Hadronic final states in pA collisions

Leif Lönnblad
(with Gösta Gustafson and Christian Bierlich)

Department of Astronomy
and Theoretical Physics
Lund University

CERN 2016-07-07

Outline

- Remeber Fritiof?
- Glauber models
- Generating final states
- RIVET

arXiv:1607.nnnnn [hep-ph]

Outline

- Remeber Fritiof? — RIP
- Glauber models
- Generating final states — Long live Fritiof!
- RIVET

arXiv:1607.nnnnn [hep-ph]

Remember Fritiof?

Simple picture of pp collisions

- Flat rapidity plateau.
- High mass diffractions $d\sigma/dM_X^2 \propto M_X^{-2(1+\epsilon)}$ were ϵ is small.
- Works surprisingly well for $\sqrt{s} \leq$ ISR.
- Fritiof + Glauber gives heavy Ion collisions.
- Works very well at low energies.
- At higher energies we have multiple semi-hard parton–parton scatterings.

Remember Fritiof?

Simple picture of pp collisions

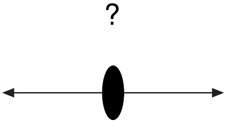
- Flat rapidity plateau.
- High mass diffractions $d\sigma/dM_X^2 \propto M_X^{-2(1+\epsilon)}$ were ϵ is small.
- Works surprisingly well for $\sqrt{s} \leq$ ISR.
- Fritiof + Glauber gives heavy Ion collisions.
- Works very well at low energies.
- At higher energies we have multiple semi-hard parton–parton scatterings.

Remember Fritiof?

Simple picture of pp collisions

- Flat rapidity plateau.
- High mass diffractions $d\sigma/dM_X^2 \propto M_X^{-2(1+\epsilon)}$ were ϵ is small.
- Works surprisingly well for $\sqrt{s} \leq$ ISR.
- Fritiof + Glauber gives heavy Ion collisions.
- Works very well at low energies.
- At higher energies we have multiple semi-hard parton–parton scatterings.

Remember Fritiof?



- Flat rapidity plateau.
- High mass diffractions $d\sigma/dM_X^2 \propto M_X^{-2(1+\epsilon)}$ were ϵ is small.
- Works surprisingly well for $\sqrt{s} \leq$ ISR.
- Fritiof + Glauber gives heavy Ion collisions.
- Works very well at low energies.
- At higher energies we have multiple semi-hard parton–parton scatterings.

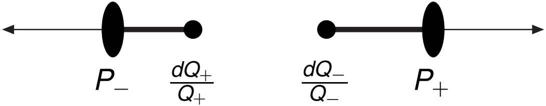
Remember Fritiof?

multiple soft gluon exchanges

- Flat rapidity plateau.
- High mass diffractions $d\sigma/dM_X^2 \propto M_X^{-2(1+\epsilon)}$ were ϵ is small.
- Works surprisingly well for $\sqrt{s} \leq$ ISR.
- Fritiof + Glauber gives heavy Ion collisions.
- Works very well at low energies.
- At higher energies we have multiple semi-hard parton–parton scatterings.

Remember Fritiof?

Longitudinal excitation of both protons



- Flat rapidity plateau.
- High mass diffractions $d\sigma/dM_X^2 \propto M_X^{-2(1+\epsilon)}$ were ϵ is small.
- Works surprisingly well for $\sqrt{s} \leq$ ISR.
- Fritiof + Glauber gives heavy Ion collisions.
- Works very well at low energies.
- At higher energies we have multiple semi-hard parton–parton scatterings.

Remember Fritiof?

String ends evenly distributed in rapidity

- Flat rapidity plateau.
- High mass diffractions $d\sigma/dM_X^2 \propto M_X^{-2(1+\epsilon)}$ were ϵ is small.
- Works surprisingly well for $\sqrt{s} \leq$ ISR.
- Fritiof + Glauber gives heavy Ion collisions.
- Works very well at low energies.
- At higher energies we have multiple semi-hard parton–parton scatterings.

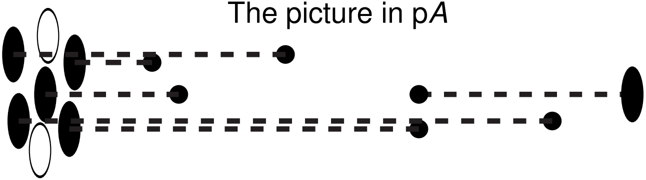
Remember Fritiof?

