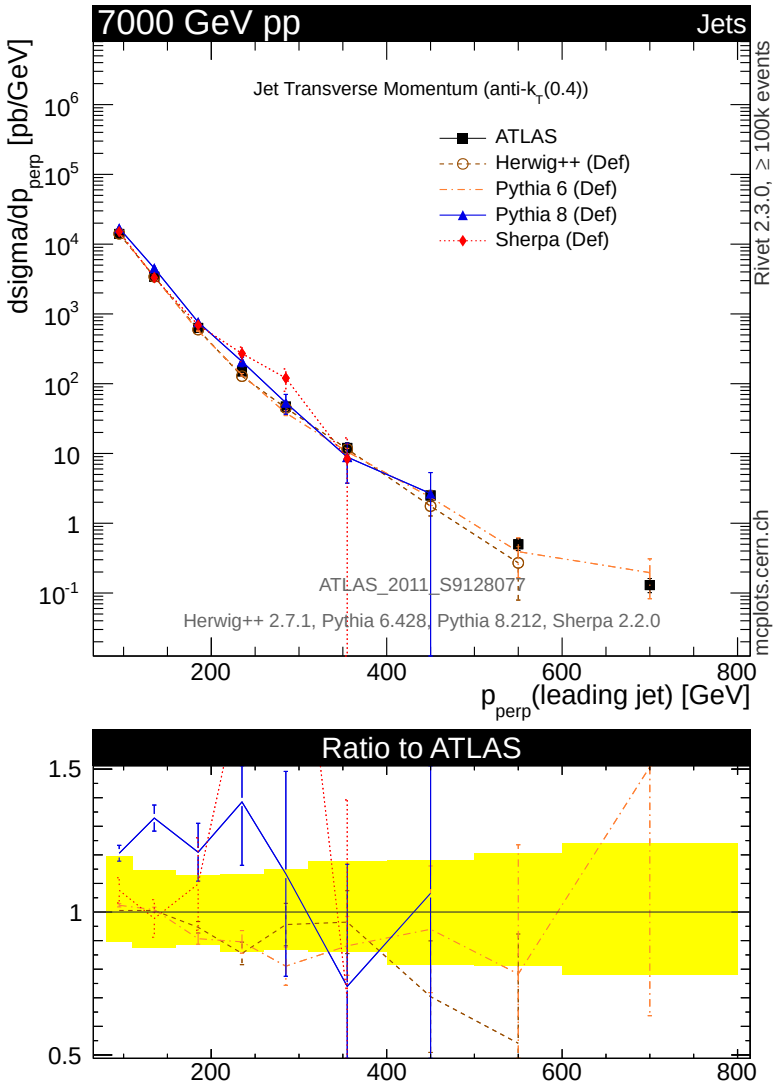
wide-spread possibilities,
**biased selection of examples**

# jets




[mcplots.cern.ch]

- spectra [arXiv:1107.2092]
  - crucial check of hard interactions
  - also critical as background
- fragmentation [ATLAS-CONF-2010-049]
  - longitudinal momentum fraction
    probes parton shower
    and hadronisation
- transverse shape [arXiv:1101.0070]
  - radial dependence
    probes transverse evolution
  - mostly sensitive to shower

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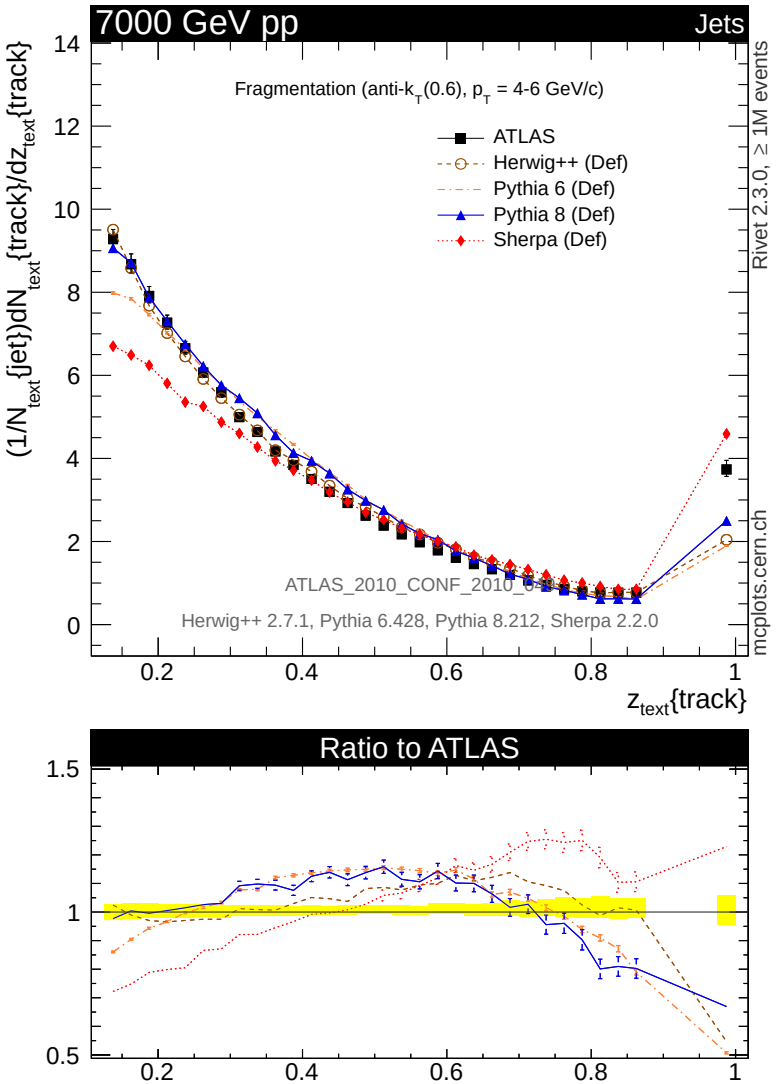


