Tuning of the Pythia 8 hadronic interaction model for simulations of UHECR induced air showers

SFB1491 General assembly

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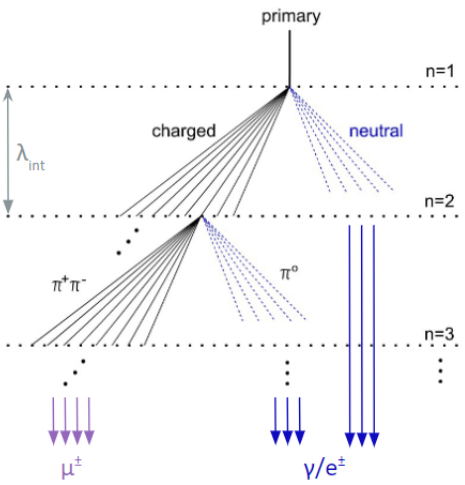
PIERRE AUGER OBSERVATORY

BERGISCHE UNIVERSITÄT WUPPERTAL

SFB1491

DFG Deutsche Forschungsgemeinschaft German Research Foundation



Phys. Rev. D83, 054026 (2011)

Extensive air showers (EAS)

↳ particle interacts with Earth's atmosphere inducing a cascade of secondary particles

$\gamma/e^\pm$ electromagnetic profile

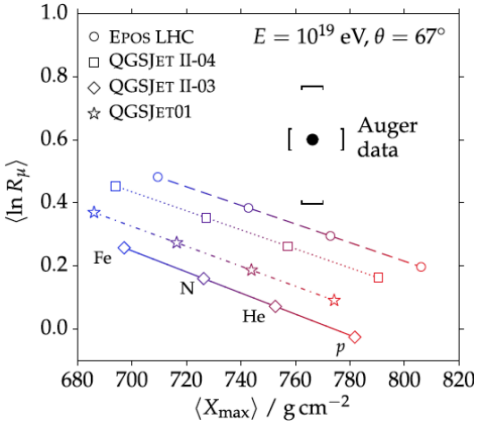
$\mu^\pm$ muons at ground

Need for air shower simulations to interpret EAS observations

- key observable N_μ

↳ infer mass composition of cosmic rays

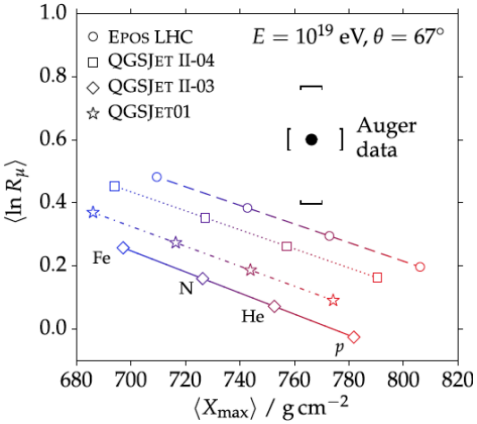
Muon puzzle: significant muon deficit in air shower simulations with respect to measurements from the TeV scale, increasing with energy.



Phys. Rev. D 91, 032003 (2015)

↳ composition of secondary particles

Muon puzzle: significant muon deficit in air shower simulations with respect to measurements from the TeV scale, increasing with energy.



Phys. Rev. D 91, 032003 (2015)

Forward phase space probed at E < 350 GeV

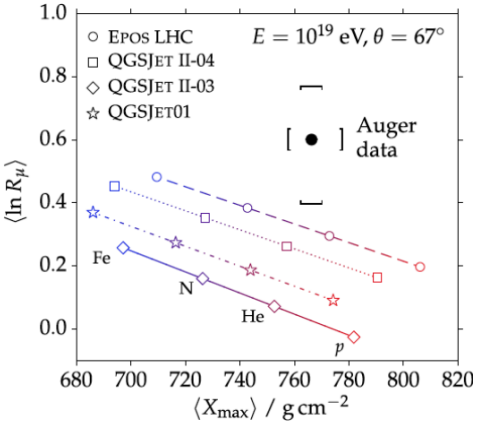
↳ require extrapolation to PeV energies

Largest uncertainties in EAS simulations

↳ limited knowledge of hadronic interactions at high energies

↳ need to improve models

Muon puzzle: significant muon deficit in air shower simulations with respect to measurements from the TeV scale, increasing with energy.