Hadronises as if doubly diffractive excitation

- Flat rapidity plateau.
- High mass diffractions $d\sigma/dM_X^2 \propto M_X^{-2(1+\epsilon)}$ were ϵ is small.
- Works surprisingly well for $\sqrt{s} \leq$ ISR.
- Fritiof + Glauber gives heavy Ion collisions.
- Works very well at low energies.
- At higher energies we have multiple semi-hard parton–parton scatterings.

Remember Fritiof?

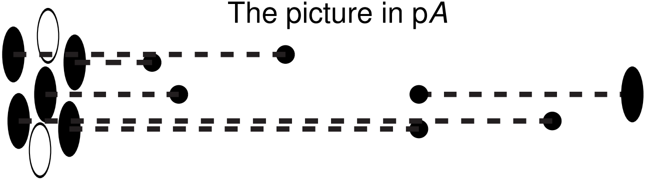
The picture in pA



- Flat rapidity plateau.
- High mass diffractions $d\sigma/dM_X^2 \propto M_X^{-2(1+\epsilon)}$ were ϵ is small.
- Works surprisingly well for $\sqrt{s} \leq$ ISR.
- Fritiof + Glauber gives heavy Ion collisions.
- Works very well at low energies.
- At higher energies we have multiple semi-hard parton–parton scatterings.

Remember Fritiof?

The picture in pA



- Flat rapidity plateau.
- High mass diffractions $d\sigma/dM_X^2 \propto M_X^{-2(1+\epsilon)}$ were ϵ is small.
- Works surprisingly well for $\sqrt{s} \leq$ ISR.
- Fritiof + Glauber gives heavy Ion collisions.
- Works very well at low energies.
- At higher energies we have multiple semi-hard parton–parton scatterings.

- We need hard parton scatterings
- We need MPI
- Which nucleons are actually diffractively excited?
- How are the particles from the non-diffractively wounded nucleons distributed.?

- We need hard parton scatterings – PYTHIA8
- We need MPI – PYTHIA8
- Which nucleons are actually diffractively excited?
- How are the particles from the non-diffractively wounded nucleons distributed.?

Hadron scattering cross sections

Working with the optical theorem in impact parameter space

$$T = -iA_{\mathrm{el}}$$

averaging over initial states of the target and projectile $T_{pt}(b)$:

$$\begin{aligned}
\frac{d\sigma_{\mathrm{tot}}}{d^2b} &= 2\langle T(b)\rangle \\
\frac{d\sigma_{\mathrm{el}}}{d^2b} &= \langle T(b)\rangle^2 \\
\frac{d\sigma_{\mathrm{in}}}{d^2b} &= 2\langle T(b)\rangle - \langle T(b)\rangle^2
\end{aligned}$$

Diffractive excitation

Following Good–Walker

$$\frac{d\sigma_{\mathrm{Dp}}}{d^2b} = \left\langle \langle T_{pt}(b)\rangle_t^2 \right\rangle_p - \left\langle T_{pt}(b) \right\rangle_{pt}^2$$
$$\frac{d\sigma_{\mathrm{Dt}}}{d^2b} = \left\langle \langle T_{pt}(b)\rangle_p^2 \right\rangle_t - \left\langle T_{pt}(b) \right\rangle_{pt}^2$$
$$\frac{d\sigma_{\mathrm{DD}}}{d^2b} = \left\langle T_{pt}^2(b) \right\rangle_{pt} - \left\langle \langle T_{pt}(b)\rangle_t^2 \right\rangle_p - \left\langle \langle T_{pt}(b)\rangle_p^2 \right\rangle_t + \left\langle T_{pt}(b) \right\rangle_{pt}^2$$

Diffractive excitation is related to fluctuations.

$$\frac{d\sigma_{\mathrm{in,ND}}}{d^2b} \equiv \frac{d\sigma_{\mathrm{abs}}}{d^2b} = 2\left\langle T_{pt}(b) \right\rangle_{pt} - \left\langle T_{pt}^2(b) \right\rangle_{pt}$$

Also the non-diffractive cross section depends on fluctuations.

How do we estimate nuclear effects?

- Estimate number distribution of wounded/participating nucleons *using Glauber*.
- Find a centrality observable that should be sensitive to the number of hit nucleons.
- Build up a reference sample by stacking pp-events, fudging them a bit to fit the centrality distribution.