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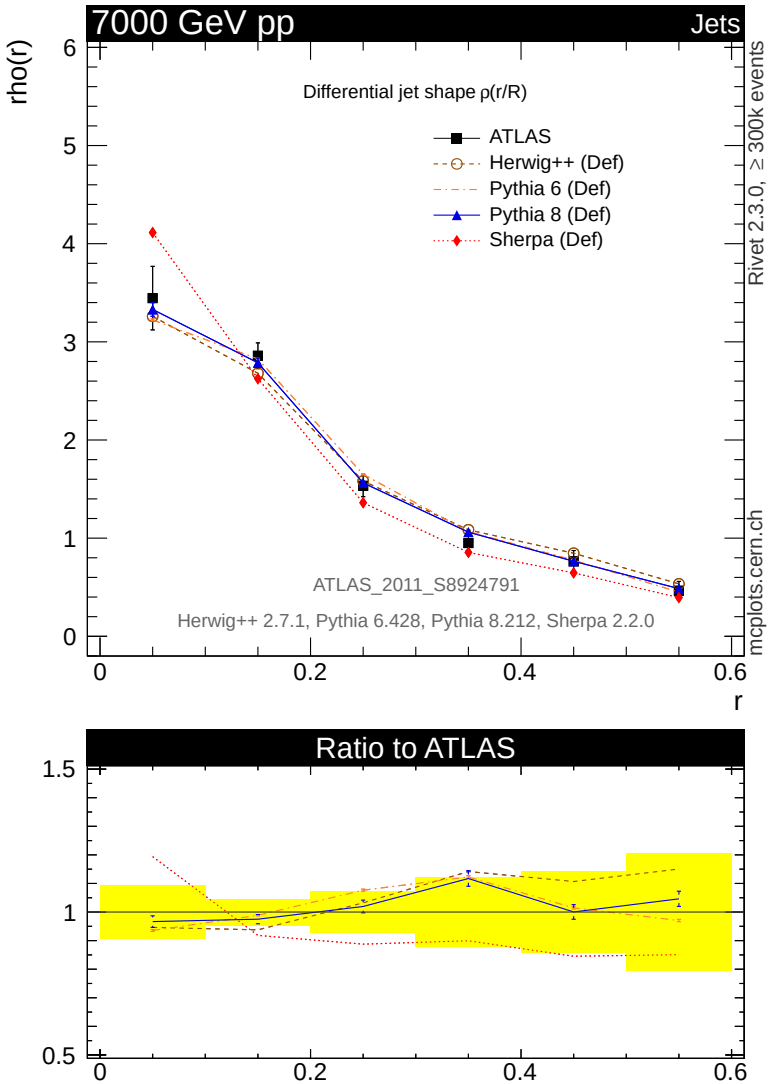


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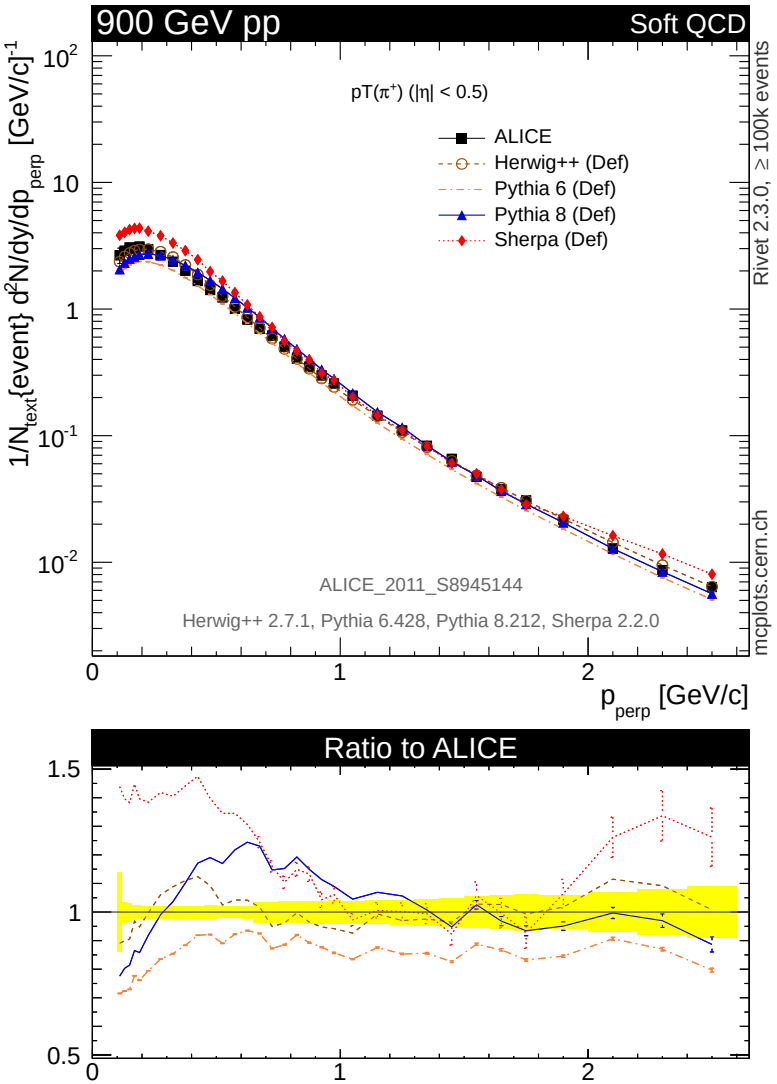
# identified particle spectra




[mcplots.cern.ch]

- spectra of [arXiv:1101.4110]
  - pions
  - kaons
  - protons
- contributions at low and high $p_\perp$
- important to constrain fragmentation and hadronisation
- collective effects (HI-like) modify spectra

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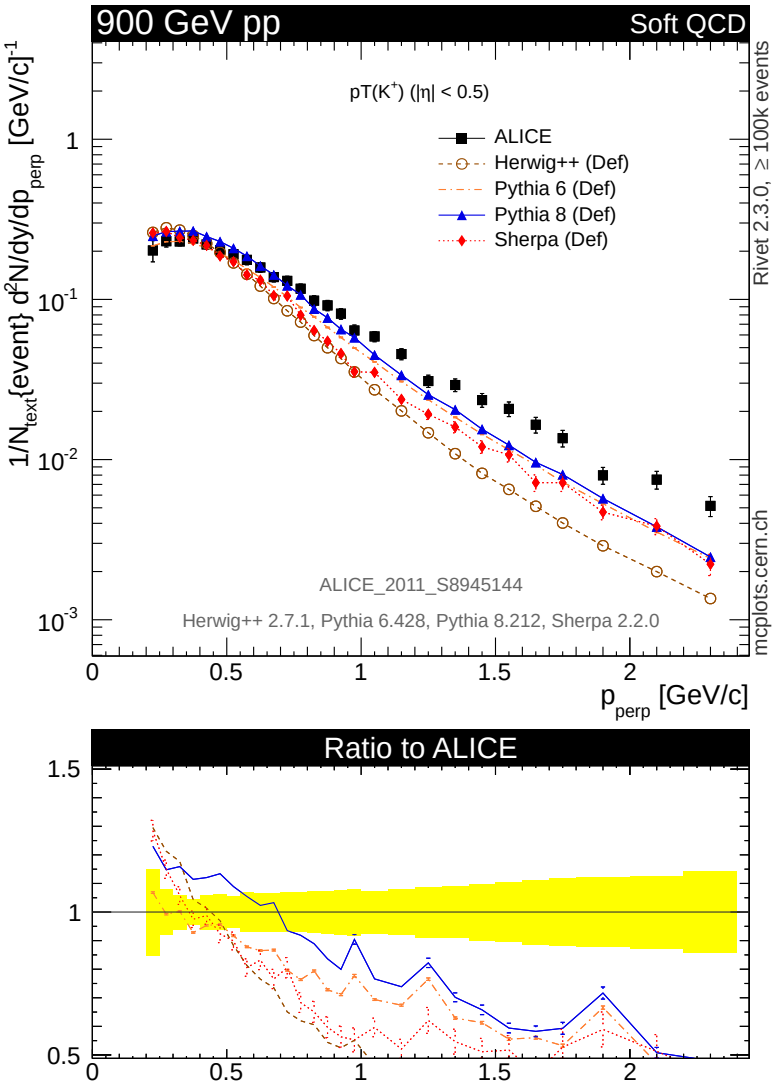


