Flavor aspects of parton energy loss

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M.S., Brian Cole, EPJC 76 (2016) no.2 50
M.S., arXiv:1606.00903
+ new
Features:

1) only modest (if any) rise with increasing jet $p_T$,
Inclusive jet $R_{AA}$

Features:
1) only modest (if any) rise with increasing jet $p_T$,
2) almost no rapidity dependence
Charged particle $R_{AA}$

Features:
1) steep increase for $p_T > 10$ GeV
2) almost no rapidity dependence

EPJC 72 (2012) 1945
PLB 720 (2013) 52
JHEP09 (2015) 050
Charged particles in jets

Features:
1) enhancement of soft particles, depletion at intermediate $\xi$ (or $z$)
2) enhancement at high $z$ (low $\xi$)

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CMS
PbPb $\sqrt{s_{NN}} = 2.76$ TeV

ATLAS Preliminary
Pb+Pb 0-10%
$|\eta| < 2.1$

ATLAS-CONF-2015-055

PRC 90 (2014) 024908

PLB 739 (2014) 320
Jets and charged particles – some basic questions

- Why do have the jet and charge particle \( R_{AA} \) almost no rapidity dependence given quite different input parton spectra and flavor composition at different rapidities?

- What is responsible for the enhancement at high \( z \) seen in the fragmentation?

- Can we find connection among charged particle \( R_{AA} \), jet \( R_{AA} \) and jet fragmentation?
Jets and charged particles – some basic questions

- Why do have the jet and charge particle $R_{AA}$ almost no rapidity dependence given quite different input parton spectra and flavor composition at different rapidities?
- What is responsible for the enhancement at high $z$ seen in the fragmentation?
- Can we find connection among charged particle $R_{AA}$, jet $R_{AA}$ and jet fragmentation?

→ Use a simple model with minimal assumptions on the quenching physics to extract basic properties of the jet quenching
The simplest modeling of parton energy loss

\[
\frac{dN}{dp_T^{\text{jet}}} = A \left[ f_{q_0} \left( \frac{p_{T_0}}{p_T^{\text{jet}}} \right)^{n_q} + (1 - f_{q_0}) \left( \frac{p_{T_0}}{p_T^{\text{jet}}} \right)^{n_g} \right]
\]

Jet spectra parameterized by a power law

\[
f_q \left( p_T^{\text{jet}} \right) = \frac{1}{1 + \left( \frac{1-f_{q_0}}{f_{q_0}} \right) \left( \frac{p_{T_0}}{p_T^{\text{jet}}} \right)^{n_g-n_q}}
\]

Fraction of jets of a given flavor (i.e. quark or gluon initiated)
The simplest modeling of parton energy loss

\[
\frac{dn_Q(p_T^{\text{jet}})}{dp_T^{\text{jet}}} = \frac{dn \left( p_T^{\text{jet}} + S(p_T^{\text{jet}}) \right)}{dp_T^{\text{jet}}} \times \left(1 + \frac{dS}{dp_T^{\text{jet}}}\right)
\]

Yield of quenched jets of a given flavor at given \( p_T \)

\( R_{AA} \) in the approximation of fractional energy loss

\[
R_{AA} = f_q \left( \frac{1}{1 + S_q/p_T^{\text{jet}}} \right)^{n_q} \times \left(1 + \frac{dS_q}{dp_T}\right) + (1 - f_q) \left( \frac{1}{1 + S_g/p_T^{\text{jet}}} \right)^{n_g} \times \left(1 + \frac{dS_g}{dp_T}\right)
\]

\( S_q \equiv s p_T \)

\( S_g = c_F \times S_q \)

Fractional energy loss
Jet $R_{AA}$ in the simplest model

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Jet $R_{AA}$ in the simplest model

The simplest model does not work …
Jet $R_{AA}$ in the simplest model

The simplest model does not work … why?