Phys. Rev. D 91, 032003 (2015)

- What is the impact of high- and low-energy interactions on EAS observables?
- Which model parameters can we tune?
- What kind of accelerator data do we need ?

Study case

- focus on NA61/SHINE[1] dataset for π^-**C @ 158 & 350 GeV/c**

↳ compare Pythia 8.3 Angantyr to hA data

↳ tune Pythia 8.3 to selected dataset

↳ using Apprentice python library

↳ discuss the effects of tune parameters on muon production

↳ using air shower simulation code Corsika 8[2]

↳ using coupled cascade equations solver MCEq [3]

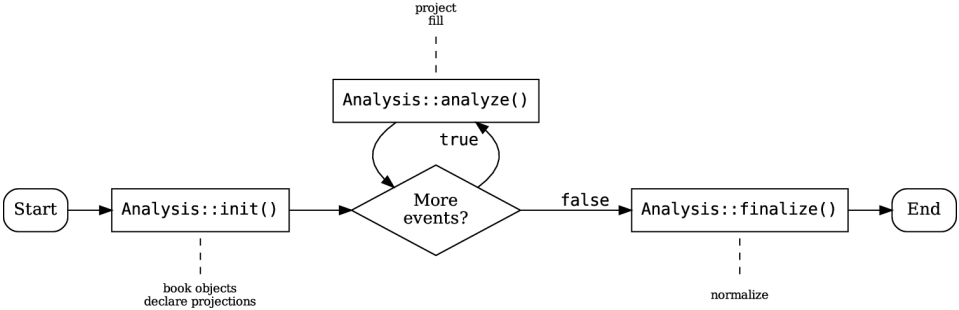
[1] Phys. Rev. D 107, 062004 (2023)

[2] gitlab.iap.kit.edu/AirShowerPhysics/corsika

[3] github.com/mceq-project/MCEq

Testing Pythia 8.3

- fixed-target collisions settings
  - ↳ π^-C interactions
  - ↳ $p_z(\pi^-) = 158, 350$ GeV/c
- using **Rivet** analysis framework & internal Pythia toolkit



Eur. Phys. J. C (2020) 80:485

Measurement of Hadron Production in π^-C Interactions at 158 and 350 GeV/c with NA61/SHINE at the CERN SPS[4]

- particle production spectra $\rightarrow p\frac{\mathrm{d}n}{\mathrm{d}p}$ distributions
- outgoing identified particles: π^+, π^-, K^+, K^-, p and $\overline{p}$ $\quad (+ K^0_s, \Lambda, \overline{\Lambda})$
- incoming π^- momenta: 158 and 350 GeV/c

[4] Phys. Rev. D 107, 062004 (2023)

Pythia 8.2.30

- new Angantyr class
  - ↳ pA and AA collisions with a simple model

Pythia 8.3.08

- `PythiaCascade` wrapper class
  - ↳ simplified model unrelated to Angantyr
  - ↳ fixed-target hA collisions and decays
  - ↳ $E^{\text{hadron}}_{\text{kin, min}} = 0.2$ GeV

Pythia 8.3.09

- Angantyr model updated
  - ↳ several nuclear geometries[5]
  - ↳ harmonic oscillator shell model ($A \leq 16$)

