

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

Astroparticle physics school 2023

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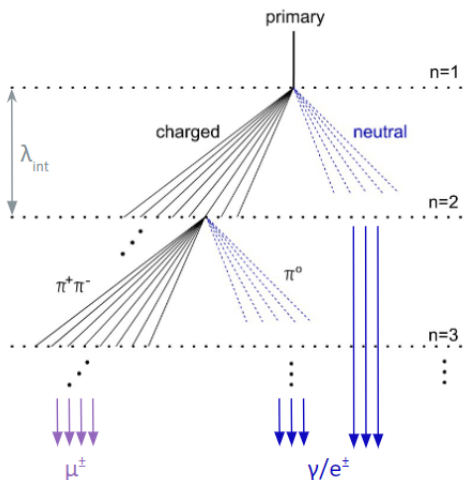
11.10.2023



**BERGISCHE  
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WUPPERTAL**



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

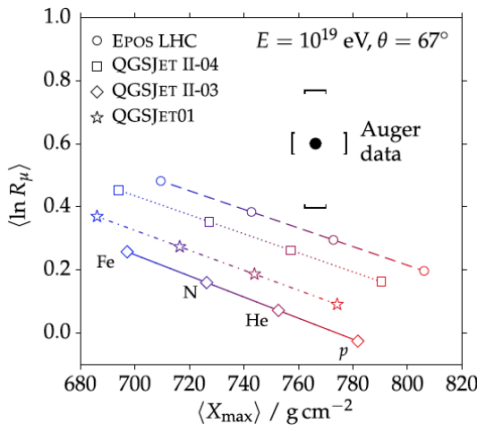
- key observable  $N_\mu$

↳ 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.

↳ composition of secondary particles

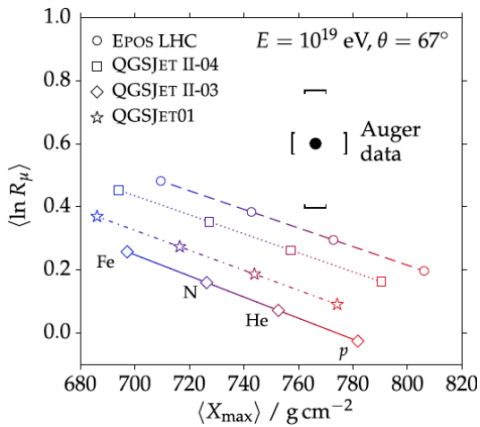
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*Phys. Rev. D 91, 032003 (2015)*

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Forward phase space probed at  $E < 350 \text{ GeV}$

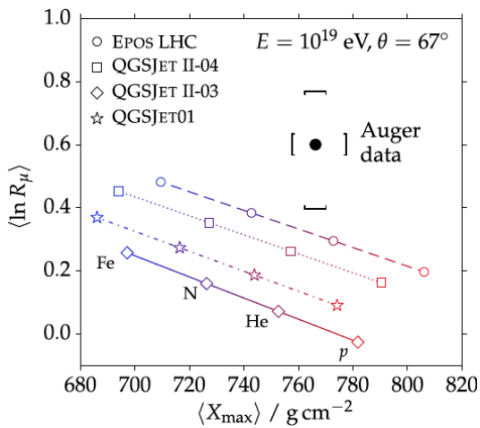
↳ require extrapolation to PeV energies

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<sup>1</sup> dataset for  $\pi^-$  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](#) <sup>2</sup>
    - ↳ using coupled cascade equations solver [MCEq](#) <sup>3</sup>