$\rightarrow$ jet spectra are not a simple power low
$\rightarrow$ fractional energy loss is not realized in the nature
Extending the model

More precise parameterization of input jet spectra

More general modeling of jet energy loss

\[
\frac{dn}{dp_T^{\text{jet}}} = A \left( \frac{p_{T0}}{p_T^{\text{jet}}} \right)^{n+\beta \log \left( \frac{p_T^{\text{jet}}}{p_T} \right)}
\]
Jet $R_{AA}$ in extended model
Jet $R_{AA}$ in extended model

$\rightarrow$ Flatness and no rapidity dependence of jet $R_{AA}$ are due to different energy loss of quark and gluon initiated jets
Flatness and no rapidity dependence of jet $R_{AA}$ are due to different energy loss of quark and gluon initiated jets.
Quantifying the parton energy loss (I.)

\[ S = s' \left( \frac{p_T^{\text{jet}}}{p_{T0}} \right)^\alpha \]

Energy loss parameterized = encapsulated into two free parameters

\[ \alpha \]

Minimization 1

Minimization 2

\[ s' \text{ [GeV]} \]

Minimization 1

Minimization 2

\[ N_{\text{part}} \]

\[ N_{\text{part}} \]
Quantifying the parton energy loss (I.)

Energy loss parameterized = encapsulated into two free parameters

\[ S = s' \left( \frac{p_T^{\text{jet}}}{p_T^{0}} \right)^{\alpha} \]

Quark with \( p_T = 40 \text{ GeV} \) \((p_{T,0})\) looses ~ 5 GeV.
100 GeV quark looses 8 GeV

Effective power \( \sim 0.55 \)
Quantifying the parton energy loss (I.)

Energy loss parameterized = encapsulated into two free parameters

$$S = s' \left( \frac{p_T^{\text{jet}}}{p_{T0}} \right)^\alpha$$

Quark with $p_T=40$ GeV ($p_{T,0}$) looses ~ 5 GeV. 100 GeV quark looses 8 GeV

Energy loss does not extrapolate to zero. Hot medium even in peripheral? Some other physics? (nPDFs?, limits of Glauber?, …)

Effective power ~ 0.55

Linear dependence of $s'$ on $N_{\text{part}}$
Predictions for 2.76 TeV

\[ \text{Forward should exhibit a decrease of } R_{AA} \]

\[ 2.1 < |\eta| < 2.8 \]

\[ 2.8 < |\eta| < 3.5 \]
Predictions for 5 TeV

→ If the jet quenching is the same at 2.76 and 5 TeV, the jet $R_{AA}$ will be very similar to that measured at 2.76 TeV
b-jets

$R_{AA}$ vs $p_T$ (GeV)

- $b$-jets CMS PRL
- u,d,s jets
- b-jets
- b-jets (suppression $\times 2.2$)

Same parameters as for light jets

$R_{AA}$ vs $N_{part}$

$P_{T,jet} = 90-110$ GeV

$R_{AA}$ vs jet $p_T$ (GeV)

$R_{AA}$ vs $N_{part}$

$P_{T,jet} = 90-110$ GeV

$b$-jets are suppressed more than light-quark jets

$\Rightarrow$ more precise data needed to quantify by how much
Modifications of fragmentation functions

Y. Mehtar-Tani, C. A. Salgado, K. Tywoniuk, Phys. Rev. Lett. 106 (2011)
Y. Mehtar-Tani, C. A. Salgado, K. Tywoniuk, Phys. Lett. B707 (2012)
J. Casalderrey-Solana, Y. Mehtar-Tani, C. A. Salgado, K. Tywoniuk, Phys. Lett. B725 (2013)
J.-P. Blaizot, E. Iancu, Y. Mehtar-Tani, Phys. Rev. Lett. 111 (2013) 052001.

Figure from

hardest resolved next-to-hardest soft fragments

... color coherence likely very important in the quenching physics
Modifications of fragmentation functions

-> Subtract the energy from the jet / initial parton and then let it fragment as in the vacuum
Modifications of fragmentation functions

$\rightarrow$ Subtract the energy from the jet / initial parton and then let it fragment as in the vacuum

(Ratio of fragmentation functions)
Modifications of fragmentation functions

–> Subtract the energy from the jet / initial parton and then let it fragment as in the vacuum

–> Structure seen at intermediate and high-z is due to the difference in quenching of quark and gluon initiated jets

–> Direct verification of a presence of color coherence effects in the data
Modifications of fragmentation functions – prediction

... central rapidity – higher yields at high-z (but not by much)
Modifications of fragmentation functions – prediction

... central rapidity – higher yields at high-z (but not by much)

ATLAS Preliminary
Modifications of fragmentation functions – prediction

... central rapidity – higher yields at high-z (but not by much)
Modifications of fragmentation functions – a detail

Excess of low-$z$ not due to flavor effects (maybe due to in-cone radiation, recoil, collective response, ...)