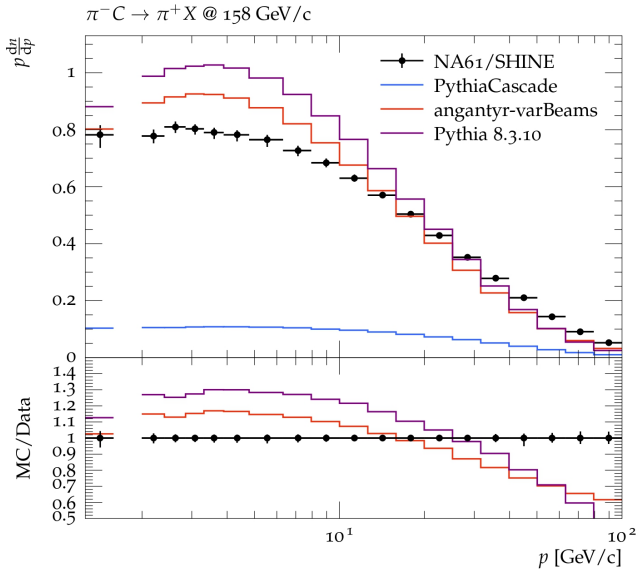
git branch `angantyr-varBeams`

- Angantyr model updated
  - ↳ attempt to allow variable beams

Pythia 8.3.10

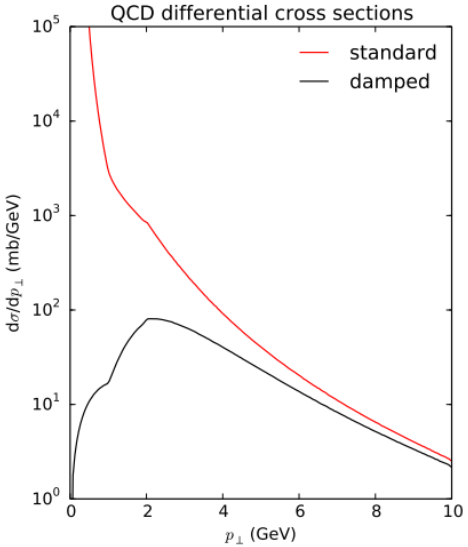
- Angantyr model updated
  - ↳ variable energies usable
  - ↳ all `Beams:frameType` handled
  - ↳ MPI initialization reuse enabled

[5] /pythia.org/manuals/pythia8309/HeavyIons.html



- $\pi^-\mathrm{C} \to \pi^+\mathrm{X}$ @158 GeV/c
- $p\frac{\mathrm{d}n}{\mathrm{d}p} = f(p\ [\mathrm{GeV/c}])$

- Ratio plot: $\frac{\textbf{Pythia 8.3}}{\text{NA61/SHINE data}}$



SciPost Phys. Codebases 8 (2022)

Partonic cross-section

$$\frac{d\hat{\sigma}}{dp_T^2} \propto \frac{\alpha_S^2(p_T^2)}{p_T^4}$$

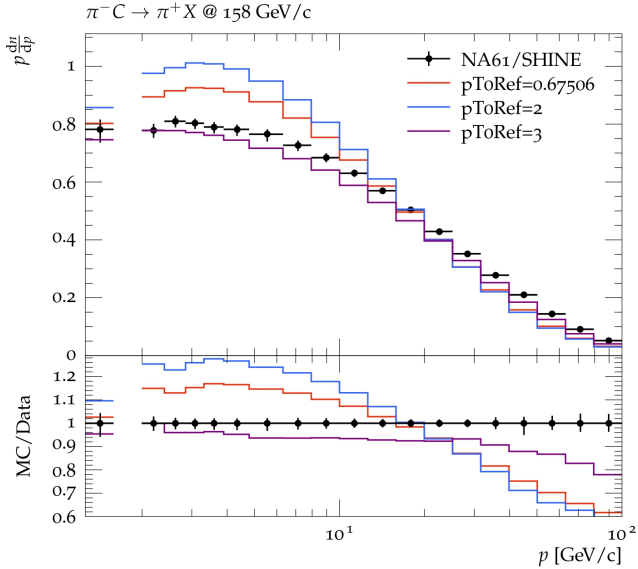
↳ divergent for $p_T \to 0$

- multiplicative damping factor with $p_{T,0}$ as free parameter

$$\frac{d\hat{\sigma}}{dp_T^2} \to \frac{\alpha_S^2(p_{T,0}^2 + p_T^2)}{\left(p_{T,0}^2 + p_T^2\right)^2}$$

`MultipartonInteractions:pT0Ref`

↳ sets $p_{T,0}^{\text{Ref}}$ so $p_{T,0}^{\text{Ref}} = p_{T,0}(E_{\text{CM}}^{\text{Ref}})$