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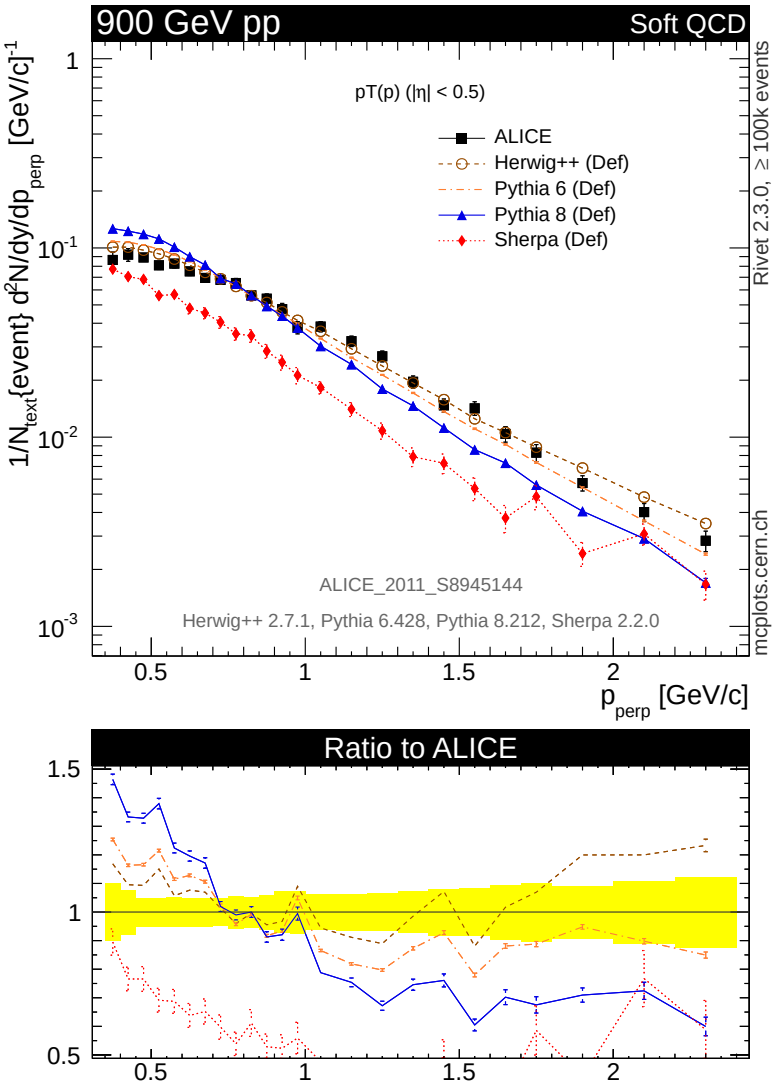


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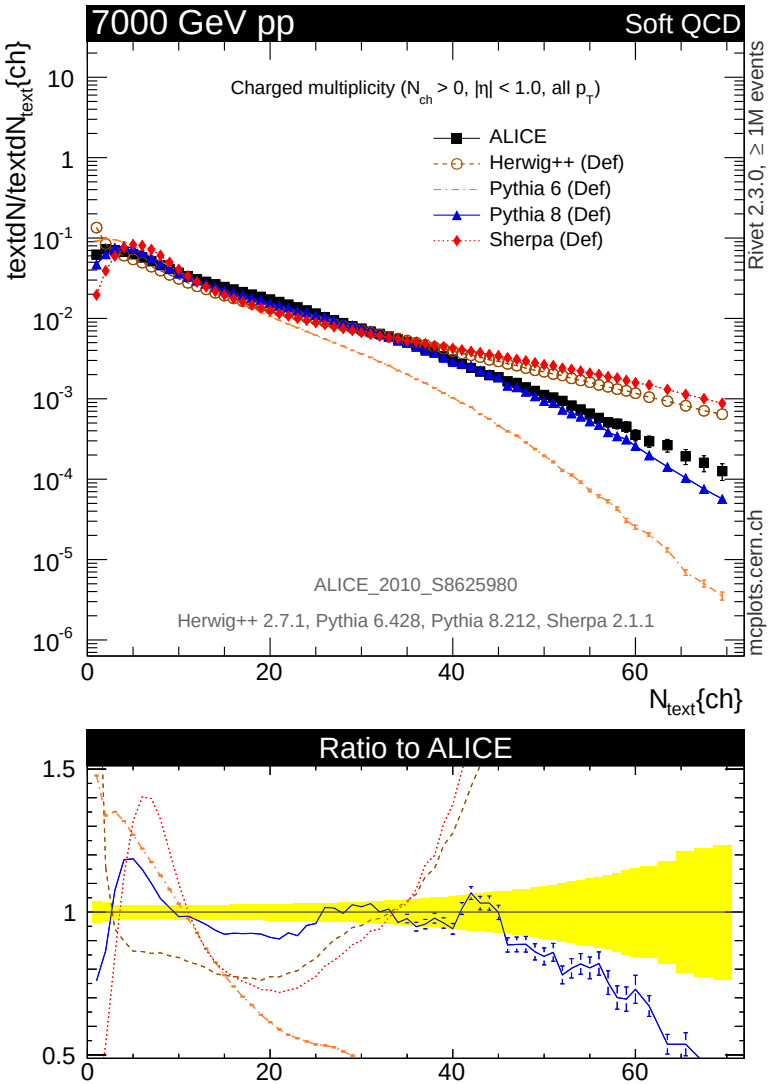