![Graph](image_url)
Modifications of fragmentation functions – a detail

Excess of low-z not due to flavor effects (maybe due to in-cone radiation, recoil, collective response, …)

- These low-z hadrons contribute to the measured jet energy. Parameter $s'$ contains this soft part.
- Soft part contributes to the measured fragmentation via denominator of $z$.

$$p_{T,\text{jet}}^{\text{measured}} = p_{T,\text{jet}}^{\text{quenched}} + p_{T}^{\text{soft}}$$
Excess of low-\(z\) not due to flavor effects (maybe due to in-cone radiation, recoil, collective response, ...) 

- These low-\(z\) hadrons contribute to the measured jet energy. Parameter \(s'\) contains this soft part.
- Soft part contributes to the measured fragmentation via denominator of \(z\).

Contribution of soft hadrons to the jet energy can be estimated from the measurement at low-\(z\) => fragmentation distributions w/ correct soft contribution
Modifications of fragmentation functions – a detail

→ Prediction: detailed measurement of fragmentation at the highest-$z$ (or lowest-$\xi$) should exhibit a depletion
From jet internal structure to charged particle $R_{AA}$

Each particle of a given $p_T$ must be in a jet of the same or higher $p_T$  
$\implies$ Charged particle $R_{AA}$ (at high-$p_T$) = convolution of flavor dependent jet suppression and fragmentation functions
From jet internal structure to charged particle $R_{AA}$
High-$p_T$ jets are more suppressed than charged particles – a puzzle?
High-\(p_T\) jets are more suppressed than charged particles – a puzzle?

– No, it is the same puzzle as the excess in \(D(z)\) at high \(z\).

The charged particle \(R_{AA}\) (at high-\(p_T\)) = convolution of flavor dependent jet suppression and fragmentation functions.
From jet internal structure to charged particle $R_{AA}$

... we should not do this kind of plots – it is misleading
Flavor sensitivity

**Definition:** Flavor sensitivity = sensitivity of a given observable to the flavor (and spectra) of the initial parton leading to a possible incorrect interpretation of that observable.

**Example:** fragmentation functions at intermediate $z$ and high $z$, charged particle $R_{AA}$

=> Checking other observables
Dijet asymmetry

**ATLAS** Preliminary
anti-\(k_t\) \(R = 0.4\) jets, \(\sqrt{s_{NN}} = 2.76\) TeV

\[ x_J = \frac{p_{T,\text{subleading}}}{p_{T,\text{leading}}} \]

- \(\text{Pb+Pb}\)
- \(\text{pp}\)

100 < \(p_T\) < 126 GeV

0 - 10 %
Dijet asymmetry

→ Measured asymmetry is not due to different quenching of q/g jets.
→ NLO generators may start to be important (shape matches w/ data).
Dijet asymmetry

→ The subleading jet is quenched very differently than the leading jet → quantify

→ The subleading jet in the maximum of the $x_J$ is suppressed by a factor of $\sim 3$ larger than the leading jet
Jet substructure using splitting

Splitting, $z_g$ – defined by the 'Soft Drop' algorithm (used in pp studies of boosted objects):

- Run C/A algorithm in the jet
- Compare subjets; if
  
  $$\frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} < 0.1$$

- drop the softer partner and repeat the same calculation with two “parents” of harder subject; else

  $$\frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} = z_g$$
Jet substructure using splitting

→ Jets with a distinct subject structure ($p_{T1}$ closer to $p_{T2}$) quenched more (or more jets with less splitting)

→ Looks significant, but the change involves only 5-10% of jets

![Graph showing CMS Preliminary results with data points and line graphs comparing $1/N_{jet} dN/dz_g$ between pp smeared, PbPb, and pp 25.8 pb$^{-1}$, PbPb 404 μb$^{-1}$]
Jet substructure using splitting

Use the quenching model in the same way as before for the fragmentation

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Jet substructure using splitting

Modification not due to a simple flavor bias ...