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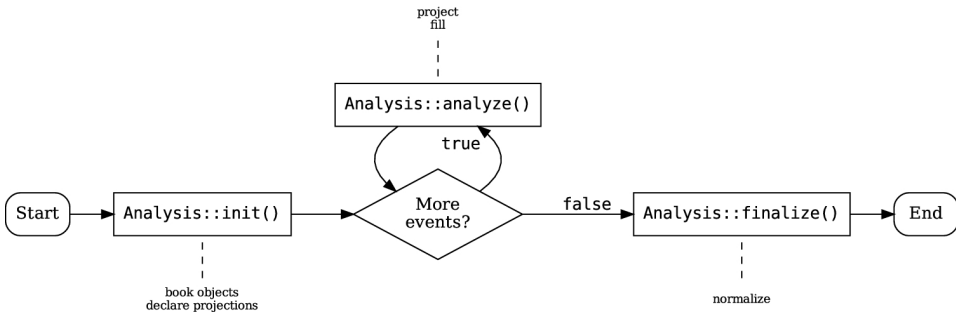
<sup>1</sup>Phys. Rev. D 107, 062004 (2023)

<sup>2</sup>[gitlab.iap.kit.edu/AirShowerPhysics/corsika](https://gitlab.iap.kit.edu/AirShowerPhysics/corsika)

<sup>3</sup>[github.com/mceq-project/MCEq](https://github.com/mceq-project/MCEq)

## Testing Pythia 8.3

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



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



## Measurement of Hadron Production in $\pi^-$ C Interactions at 158 and 350 GeV/c with NA61/SHINE at the CERN SPS<sup>4</sup>

- particle production spectra  $\rightarrow p \frac{dn}{dp}$  distributions
- outgoing identified particles:  $\pi^+$ ,  $\pi^-$ ,  $K^+$ ,  $K^-$ ,  $p$  and  $\bar{p}$  ( +  $K_s^0$ ,  $\Lambda$ ,  $\bar{\Lambda}$  )
- incoming  $\pi^-$  momenta: 158 and 350 GeV/c

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- new Angantyr class
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  - ↳ fixed-target hA collisions and decays
  - ↳  $E_{\text{kin, min}}^{\text{hadron}} = 0.2 \text{ GeV}$

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- Angantyr model updated
  - ↳ several nuclear geometries<sup>5</sup>
  - ↳ harmonic oscillator shell model ( $A \leq 16$ )

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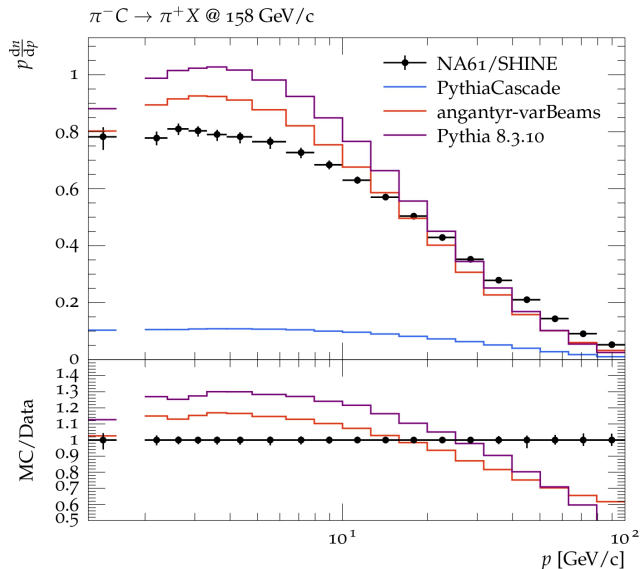
- Angantyr model updated
  - ↳ attempt to allow variable beams

### Pythia 8.3.10

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

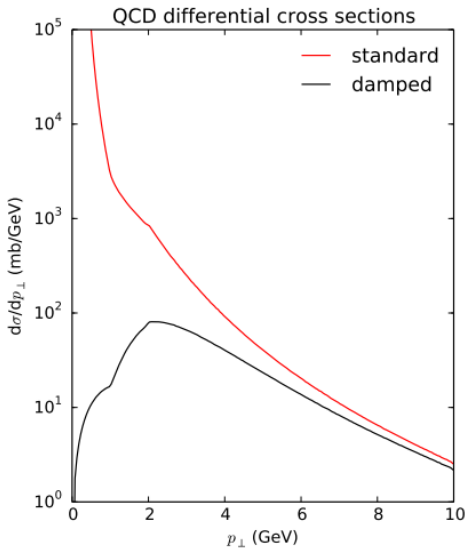
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- $\pi^- C \rightarrow \pi^+ X @ 158 \text{ GeV}/c$
- $p \frac{dn}{dp} = f(p \text{ [GeV}/c])$