[mcplots.cern.ch]

- charged particles around mid-rapidity [arXiv:1004.3514]
- addresses question of particle production
- differently well described by Monte Carlo generators
- comparison to
  - different generators
  - different tunes of PYTHIA 8

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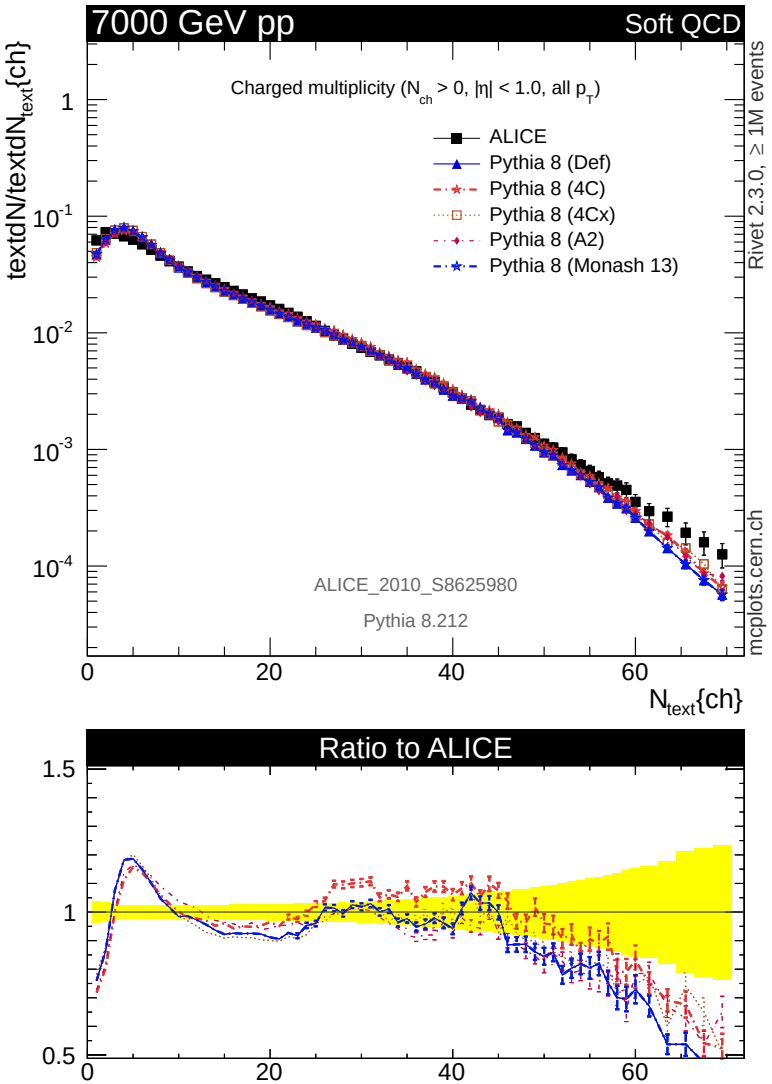


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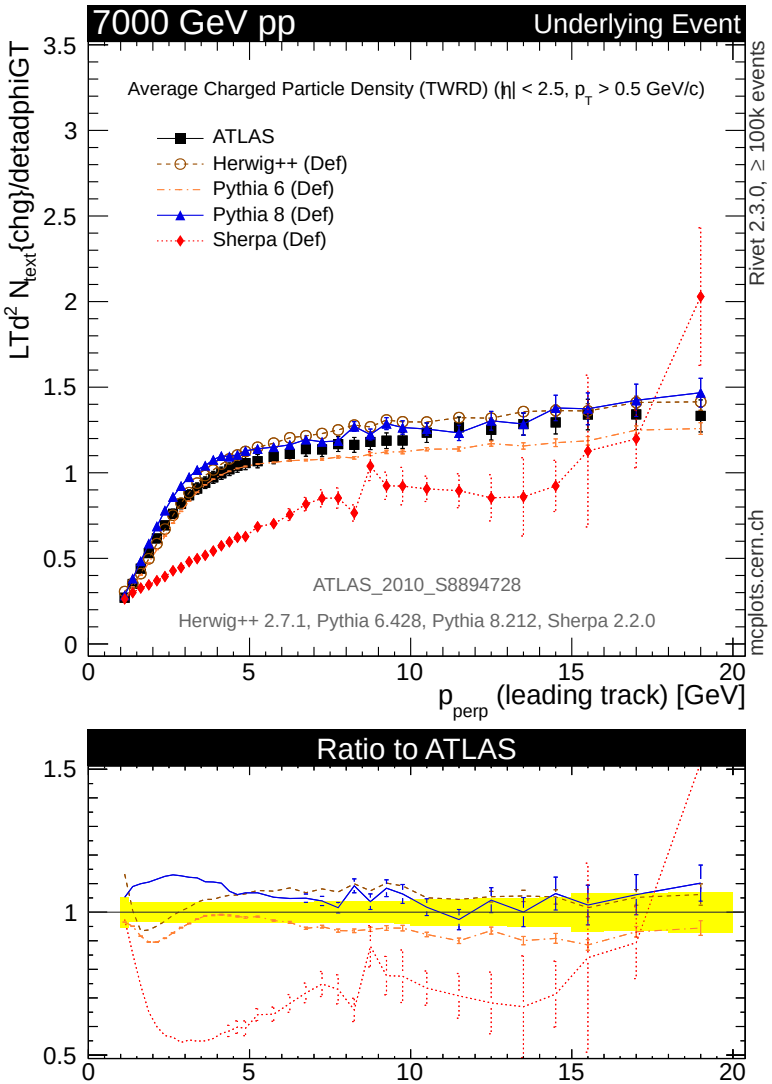
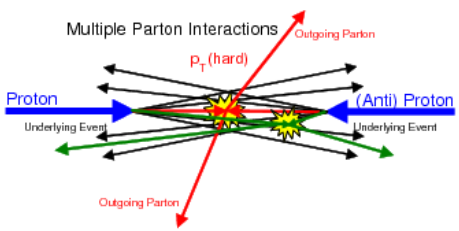
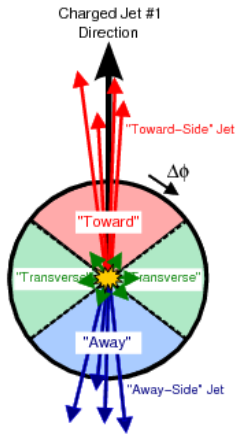
# underlying event