... since $z_g$ does not depend much on the flavor or jet $p_T$
Puzzling difference between RHIC and LHC

Andrés et. al (EPJ C76 (2016) 475) … K factor 2-3 times larger at RHIC than at the LHC, with only mild centrality dependence,…

Horowitz, Gyulassy (Nucl.Phys. A872, 265) … suppression at RHIC is larger

\[ \hat{q} = K \cdot \hat{q}_{ideal} = K \cdot 2\epsilon^{3/4} \]

\[ R_{AA} \]

\[ p_T \text{ (GeV)} \]

Nestor Armesto (Fri), Andres Casas (Sat)

How is the extraction of the quenching from charged particles influenced by the underlying parton/jet kinematics?
Jets at RHIC versus LHC

- Jets very different between LHC and RHIC
- Jet spectra for a given flavor more steep at RHIC
- Flavor composition also different
  
  → Will impact charged particle $R_{AA}$
  
  → Apply the effective quenching factors extracted at the LHC to RHIC jets
Charged particle $R_{AA}$
RHIC vs LHC

- Effective quenching factors from LHC applied to RHIC parton/jet spectra
- Same quenching leads to smaller $R_{AA}$ in the case of RHIC

$N_{\text{part}} = 260$
- $200 \text{ GeV}$
- $2.76 \text{ TeV}$

$R_{AA}$ vs charged particle $p_T$ [GeV]

=> Initial parton spectra and flavor composition are crucial for the extraction of the size of jet quenching
Flavor sensitivity

**Definition:** Flavor sensitivity = sensitivity of a given observable to the flavor (and spectra) of the initial parton leading to a possible incorrect interpretation of that observable.

**Flavor sensitive:** jet $R_{AA}$, fragmentation functions at intermediate $z$ and high $z$, charged particle $R_{AA}$

**Likely flavor sensitive:** jet width, jet mass, single particles

**Almost flavor insensitive:** $z_g$ distribution, $x_J$ distribution, fragmentation at low $z$ (= high $\xi$)
Quantifying the parton energy loss (II.)

\[
\frac{dn_Q(p_T^{\text{jet}})}{dp_T^{\text{jet}}} = \frac{dn}{dp_T^{\text{jet}}} \left( p_T^{\text{jet}} + S(p_T^{\text{jet}}) \right) \times \left( 1 + \frac{dS}{dp_T^{\text{jet}}} \right)
\]

Yield of quenched jets of a given flavor at given \( p_T \)

\[
S_q = s' \left( \frac{p_T^{\text{jet}}}{p_T,0} \right)^\alpha
\]

\[
S_g = C_F \times S_q
\]

• So far \( \alpha \) and \( s' \) free, \( C_F = 9/4 \) fixed

• \( C_F = 9/4 \) … difference in the probability to radiate a gluon from a gluon and quark source in the vacuum in large \( Q^2 \) limit or soft limit

• Vacuum value of \( C_F \) measured and calculated in pQCD (MLLA)
Quantifying the parton energy loss (II.)

- So far $a$ and $s'$ free, $c_F = 9/4$ fixed
- $c_F = 9/4$ ... difference in the probability to radiate a gluon from a gluon and quark source in the vacuum in large $Q^2$ limit or soft limit
- Vacuum value of $c_F$ measured and calculated in pQCD (MLLA)

Graph: NLLA limit, $r = C_A / C_F = 2.25$

- $r = N_g / N_q$
- Data points and fit curves for CDF, $E_{jet} = 41$ GeV and $E_{jet} = 53$ GeV
- CLEO and OPAL data points

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Quantifying the parton energy loss (II.)

- c_F = 1.7-1.8 for Q = 20-100 GeV

- Vacuum value of c_F measured and calculated in pQCD (MLLA)
Quantifying the parton energy loss (II.)

\[ S_q = s' \left( \frac{p_T^{\text{jet}}}{p_{T,0}} \right)^{\alpha} \quad S_g = c_F \times S_q \]

- Use rapidity differential jet R_{AA} measurement to perform a multidimensional fit and extract \( \alpha \), \( s' \) and \( c_F \) simultaneously.