The centrality measure is typically defined in terms of some multiplicity or energy in the nucleus direction.

Which nucleons are participating/wounded

The simplest Glauber model uses nucleons distributed with a Wood–Saxon and treating them as solid, fixed-size black disks.

Looking at the cross sections for a projectile on a single nucleon, we have $T(b) = \Theta(\sqrt{\sigma/\pi} - b)$, and for $\sigma = \sigma_{\rm tot}$ we get

$$
\begin{aligned}
\sigma_{\rm tot} &= \int d^2b\, 2\left\langle T(b)\right\rangle \\
\sigma_{\rm el} &= \int d^2b\, \left\langle T(b)\right\rangle^2 = \sigma_{\rm tot}/2 \\
\sigma_{\rm abs} &= \int d^2b\, \left(2\left\langle T(b)\right\rangle - \left\langle T(b)\right\rangle^2\right) = \sigma_{\rm tot}/2 \\
\sigma_{\rm diff} &= \int d^2b\, \left(\left\langle T^2(b)\right\rangle - \left\langle T(b)\right\rangle^2\right) = 0
\end{aligned}
$$

The black disk approach, clearly cannot properly take diffractive excitation into account

It can be fudged, by setting e.g. $\sigma = \sigma_{\mathrm{in}}$ or $\sigma = \sigma_{\mathrm{abs}}$, but we want to do better.

We want to be able to see which nucleons that contributes to the centrality observable.

- absorptively wounded nucleons.
- diffractively wounded nucleons.
- …Not elastically scattered nucleons.

$$\sigma_{\mathrm{W}} \equiv \sigma_{\mathrm{abs}} + \sigma_{\mathrm{Dt}} + \sigma_{\mathrm{DD}} = \sigma_{\mathrm{tot}} - \sigma_{\mathrm{el}} - \sigma_{\mathrm{Dp}}$$

The black disk approach, clearly cannot properly take diffractive excitation into account

It can be fudged, by setting e.g. $\sigma = \sigma_{\mathrm{in}}$ or $\sigma = \sigma_{\mathrm{abs}}$, but we want to do better.

We want to be able to see which nucleons that contributes to the centrality observable.

- absorptively wounded nucleons.
- diffractively wounded nucleons.
- ...Not elastically scattered nucleons.

$$\sigma_{\mathrm{W}} \equiv \sigma_{\mathrm{abs}} + \sigma_{\mathrm{Dt}} + \sigma_{\mathrm{DD}} = \sigma_{\mathrm{tot}} - \sigma_{\mathrm{el}} - \sigma_{\mathrm{Dp}}$$

The black disk approach, clearly cannot properly take diffractive excitation into account

It can be fudged, by setting e.g. $\sigma = \sigma_{\text{in}}$ or $\sigma = \sigma_{\text{abs}}$, but we want to do better.

We want to be able to see which nucleons that contributes to the centrality observable.

- absorptively wounded nucleons.
- diffractively wounded nucleons.
- ... Not elastically scattered nucleons.

$$\sigma_{\text{w}} \equiv \sigma_{\text{abs}} + \sigma_{\text{Dt}} + \sigma_{\text{DD}} = \sigma_{\text{tot}} - \sigma_{\text{el}} - \sigma_{\text{Dp}}$$

$$\sigma_{\rm w} \equiv \sigma_{\rm abs} + \sigma_{\rm Dt} + \sigma_{\rm DD} = \sigma_{\rm tot} - \sigma_{\rm el} - \sigma_{\rm Dp}$$

Note that this definition of a wounded cross section does not depend on the fluctuation in the target nucleon.

But setting $\sigma = \sigma_{\rm w}$ in a fixed black-disk is not enough since we want to model also the fluctuations in the projectile.

$$\sigma_{\mathrm{w}} \equiv \sigma_{\mathrm{abs}} + \sigma_{\mathrm{Dt}} + \sigma_{\mathrm{DD}} = \sigma_{\mathrm{tot}} - \sigma_{\mathrm{el}} - \sigma_{\mathrm{Dp}}$$

Note that this definition of a wounded cross section does not depend on the fluctuation in the target nucleon.

But setting $\sigma = \sigma_{\mathrm{w}}$ in a fixed black-disk is not enough since we want to model also the fluctuations in the projectile.