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



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  $p_T \rightarrow 0$

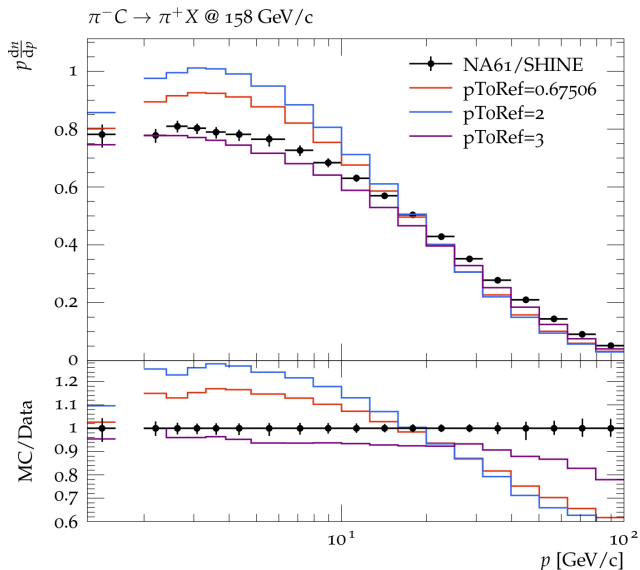
- multiplicative damping factor with  $p_{T,0}$  as free parameter

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

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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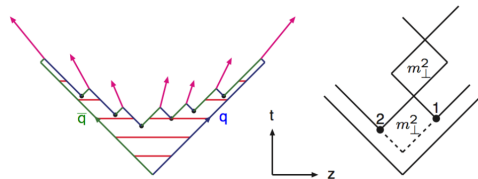
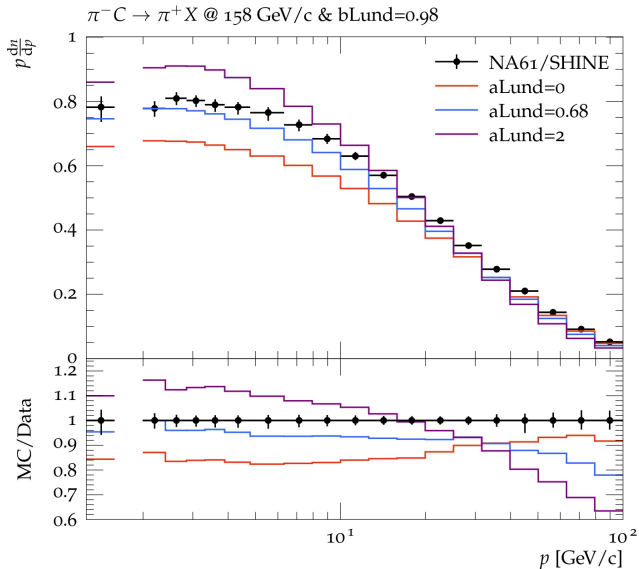
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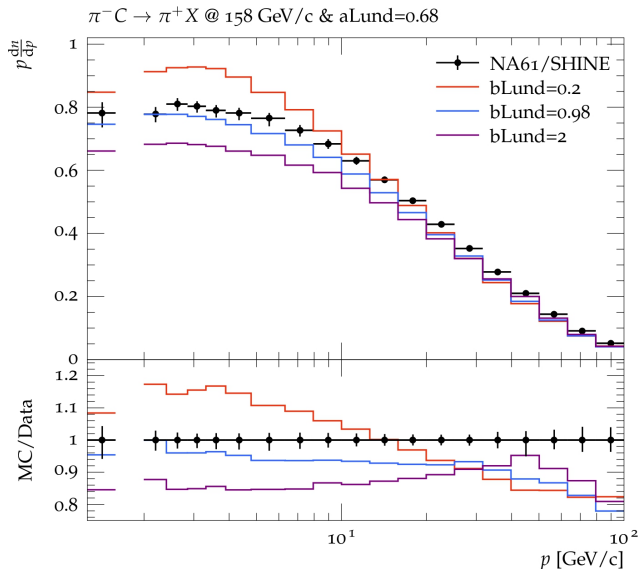
Torbjörn Sjöstrand