[mcplots.cern.ch]

- UE contributes to particle yield critical for proper description
- particle yield [arXiv:1012.0791] in regions w.r.t. trigger particle
  - towards
  - away
  - transverse




- ALICE results [arXiv:1112.2082] not in Rivet yet

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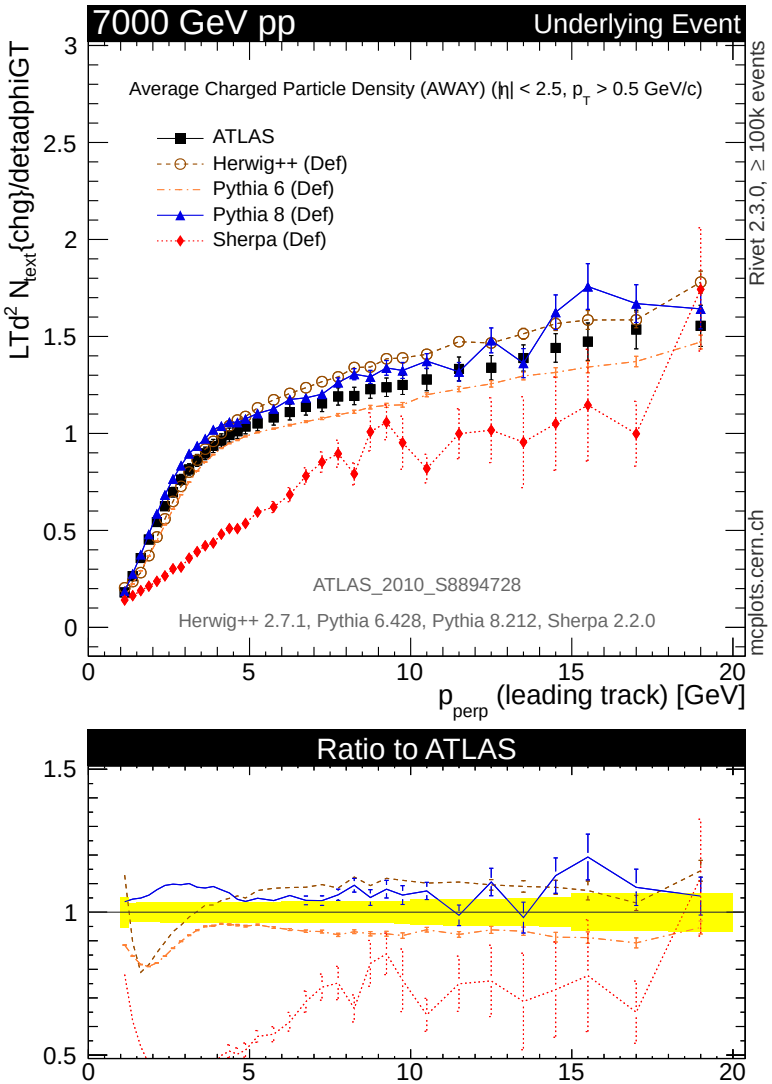


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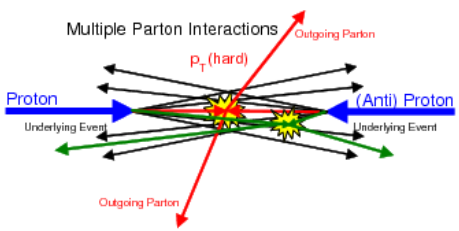


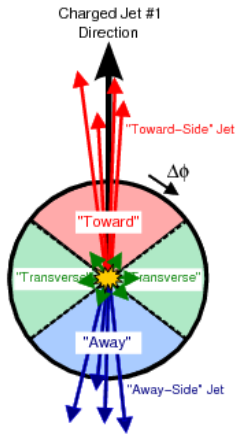


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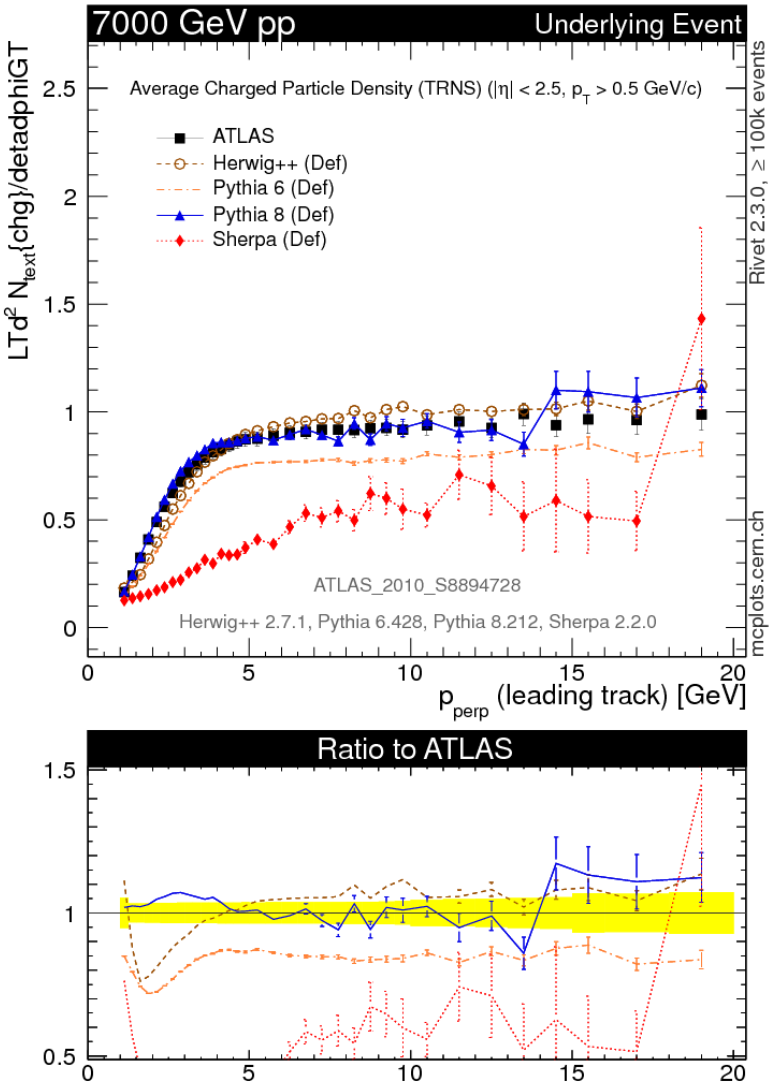