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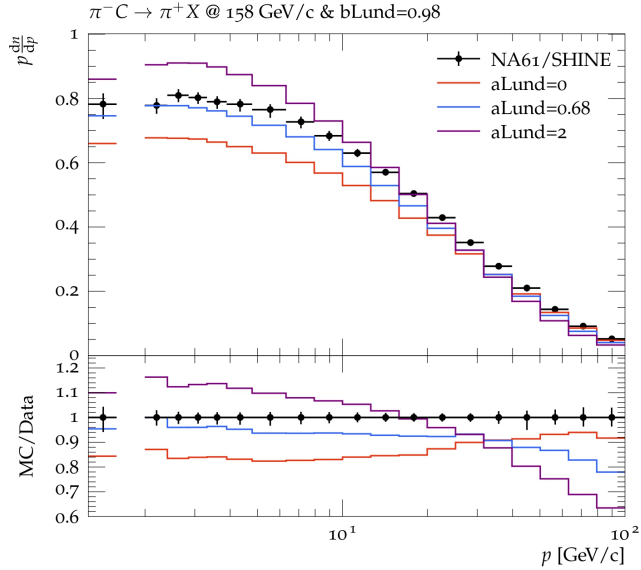
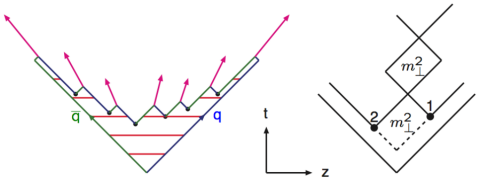