The two-radii model

A simple extension of the black-disk Glauber model is to assume that the target and nucleus fluctuates between two states with different radii, R and r, with the probability c and $1 - c$ respectively.

Since we have four independent cross sections σ_{abs}, σ_{el}, $\sigma_{\mathrm{Dp}} = \sigma_{\mathrm{Dt}}$, and σ_{DD}, we introduce a fourth transparency parameter, α with

$$T_{pt}(b) = \alpha\Theta(r_p + r_t - b).$$

α, c, r and R can now be fit to reproduce all relevant cross sections.

But the fluctuations are very crude.

Glauber–Gribov and Colour Fluctuations

Arguable the most advanced model is by Strickman et al. (GG)

Assume a fluctuating cross section:

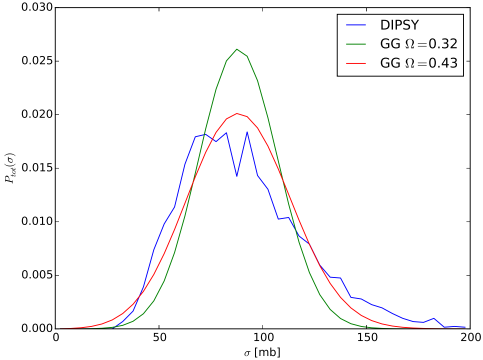
$$\sigma_{\mathrm{tot}} = \int d\sigma P_{\mathrm{tot}}(\sigma) = \int d\sigma \rho \frac{\sigma}{\sigma + \sigma_0} \exp\left\{ -\frac{(\sigma/\sigma_0 - 1)^2}{\Omega^2} \right\}$$

Experiments typically use this together with a black disk, $T(b) = \Theta(\sqrt{\sigma/\pi} - b)$, with $\Omega = 1.01$ or 0.55, with the $\mathrm{P}_{\mathrm{tot}}$ scaled to get the total inelastic cross section

$$\sigma_{\mathrm{in}} = \int d\sigma P_{\mathrm{in}}(\sigma) \equiv \int d\sigma P_{\mathrm{tot}}(\sigma/\lambda_{\mathrm{in}}), \qquad \lambda_{\mathrm{in}} = \sigma_{\mathrm{in}}/\sigma_{\mathrm{tot}}$$

GG vs. DIPSY

Let's analyse what GG does by comparing with DIPSY.



Assuming the GG distribution corresponds to fluctuations in the projectile only.

Assuming that GG describes the fluctuations in the projectile only, we can fit the parameters to three cross section:

$$
\begin{aligned}
\sigma_{\mathrm{tot}} &= \int d^2b \int d\sigma P_{\mathrm{tot}}(\sigma) 2T(\sigma,b) \\
\sigma_{\mathrm{el}} &= \int d^2b \left| \int d\sigma P_{\mathrm{tot}}(\sigma) T(\sigma,b) \right|^2 \\
\sigma_{\mathrm{w}} &= \int d^2b \int d\sigma P_{\mathrm{tot}}(\sigma) \left(2T(\sigma,b) - T^2(\sigma,b) \right)
\end{aligned}
$$

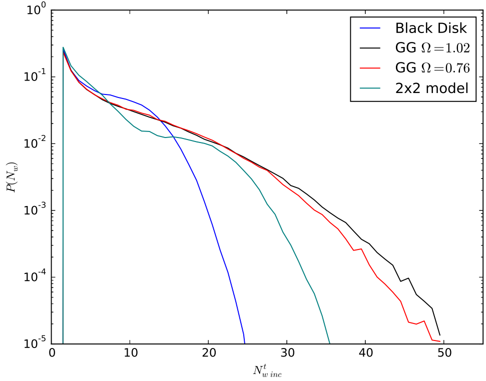
We have tried

$$
\begin{aligned}
T(\sigma,b) &\propto \exp(-b^2/2B), \qquad (B \propto 1/\sigma) \qquad \text{and} \\
T(\sigma,b) &= \alpha\Theta(\sqrt{\sigma/2\pi\alpha} - b).
\end{aligned}
$$

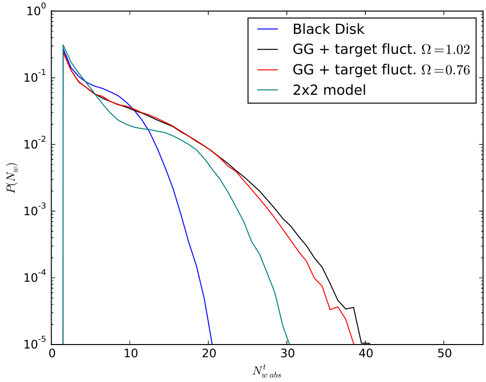
But only with the latter was it possible to fit experimental cross sections.