Lund fragmentation function

$$f(z) = \left(\frac{1}{z}\right)(1-z)^a \times \exp\left(-\frac{bm^2_T}{z}\right)$$

StringZ:aLund

↳ sets exponent value  $a$

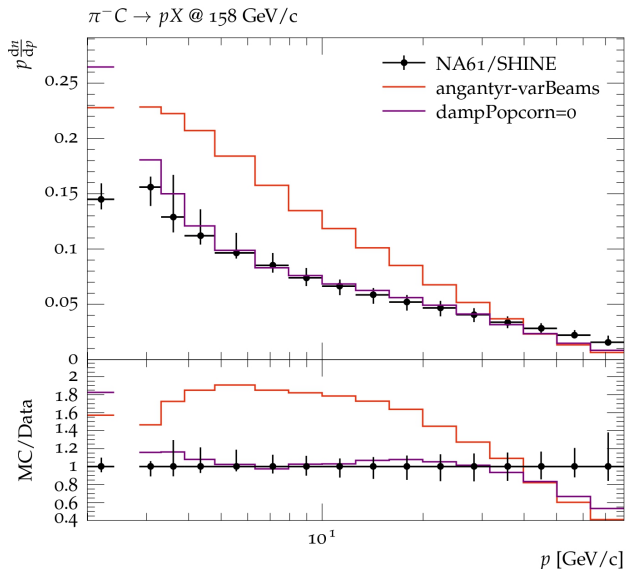


Lund fragmentation function

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

StringZ:bLund

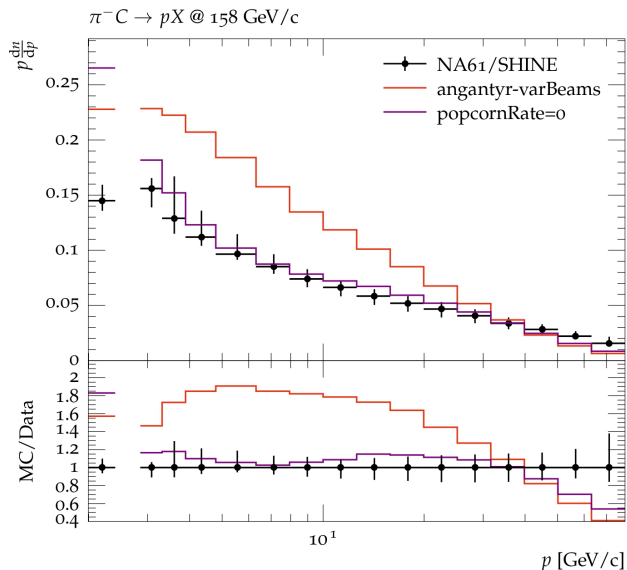
↳ sets exponent value  $b$



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

BeamRemnants:dampPopcorn

- ↳ 1: ordinary hadronization
- ↳ 0: diquark  $\longrightarrow$  leading baryon  
always



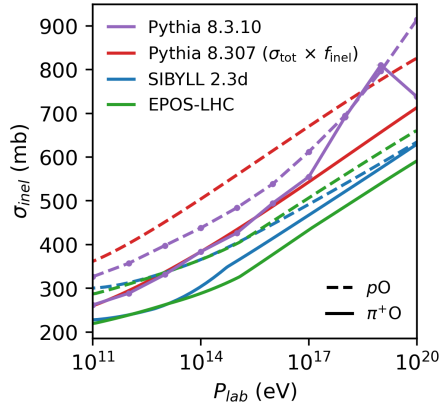
If popcorn production allowed, mesons may be produced in between baryon & antibaryon