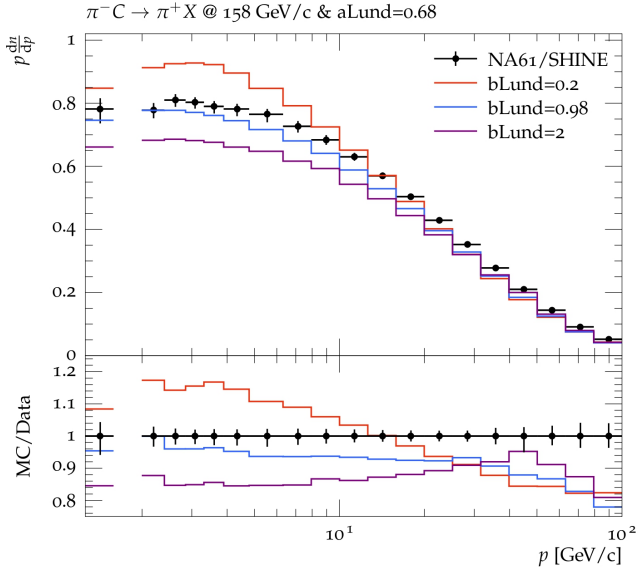
Torbjörn Sjöstrand

Lund fragmentation function

$$f(z) = (\frac{1}{z})(1-z)^a \times \exp(-\frac{bm_T^2}{z})$$

`StringZ:aLund`

↳ sets exponent value a

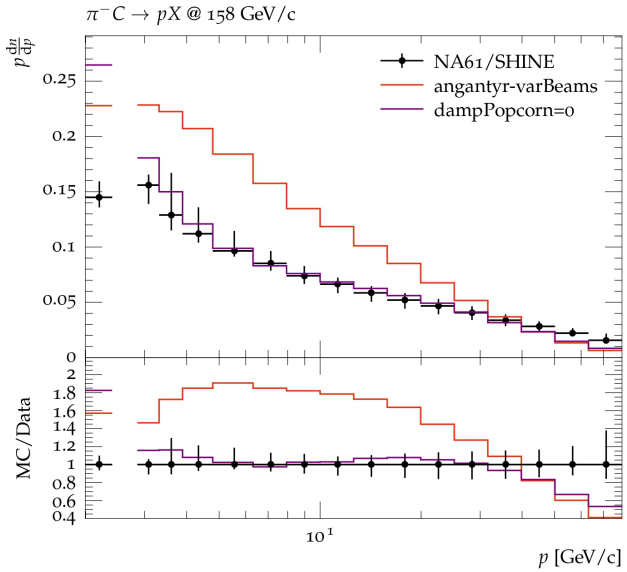


Lund fragmentation function

$$f(z) = (\frac{1}{z})(1-z)^a \times \exp(-\frac{bm_T^2}{z})$$

`StringZ:bLund`

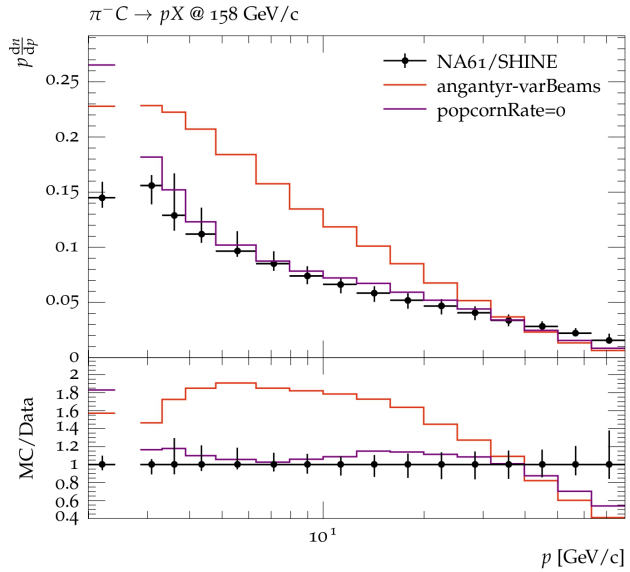
↳ sets exponent value b



Controls whether a beam remnant diquark can hadronize to a leading meson by the popcorn mechanism

`BeamRemnants:dampPopcorn`

- 1: ordinary hadronization
- 0: diquark $\xrightarrow[\text{always}]{}$ leading baryon



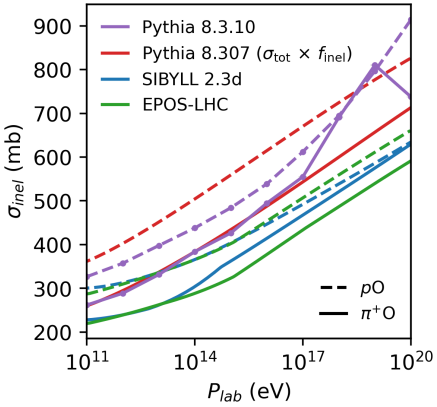
If popcorn production allowed,
mesons may be produced
in between baryon & antibaryon

`StringFlav:popcornRate`

↳ sets the relative rates of $B,\bar{B}$ and $B,M,\bar{B}$ production

$$\frac{\mathrm{P}(B,M,\bar{B})}{(\mathrm{P}(B,\bar{B})+\mathrm{P}(B,M,\bar{B}))} = \frac{\texttt{popcornRate}}{(0.5+\texttt{popcornRate})}$$

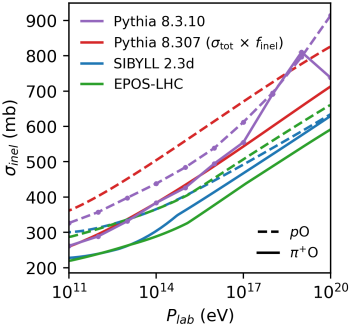
- Pythia 8.3
  - ↳ `MultipartonInteractions:pT0Ref`
  - ↳ `StrinZ:aLund` & `StringZ:bLund`
  - ↳ `BeamRemnants:dampPopcorn`?
  - ↳ `StringFlav:popcornRate`?
- Rivet
  - ↳ `NA61SHINE_2022_I2155140` plug-in
- Corsika 8
  - ↳ interface computation of cross-section tables from Pythia 8.3
- MCEq
  - ↳ interface Pythia 8.3 with chromo to compute $\mathrm{d}E/\mathrm{d}X$ tables

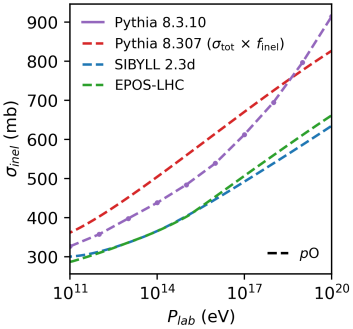


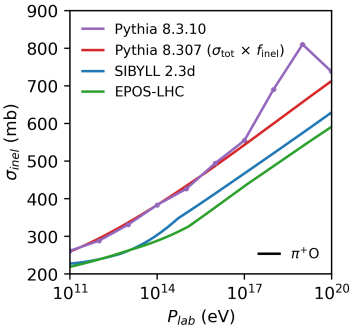
EPJ Web Conf. 283 (2023) 05010

- Study case π^-C
- Air-shower case
  - ↳ π^+O
  - ↳ pO

$p_z(\pi^-)$	$\sigma_{\text{inel}}(\pi^-\text{C})$
158 GeV/c	210.027 mb
350 GeV/c	221.526 mb