Distribution of wounded nucleons

We can now use our modified GG tuned to experimental data and obtain a distribution of wounded nucleons.



But we also need the absorptively wounded nucleons



Using the simple 2-radii model to estimate target fluctuations

Generating finalstates in pA

How much does a wounded nucleon contribute to particle production?

An absorptive pN scattering would distribute particles evenly in η. But what about projectile wounding two nucleons absorptively?

For a diffractively wounded nucleon, we expect a high-mass tail:

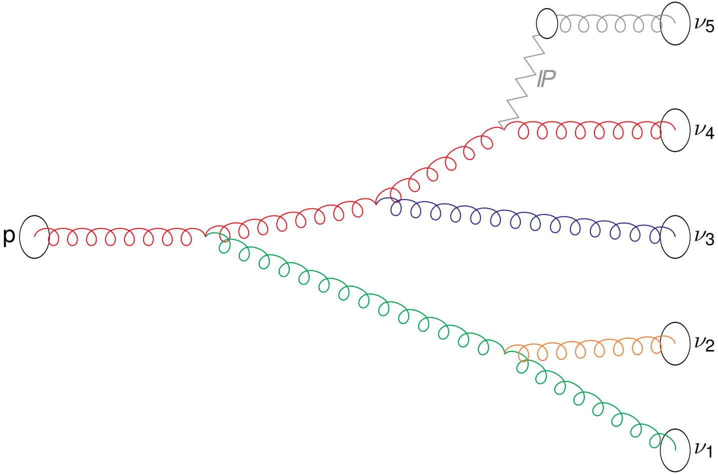
$$\frac{d\sigma}{dM_X^2} \propto \frac{1}{M_X^{2(1+\epsilon)}}$$

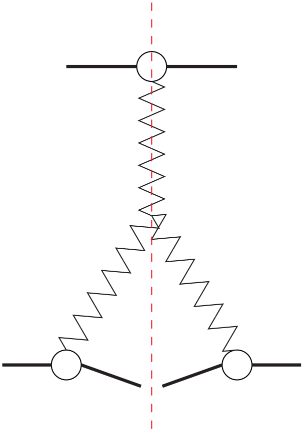
with $0 < \epsilon < 0.2$.

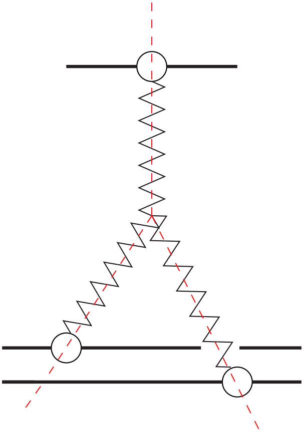
Fritiof reloaded

The old Fritiof model assumed that each wounded nucleon contributed with a string with a mass distribution corresponding to $\epsilon = 0$.

This worked very well for low energies, where perturbative effects were smallish. It does not work for LHC.


p
ν_5
$I\!P$
ν_4
ν_3
ν_2
ν_1

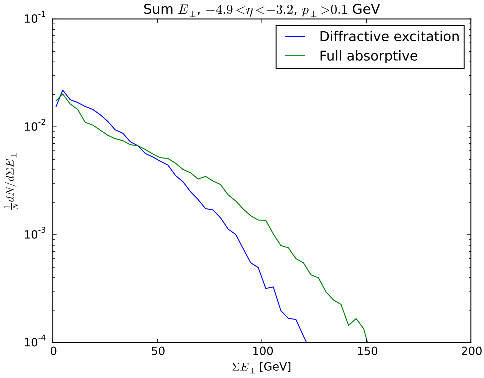

(a)