StringFlav:popcornRate

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

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

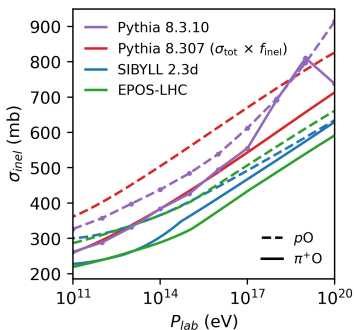
- Pythia 8.3
  - ↳ `MultipartonInteractions:pT0Ref`
  - ↳ `StrinZ:aLund & StringZ:bLund`
  - ↳ `BeamRemnants:dampPopcorn?`
  - ↳ `StringFlav:popcornRate?`
- Rivet
  - ↳ `NA61SHINE_2022_I2155140` plug-in
- Corsika 8
  - ↳ interface computation of cross-section tables from Pythia 8.3
- MCEq
  - ↳ interface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



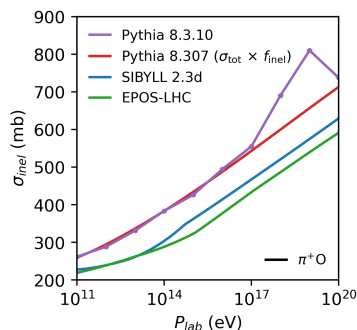
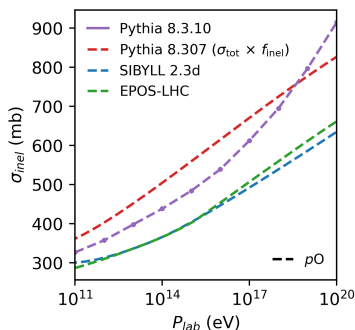
EPJ Web Conf. 283 (2023) 05010

- Study case  $\pi^- C$
- Air-shower case
  - ↳  $\pi^+ O$
  - ↳  $pO$

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



EPJ Web Conf. 283 (2023) 05010

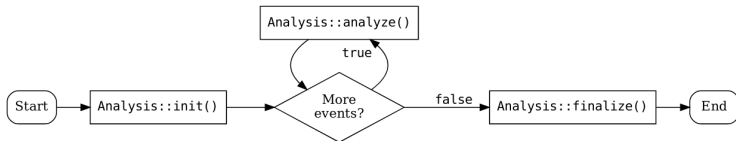


- `MultipartonInteractions:pT0Ref`
  - regularization of the divergence of  $\sigma_{\text{QCD}}$  for  $p_T \rightarrow 0$
  - ↳ sets value of  $p_{T,0}^{\text{Ref}}$  so that  $p_{T,0}^{\text{Ref}} = p_{T,0}(E_{\text{CM}}^{\text{Ref}})$
  
- `StrinZ:aLund & StringZ:bLund`
  - Lund symmetric fragmentation 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
  - $$P(B, M, \bar{B}) / (P(B, \bar{B}) + P(B, M, \bar{B})) = \text{popcornRate} / (0.5 + \text{popcornRate})$$