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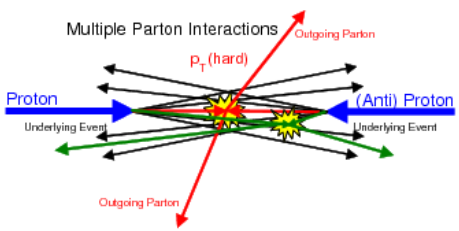


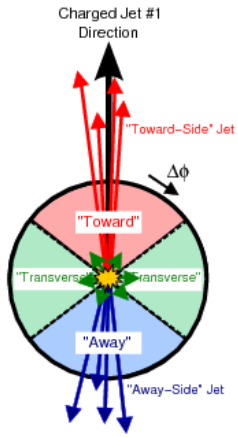


- ALICE results [arXiv:1112.2082] not in Rivet yet

# usage of Rivet-published data

some examples of Rivet usage by phenomenology community:

- Systematic event generator tuning for the LHC
  [0907.2973]
- Constraining MPI models using $\sigma_{\mathrm{eff}}$
  and recent Tevatron and LHC Underlying Event data
  [1307.5015]
- Hydrodynamics and Jets in Dialogue
  [1407.1782]
- Origins of the di-jet asymmetry in heavy ion collisions
  [1512.08107]
- Sensitivities to PDFs
  in parton shower MC generator reweighting and tuning
  [1601.04229]
- many more,
  e.g. more than 200 Rivet-citing papers on inspire

# ALICE analyses

```
rivet --list-analyses ALICE_
```

| | |
|---|---|
| ALICE_2010_S8624100 | Charged particle multiplicities at 0.9 and 2.36 TeV in three different pseudorapidity intervals |
| ALICE_2010_S8625980 | Pseudorapidities at three energies, charged multiplicity at 7 TeV |
| ALICE_2010_S8706239 | Charged particle $\langle p_{\mathrm{T}} \rangle$ vs. $N_{\mathrm{ch}}$ in pp collisions at 900 GeV |
| ALICE_2011_S8909580 | Strange particle production in proton-proton collisions at $\sqrt{s} = 0.9$ TeV with ALICE at the LHC |
| ALICE_2011_S8945144 | Tranverse momentum spectra of pions, kaons and protons in pp collisions at 0.9 TeV |
| ALICE_2012_I1181770 | Measurement of inelastic, single- and double-diffraction cross sections in protonproton collisions at the LHC with ALICE |
| ALICE_2014_I1300380 | Production of $\Sigma(1385)^{\pm}$ and $\Xi(1530)^{0}$ in proton-proton collisions at $\sqrt{s} = 7$ TeV |
| ALICE_2015_I1357424 | Tranverse momentum spectra of pions, kaons and protons in pp collisions at 7 TeV |

# prospects for ALICE

- ALICE covers complementary aspects in pp physics (low $p_\perp$ tracking, particle identification, ...)
- relevant analyses
  - jet shapes
  - identified particles in jets
  - underlying event
  - strangeness production
  - multiplicity dependence
  - ...
- on-going efforts to publish Rivet plugins for more analyses, both on-going and already published ones

# tuning

# tuning

- so far considered MC generator and tune as given
- large parameter space
  at least for phenomenological descriptions
- **parameters need to be tuned** to experimental data
  - manually by eye
    good control of changes
    but needs understanding of model and parameter effect
  - brute-force scan of parameter space
    infeasible for more than a few parameters
- some commonly used tunes
  - Pythia 6: Perugia 0, 2011, 2012 (manual)
  - Pythia 8: Monash 2013 (manual)
  - ...

---

$\rightsquigarrow$ **Professor** [arXiv:0907.2973]

# Professor

- **problem**: MC performance depends on choice of parameters
- **goal**: find optimal vector of parameters (**P**)
- **criterion**: minimal Goodness-of-Fit for deviation
  based on comparison using Rivet analyses for judgement
- **but**: numerical minimisation requires many evaluations of GoF,
  each evaluation requires large generator run

---

with **PROcedure For EStimating Systematic errORs**
(long form abandoned):

- parameterize per-bin response
  by sampling of parameter space
- minimize GoF based on parameterized response
- validation

# Professor tune - example

- first production tuning using Professor:
  systematic tune of Pythia 6.418 [0907.2973]
- tune in stages:
  - start from default values
  - tune flavour parameters
    using precision data from LEP/SLAC
  - tune shower and (non-flavour) hadronisation parameters
    using LEP data
  - tune UE and MPI parameters
    using data from CDF and D0
- tune verification
  by comparing parameterized and actual deviations
  around optimal parameters

---

$\rightsquigarrow$ established systematic tune
also as starting point for other tunes

# impact on tuning

- usage of Rivet analysis much less error-prone
  than re-implementation of analysis from paper
- results published for Rivet are used preferentially
  for (automatized) comparison with generators
- Rivet analyses are typically used for tunes,
  either manually or automatized
- deviations from Rivet analyses can be spotted easily
  and by everyone (e.g. on mcplots)
  $\rightsquigarrow$ good monitoring of MC performance and sensitivity

---

$\rightsquigarrow$ **strong motivation for Rivet publications**
in order for the data to be used

# heavy-ion

# heavy-ion analyses

heavy-ion (motivated) analyses often differ from HEP:

- classification of events
  - centrality (impact parameter)
  - event plane
  - event shape
  - ...
- "event-global" analyses, e.g.
  - correlations in $\Delta\varphi$, $\Delta\eta$, $p_\perp$, ...
    typically using event mixing for corrections
  - fluctuations
  - ...
- post-processing
  - comparison Pb–Pb to pp
  - yield extraction
  - ...

# heavy-ion generators

generators focus on some aspects

- HIJING [nucl-th/9502021]
  - multi jet production
- AMPT [nucl-th/0411110]
  - HIJING for initial conditions
  - parton cascade
  - relativistic transport
- EPOS [hep-ph/0007198]
  - parton ladders
  - collectivity

jet quenching:

- JEWEL [1311.0048]
  - hard interaction from PYTHIA
  - parton shower with medium interaction
    $\rightsquigarrow$ energy loss
  - PYTHIA for hadronisation
- YaJEM [1009.3740]
  - parton shower with energy loss

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$\rightsquigarrow$ **no general-purpose heavy-ion generator**

not all provide HepMC final state for usage with Rivet

# prospects for heavy-ion analyses

- there is not one universal Monte Carlo generator
  focus on some aspects of heavy-ion physics
- Monte Carlo comparisons of heavy-ion generators
  not (yet) as systematic and global as for HEP
- aim to do more global comparisons

...