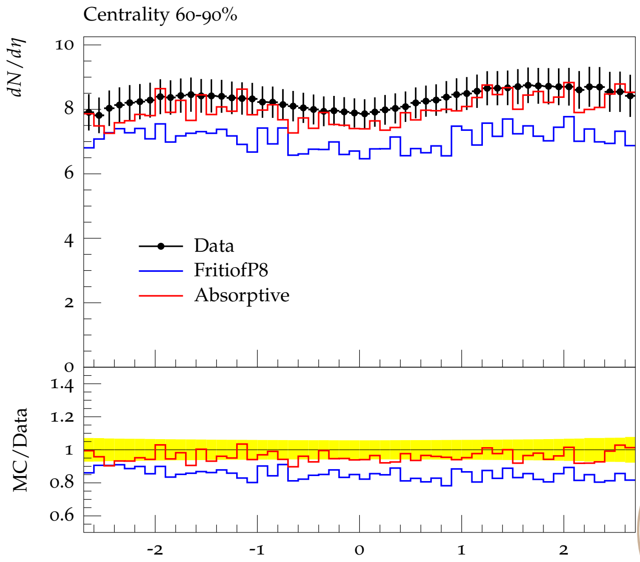

(b)

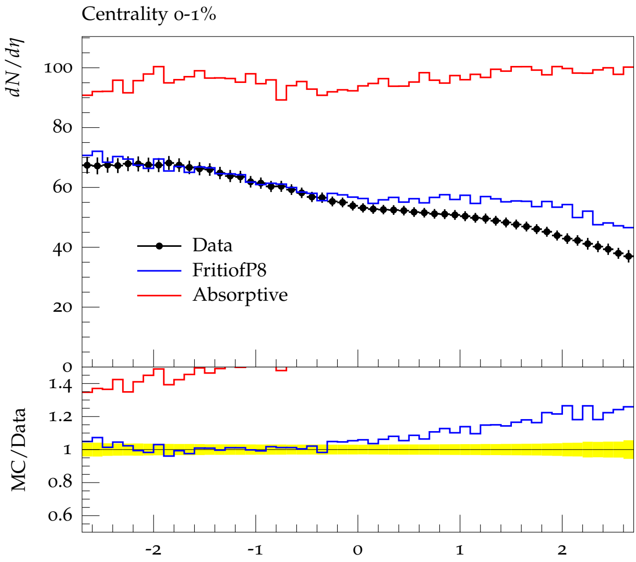
The New Model

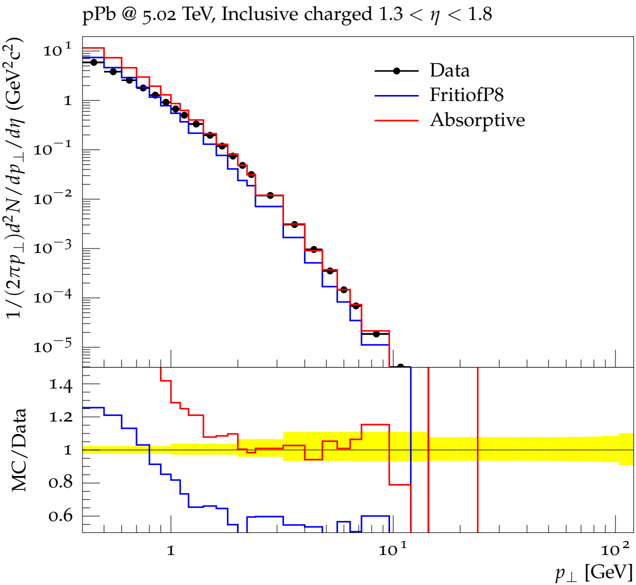
- Generate N_{abs} and N_{w}.
- Let PYTHIA8 generate one absorptive pp event, But bias the hard ME with a factor N_{abs}.
- Stack another $N_{\mathrm{w}} - 1$ diffractive events using $\epsilon = 0$ (the default in PYTHIA8).
- Make sure energy and momentum is conserved.