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_SCATTERZD_V2 /REF/ATLAS_2011_59035664/003-x01-y01
TitleRef: 1
Path: /REF/ATLAS_2011_59035664/003-x01-y01
Title:
Type: ScatterZD
...
# val yerr1_yerr2_yerr3_yerr4_yerr5
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 1.210495e+04
6.300000e+00 3.000000e-01 2.000000e-01 8.000000e+03 2.735786e+03 8.001460e+03
6.800000e+00 3.000000e-01 2.000000e-01 6.250000e+03 1.816590e+03 5.253427e+03
7.300000e+00 3.000000e-01 2.000000e-01 3.990000e+03 1.014190e+03 2.735050e+03
7.700000e+00 2.000000e-01 3.000000e-01 4.070000e+03 9.805101e+02 3.008953e+03
8.300000e+00 3.000000e-01 2.000000e-01 2.650000e+03 7.406912e+02 1.000094e+03
8.700000e+00 2.000000e-01 3.000000e-01 1.930000e+03 4.644351e+02 6.910861e+02
9.200000e+00 2.000000e-01 3.000000e-01 1.450000e+03 3.056141e+02 5.398148e+02
9.700000e+00 2.000000e-01 3.000000e-01 1.200000e+03 2.354485e+02 4.758792e+02
1.050000e+01 5.000000e-01 5.000000e-01 8.250000e+02 1.365064e+02 3.059624e+02
1.150000e+01 5.000000e-01 5.000000e-01 5.900000e+02 1.105396e+02 1.920573e+02
1.200000e+01 9.000000e-01 1.100000e+00 3.200000e+02 5.707134e+01 6.969990e+01
1.400000e+01 9.000000e-01 1.100000e+00 1.640000e+02 2.900000e+01 4.300210e+01
1.600000e+01 9.000000e-01 1.100000e+00 7.700000e+01 1.514100e+01 1.802570e+01
1.970000e+01 1.700000e+00 2.300000e+00 2.950000e+01 6.073164e+00 5.847226e+00
2.490000e+01 2.300000e+00 5.100000e+00 6.200000e+00 1.435270e+00 1.309246e+00
3.360000e+01 3.600000e+00 6.400000e+00 1.120000e+00 5.227810e-01 4.455334e-01
END YODA_SCATTERZD_V2
  
```

B .yoda

```

# BEGIN PLOT /ATLAS_2011_59035664/*
FullRange=1
LogX=1
Label=dp^2/ps1_T1$ [GeV]
Title=$\frac{d^2\sigma}{d^2p_{\perp}d^2\eta}(\text{text}[0])$ for prompt $J/\psi$ production
# END PLOT

# BEGIN PLOT /ATLAS_2011_59035664/d10-x01-y01
Title=$\frac{d^2\sigma}{d^2p_{\perp}d^2\eta}(\text{text}[0])$ for prompt $J/\psi$ production
# END PLOT

# BEGIN PLOT /ATLAS_2011_59035664/d17-x01-y01
Title=$\frac{d^2\sigma}{d^2p_{\perp}d^2\eta}(\text{text}[0])$ for prompt $J/\psi$ production
# END PLOT

# BEGIN PLOT /ATLAS_2011_59035664/d16-x01-y01
Title=$\frac{d^2\sigma}{d^2p_{\perp}d^2\eta}(\text{text}[0])$ for prompt $J/\psi$ production
# END PLOT

# BEGIN PLOT /ATLAS_2011_59035664/d15-x01-y01
Title=$\frac{d^2\sigma}{d^2p_{\perp}d^2\eta}(\text{text}[0])$ for prompt $J/\psi$ production
# END PLOT
  
```

C .plot

```

Name: ATLAS_2011_59035664
Year: 2011
Summary: Measurement of $J/\psi$ production
Experiment: ATLAS
Collider: LHC
SPinID: 893564
Inspired: 896268
Status: VALIDATED
Reentrant: true
Authors:
-
References:
- arXiv:1104.3036 [hep-ex]
RunInfo:
pp to hadrons including both prompt $J/\psi$ production and the production in B decays
HadEvents: 1000000
Beams: [p, p]
Energies: [7000]
PCuts:
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 $\sqrt{s}(s) = 7$ TeV with the ATLAS detector at the LHC, as a function of the transverse momentum and rapidity of the $J/\psi$, using $2.3\text{t}(\text{text}[nb])^{-1}$ of integrated luminosity. The cross section is measured from a minimum $\mathcal{E}_T$ of 1 GeV to a maximum of 70 GeV and for rapidities within $|y| < 2.45$ giving the widest reach of any measurement of $J/\psi$ production to date."
HadCrossSection: yes
  
```

D .info