EPJ Web Conf. 283 (2023) 05010

- `MultipartonInteractions:pT0Ref`
  - regularization of the divergence of σ_{QCD} for $p_T \to 0$
  - ↳ sets value of $p_{T,0}^{\mathrm{Ref}}$ so that $p_{T,0}^{\mathrm{Ref}} = p_{T,0}(E_{\mathrm{CM}}^{\mathrm{Ref}})$

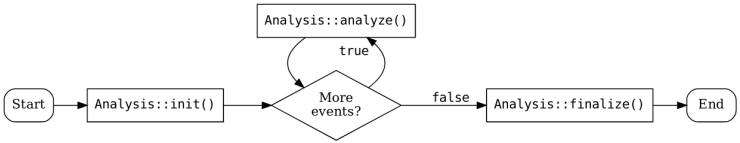
- `StrinZ:aLund` & `StringZ:bLund`
  - Lund symmetric fragmentation function: $f(z) = (\frac{1}{z})(1-z)^a \times \exp(-\frac{bm_T^2}{z})$
  - ↳ sets exponent values a and b

- `BeamRemnants:dampPopcorn`
  - ↳ controls whether a beam remnant diquark can hadronize to a leading meson
    0: diquark $\xrightarrow[\text{always}]{}$ leading baryon; 1: ordinary hadronization

- `StringFlav:popcornRate`
  - mesons (M) may be produced in between baryon (B) and antibaryon ($\bar{B}$)
  - ↳ sets the relative rates of $B,\bar{B}$ and $B,M,\bar{B}$ production
    P(B,M,$\bar{B}$) / (P(B,$\bar{B}$) + P(B,M,$\bar{B}$)) = `popcornRate` / (0.5 + `popcornRate`)

There is an analysis for every physics paper implemented.
It follows a plug-in friendly architecture.

- A Source code
- B Experimental data
- C Plotting settings
- D Paper and analysis information



A `.cc` *(Eur. Phys. J. C (2020) 80:485)*

```
BEGIN YODA_SCATTER2D_V2 /REF/ATLAS_2011_S9035664/d03-x01-y01
IsRef: 1
Path: /REF/ATLAS_2011_S9035664/d03-x01-y01
Title: ~
Type: Scatter2D
---
# xval   xerr-    xerr+    yval     yerr-    yerr+
5.300000e+00   3.000000e-01   2.000000e-01   1.590000e+04   6.613622e+03   2.925355e+04
5.800000e+00   3.000000e-01   2.000000e-01   1.350000e+04   5.008992e+03   1.210496e+04
6.300000e+00   3.000000e-01   2.000000e-01   8.800000e+03   2.736786e+03   8.081460e+03
6.800000e+00   3.000000e-01   2.000000e-01   6.290000e+03   1.816590e+03   5.253427e+03
7.300000e+00   3.000000e-01   2.000000e-01   3.990000e+03   1.014199e+03   2.715050e+03
7.700000e+00   2.000000e-01   3.000000e-01   4.070000e+03   9.885101e+02   3.008955e+03
8.300000e+00   3.000000e-01   2.000000e-01   2.650000e+03   7.490661e+02   1.860094e+03
8.700000e+00   2.000000e-01   3.000000e-01   1.930000e+03   6.644351e+02   6.910061e+02
9.200000e+00   2.000000e-01   3.000000e-01   1.450000e+03   3.956141e+02   5.398148e+02
9.700000e+00   2.000000e-01   3.000000e-01   1.280000e+03   2.354485e+02   4.758792e+02
1.050000e+01   5.000000e-01   5.000000e-01   8.290000e+02   1.365066e+02   3.059624e+02
1.150000e+01   5.000000e-01   5.000000e-01   5.980000e+02   1.105396e+02   1.920573e+02
1.290000e+01   9.000000e-01   1.100000e+00   3.200000e+02   5.707013e+01   8.969950e+01
1.490000e+01   9.000000e-01   1.100000e+00   1.640000e+02   2.900000e+01   4.369218e+01
1.690000e+01   9.000000e-01   1.100000e+00   7.780000e+01   1.514100e+01   1.882578e+01
1.970000e+01   1.700000e+00   2.300000e+00   2.990000e+01   6.073714e+00   5.847222e+00
2.490000e+01   2.900000e+00   5.100000e+00   6.200000e+00   1.435270e+00   1.389244e+00
3.360000e+01   3.600000e+00   6.400000e+00   1.120000e+00   5.227810e-01   4.455334e-01
END YODA_SCATTER2D_V2
```