# (current) limitations

Rivet was developped for HEP needs, not heavy-ions,
e.g. post-processing of results not foreseen:

- combination of results from different collisions systems,
  e.g. Pb–Pb / pp (like $R_{\mathrm{AA}}$)
- fits
  no integrated possibility for fitting,
  e.g. for determination of peak width
- yield extraction
  extraction of particle yield e.g. from invariant mass distribution
  requires fitting or bin counting and background subtraction

---

$\rightsquigarrow$ **not all analyses are straight-forward to implement**,
some technical aspects in Rivet need to be addressed

# summary

# summary

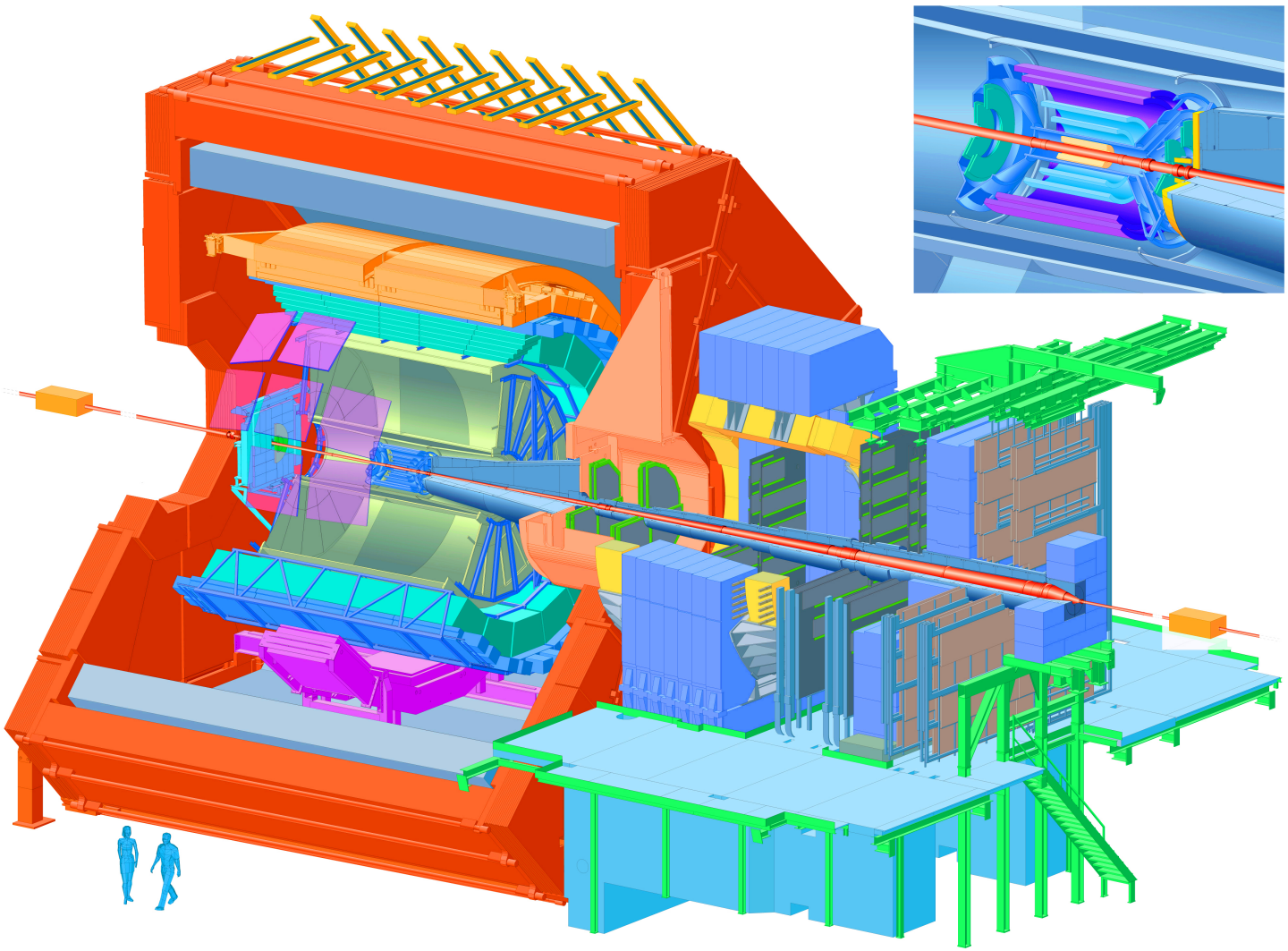
- Monte Carlo tools valuable tool for physics interpretation
- reliable comparisons of Monte Carlo generators to data needed, experiments providing Rivet analyses
- Rivet as a tool to
  - archive and publish measurements, i.e. analysis and data
  - compare different event generators