- Input spectra @ NLO (POWHEG+PYTHIA8 + 3 variations of PDFs)

--> Result:

\[
\begin{array}{|c|c|}
\hline
s' & = x \cdot N_{\text{part}} + y \\
\hline
x & = 12.3 \pm 1.4 \text{ GeV,} \\
y & = 1.5 \pm 0.2 \text{ GeV} \\
\hline \alpha & = 0.52 \pm 0.02 \\
\hline c_F & = 1.78 \pm 0.12 \\
\hline
\end{array}
\]

--> value of \( c_F \) consistent with the value in the vacuum
What about other objects?

Data tell us that the medium largely sees a jet as one object => what about other objects with a structure that are suppressed?
What about other objects?

Data tell us that the medium largely sees a jet as one object
=> what about other objects with a structure that are suppressed?
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=> what about other objects with a structure that are suppressed?

\[ J/\Psi \ & \ \Psi(2S) \]
What about other objects?

Data tell us that the medium largely sees a jet as one object
=> what about other objects with a structure that are suppressed?

\[ J/\psi \ \& \ \Psi(2S) \]

... check the differences between the suppression of jets and charmonia at high-\( p_T \) (at the LHC at mid-rapidity)

Input:
- Measured pp spectra of charmonia (cannot rely on out of the box PYTHIA or other generator)
- Energy loss extracted from jets
Charmonia

![Graphs showing the $R^{J/\psi}_{AA}$ as a function of $p_T$ and $|y|$ for different regions and models.]

- $|y| < 2.4$
  - Model - light quark
  - Model - gluon
  - CMS, JHEP 05, 063
  - CMS PAS HIN-12-014

- $6.5 < p_T < 30$ GeV
  - Model - light quark
  - Model - gluon
  - CMS, JHEP 05, 063
  - CMS PAS HIN-12-014
Charmonia

... suppression of both charmonia at $p_T > 6.5$ GeV is similar to the suppression of light quark jets
Summary

• Absence of rapidity dependence and flatness of jet $R_{AA}$, characteristic shapes of jet fragmentation at mid and high $z$ are due to flavor dependent jet quenching.

• Data say that coherence effects are important (medium largely, but not fully sees $R=0.4$ jets as one radiating object).

• Recoil (or in-cone radiation) modifies also measured high-$z$ fragmentation (same holds for all other observables).

• $b$-jets are quenched more than light quark jets.

• Dijet asymmetry: sub-leading jet is quenched $\sim$3 times more then the leading jet.

• Charged particle $R_{AA}$ @ RHIC vs LHC: initial parton spectra and flavor composition are important for the extraction of the size of quenching (for the same quenching $R_{AA}$ at 200 GeV will be smaller than $R_{AA}$ at 2.76 TeV)
Summary (cont'd)

- Average jet quenching can be parameterized as follows:
  \[ s = x \cdot N_{\text{part}} + y \]
  \[ x = 12.3 \pm 1.4 \text{ GeV}, \]
  \[ y = 1.5 \pm 0.2 \text{ GeV} \]

| \( \alpha \)   | 0.52 \pm 0.02 |
|----------------|---------------|
| \( c_F \)      | 1.78 \pm 0.12 |

\[ S_q = s' \left( \frac{p_T^{\text{jet}}}{p_{T,0}} \right)^{\alpha} \]

(... can be used in simple modeling, checking observables, comparisons w/ full quenching models).

- Color factor, extracted for the first time in HI, seems not to be modified by the medium (\( c_F = 1.78 \pm 0.12 \)).

- Parton energy loss does not extrapolate to 0 for \( N_{\text{part}} \to 0 \).