B `.yoda`

```
# BEGIN PLOT /ATLAS_2011_S9035664/.*
FullRange=1
LogY=1
LogX=1
XLabel=$p^{J/\psi}_{T}$ [GeV]
YLabel=$\frac{\text{Br}(\text{J}/\psi \rightarrow \mu^{+}\mu^{-})\sigma\mathrm{d}^2\sigma}{\mathrm{d}p_\perp\mathrm{d}y}$ [nb/GeV]
# END PLOT

# BEGIN PLOT /ATLAS_2011_S9035664/d18-x01-y01
Title=$\frac{\text{Br}(\text{J}/\psi \rightarrow \mu^{+}\mu^{-})\sigma\mathrm{d}^2\sigma}{\mathrm{d}p_\perp\mathrm{d}y}$ for prompt J/$\psi$: pp @ $\sqrt{s}$=7 TeV $\$ 2.0 < |y| < 2.4$
# END PLOT
# BEGIN PLOT /ATLAS_2011_S9035664/d17-x01-y01
Title=$\frac{\text{Br}(\text{J}/\psi \rightarrow \mu^{+}\mu^{-})\sigma\mathrm{d}^2\sigma}{\mathrm{d}p_\perp\mathrm{d}y}$ for prompt J/$\psi$: pp @ $\sqrt{s}$=7 TeV $\$ 1.5 < |y| < 2.0$
# END PLOT
# BEGIN PLOT /ATLAS_2011_S9035664/d16-x01-y01
Title=$\frac{\text{Br}(\text{J}/\psi \rightarrow \mu^{+}\mu^{-})\sigma\mathrm{d}^2\sigma}{\mathrm{d}p_\perp\mathrm{d}y}$ for prompt J/$\psi$: pp @ $\sqrt{s}$=7 TeV $\$ 0.75 < |y| < 1.5$
# END PLOT
# BEGIN PLOT /ATLAS_2011_S9035664/d15-x01-y01
Title=$\frac{\text{Br}(\text{J}/\psi \rightarrow \mu^{+}\mu^{-})\sigma\mathrm{d}^2\sigma}{\mathrm{d}p_\perp\mathrm{d}y}$ for prompt J/$\psi$: pp @ $\sqrt{s}$=7 TeV $\$ |y| < 0.75$
# END PLOT
```

C `.plot`

```
Name: ATLAS_2011_S9035664
Year: 2011
Summary: Measurement of J/Psi production
Experiment: ATLAS
Collider: LHC
InspireID: 9035664
InspireID: 896268
Status: VALIDATED
Reentrant: true
Authors:
 -
References:
 - arXiv:1104.3038 [hep-ex]
RunInfo:
  pp to hadrons including both prompt J/Psi production and the production in B decays
NumEvents: 1000000
Beams: [p+, p+]
Energies: [7000]
PtCuts:
Description:
  'The inclusive $J/\psi$ production cross-section and fraction of $J/\psi$ mesons produced in
B-hadron decays are measured in proton-proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS
detector at the LHC, as a function of the transverse momentum and rapidity of the J/psi, using
2.3$\textrm{pb}^{-1}$ of integrated luminosity. The cross section is measured from a minimum
$p_{T}$ of 1 GeV to a maximum of 70 GeV and for rapidities within $|y| < 2.4$ giving the widest
reach of any measurement of $J/\psi$ production to date.'
NeedCrossSection: yes
```

D `.info`