---

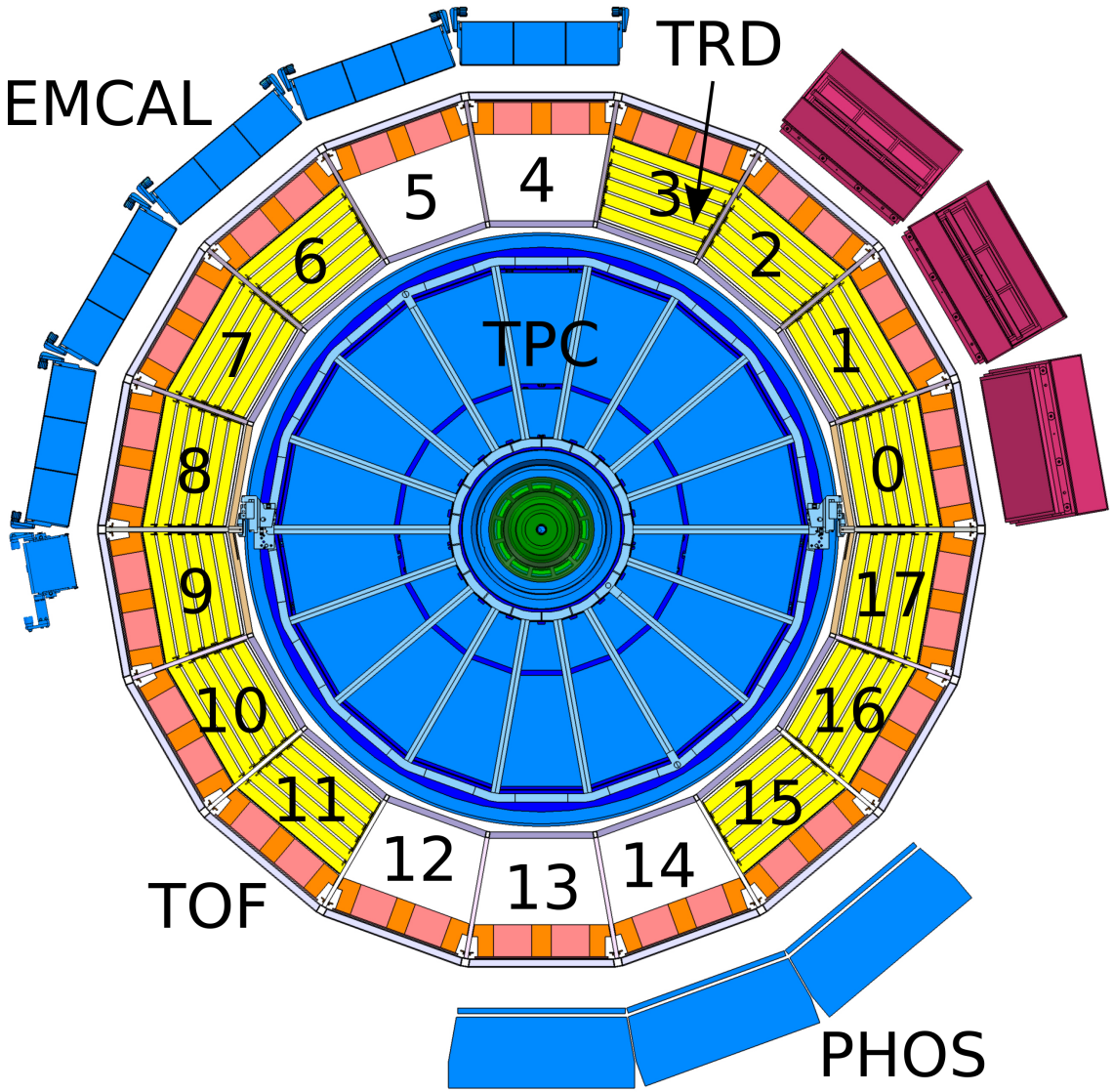
**increasing efforts in ALICE**
to contribute Rivet analyses
both for pp and p–Pb/Pb–Pb

# Backup

# ALICE detector



# ALICE detector



# ALICE coverage

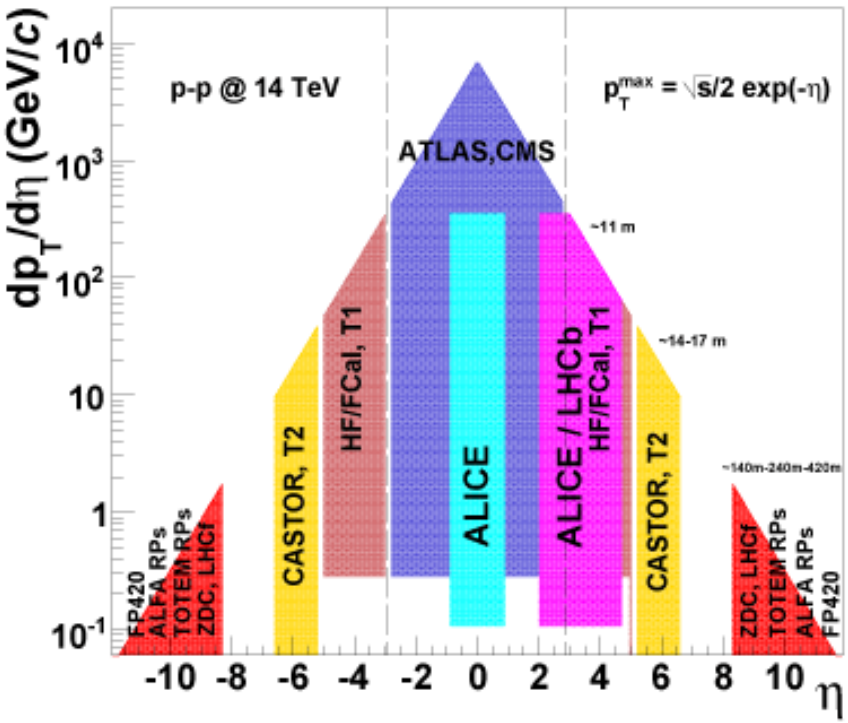
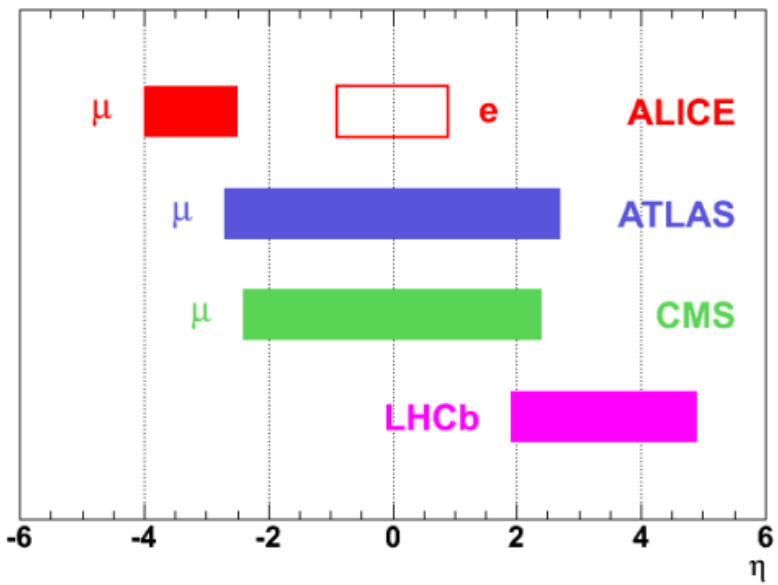



FIG. 3: Approximate $p_T$-η coverage of current (and proposed) detectors at the LHC (adapted from [2]).



# related tools

- Agile, Sacrifice
  `http://agile.hepforge.org/`
- YODA
  `http://yoda.hepforge.org/`
- AIDA
  `http://aida.freehep.org/`
- fastjet
  `http://fastjet.fr`