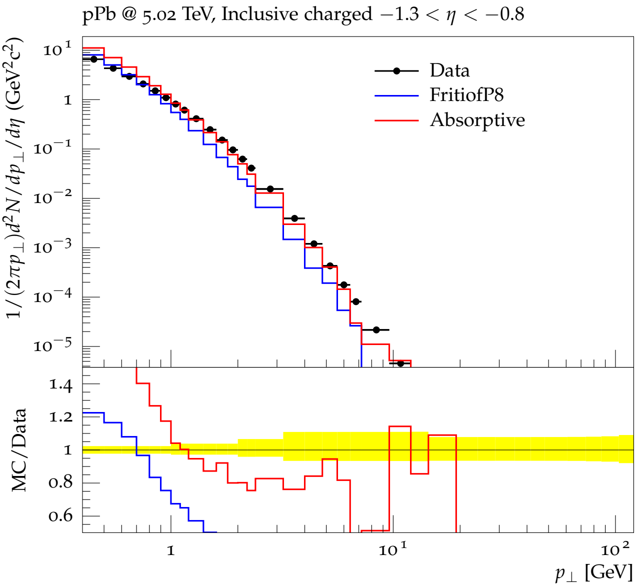
Centrality


Sum $E_\perp$, $-4.9 < \eta < -3.2$, $p_\perp > 0.1$ GeV
Diffractive excitation
Full absorptive
$\frac{1}{N} dN/d\Sigma E_\perp$
$\Sigma E_\perp$ [GeV]
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
50
100
150
200


Centrality 60-90%
dN/dη
10
8
6
4
2
0
Data
FritiofP8
Absorptive
MC/Data
1.4
1.2
1
0.8
0.6
-2
-1
0
1
2


Centrality 0-1%
dN/dη
100
80
60
40
20
0
Data
FritiofP8
Absorptive
MC/Data
1.4
1.2
1
0.8
0.6
-2
-1
0
1
2


pPb @ 5.02 TeV, Inclusive charged 1.3 < η < 1.8
Data
FritiofP8
Absorptive
1/(2πp⊥)d²N/dp⊥/dη (GeV²c²)
10¹
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
MC/Data
1.4
1.2
1
0.8
0.6
1
10¹
10²
p⊥ [GeV]


pPb @ 5.02 TeV, Inclusive charged $-1.3 < \eta < -0.8$
Data
FritiofP8
Absorptive
$1/(2\pi p_\perp) d^2N/dp_\perp/d\eta$ (GeV^{2}c^2)
MC/Data
$p_\perp$ [GeV]

Outlook

- Differentiate between wounded and absorbed nucleons
- Improve MPI modelling
- GG-like model with individually fluctuating projectile and target
- Implement simple FS effects (rope and swing)
- From pA to AA
- RIVET

RIVET

A program for publishing measurements in a way usable for everyone.

A set of tools that can be used to build analysis routines for comparison of a given measurement with event generators.

Philosophy:

- The actual analysis (with all kinematical cuts)
- Detector-independent (unfolding)
- **Model-independent**

It is ok to publish data as a function of N_{part} or N_{coll} — this is an interpretation of the data.
But it is not independent of theoretical models.

RIVET

A program for publishing measurements in a way usable for everyone.

A set of tools that can be used to build analysis routines for comparison of a given measurement with event generators.

Philosophy:

- The actual analysis (with all kinematical cuts)
- Detector-independent (unfolding)
- **Model-independent**

It is ok to publish data as a function of N_{part} or N_{coll} — this is an interpretation of the data.
But it is not independent of theoretical models.

RIVET

A program for publishing measurements in a way usable for everyone.

A set of tools that can be used to build analysis routines for comparison of a given measurement with event generators.

Philosophy:

- The actual analysis (with all kinematical cuts)
- Detector-independent (unfolding)
- **Model-independent**

It is ok to publish data as a function of $N_{\rm part}$ or $N_{\rm coll}$ — this is an interpretation of the data.
But it is not independent of theoretical models.

RIVET

A program for publishing measurements in a way usable for everyone.

A set of tools that can be used to build analysis routines for comparison of a given measurement with event generators.

Philosophy:

- The actual analysis (with all kinematical cuts)
- Detector-independent (unfolding)
- **Model-independent**

It is ok to publish data as a function of $N_{\rm part}$ or $N_{\rm coll}$ — this is an interpretation of the data.
But it is not independent of theoretical models.

RIVET

A program for publishing measurements in a way usable for everyone.

A set of tools that can be used to build analysis routines for comparison of a given measurement with event generators.

Philosophy:

- The actual analysis (with all kinematical cuts)
- Detector-independent (unfolding)
- **Model-independent**

It is ok to publish data as a function of N_{part} or N_{coll} — this is an interpretation of the data.
But it is not independent of theoretical models.

If you want to make your measurements useful for others — publish the actual measurement in RIVET!