- Suppression of charmonia at \( p_T > 6.5 \text{ GeV} \) at midrapidity behaves like the suppression of light quark jets.
Backup slides
Flavor fractions and fit parameters

Fit type | Parameter | $|y| < 2.1$ | $|y| < 0.3$ | $0.3 < |y| < 0.8$ | $1.2 < |y| < 2.1$
--- | --- | --- | --- | --- | ---
All | $f_{q_0}$ | 0.34 | 0.28 | 0.29 | 0.40
Power law | $n_q$ | 5.66 | 5.37 | 5.40 | 6.15
 | $n_g$ | 6.25 | 5.97 | 6.09 | 6.92
Extended power law | $n_q$ | 4.19 | 4.34 | 4.27 | 3.75
 | $\beta_q$ | 0.71 | 0.49 | 0.54 | 1.2
 | $n_g$ | 4.69 | 4.55 | 4.57 | 4.60
 | $\beta_g$ | 0.80 | 0.71 | 0.76 | 1.2

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D(z) parameterization

\[
D(z) = a \cdot \frac{(1 + d z)^b}{(1 + e z)^c} \cdot \exp(-f z)
\]

|       | a   | b   | c   | d   | e   | f   |
|-------|-----|-----|-----|-----|-----|-----|
| Quark | 318 | 2.51| 1.44| -0.85| 52.4| 0   |
| Gluon | 574 | 1.87| 2.32| 9.09| 32.0| 10.3|
\[ R_{AA} = f_q \left( \frac{1}{1 + S_q / p_T^{jet}} \right)^{n_q + \beta_q \log((p_T^{jet} + S_q) / p_T^{jet})} \]

\[ \times \left( \frac{p_T^{jet}}{p_T^{jet}} \right)^{\beta_q \log(1 + S_q / p_T^{jet})} \left( 1 + \frac{dS_q}{dp_T^{jet}} \right) \]

\[ + (1 - f_q) \left( \frac{1}{1 + S_g / p_T^{jet}} \right)^{n_g \beta_g \log((p_T^{jet} + S_g) / p_T^{jet})} \]

\[ \times \left( \frac{p_T^{jet}}{p_T^{jet}} \right)^{\beta_g \log(1 + S_g / p_T^{jet})} \left( 1 + \frac{dS_g}{dp_T^{jet}} \right) , \]

\[ f_q \left( p_T^{jet} \right) = \frac{1}{1 + \left( \frac{1 - f_q}{f_q} \right) \left( \frac{p_T^0}{p_T^{jet}} \right)^{n_g - n_q + (\beta_g - \beta_q) \log \left( p_T^{jet} / p_T^{jet} \right)}} . \]
Minimization in (I.)

10-20%

60-70%

$N_{\text{part}} = 261$

$N_{\text{part}} = 15$
Modifications of fragmentation functions – a detail

How the soft excess is estimated:

Measured (at least partially)

\[ \Phi_{\text{inc}}^{\text{soft}} = f_q^{\text{int}} \Phi_q^{\text{soft}} + (1 - f_q^{\text{int}}) \Phi_g^{\text{soft}} \]

\[ \Phi_g^{\text{soft}} = c_F \Phi_q^{\text{soft}} \]

\[ D^{\text{meas}}(z) = f_q^{\text{int}} D_q(z[1 + \Phi_q^{\text{soft}}]) + (1 - f_q^{\text{int}}) D_g(z[1 + \Phi_g^{\text{soft}}]) \]
Charmonia in p+Pb

\[ R_{ppb} \]

\[ p_T \text{ [GeV]} \]

\[ R_{ppb} \]

\[ p_T \text{ [GeV]} \]

ATLAS Preliminary

\[ p+Pb \sqrt{s_{NN}} = 5.02 \text{ TeV} \]

Prompt J/\psi
-1.5 < y^* < 1.5

Prompt \psi(2S)
-1.5 < y^* < 1.5
Feed down

\[ R_{\chi_c} \]

\[ \sqrt{s} = 7 \text{ TeV} \int L \, dt = 4.5 \text{ fb}^{-1} \]

Isotropic Decay

\text{Prompt} \ \left| y^{J/\psi} \right| < 0.75

\text{Data}

\text{LHCb } 2.0 < y^{J/\psi} < 4.5

\text{NLO NRQCD}

ATLAS, JHEP 07 (2014) 154
Feed down

ATLAS, JHEP 07 (2014) 154
Modifications of fragmentation functions

\[ R_{\text{MC}} \]

- ATLAS 0-10%
- ATLAS 10-20%
- ATLAS 20-30%
- ATLAS 30-40%
- ATLAS 40-50%
- ATLAS 50-60%

\[ R_{\text{analytic}} \]

MC vs. analytic for different ATLAS bins.