Probing Quark Gluon Plasma using B Mesons

- Measurement of B+ and Bs meson production in pp collisions at 5 TeV with CMS at the LHC -

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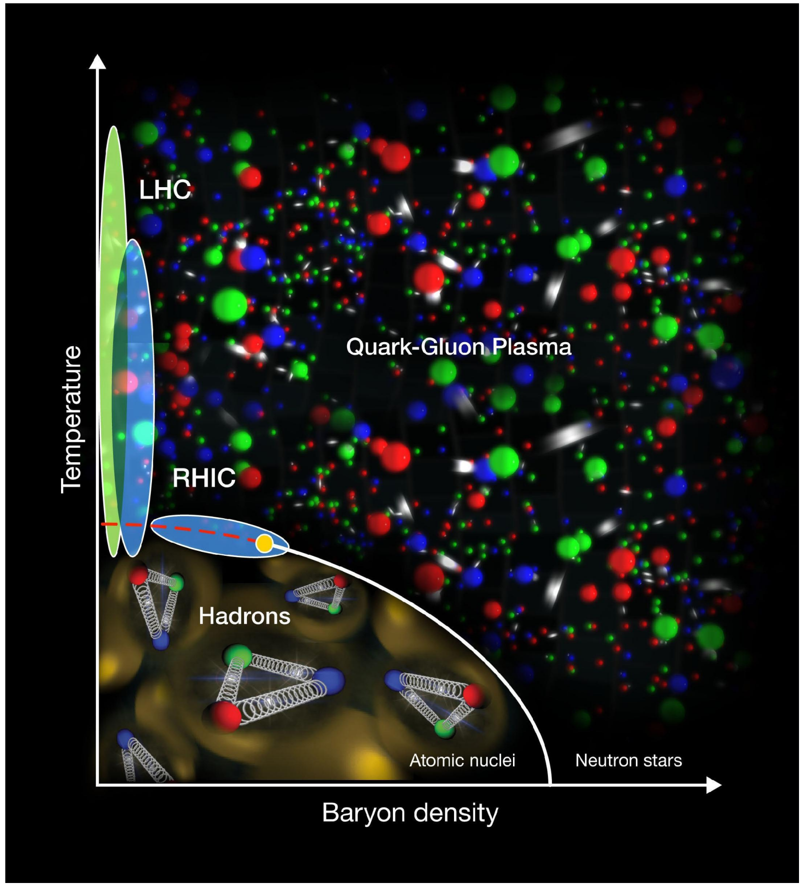
Quark-Gluon Plasma (QGP)

- **A state of matter** that only exists under **extreme conditions** (very high temperature/density)

- Quarks and gluons become '**free**' **instead of being bound together into hadrons**

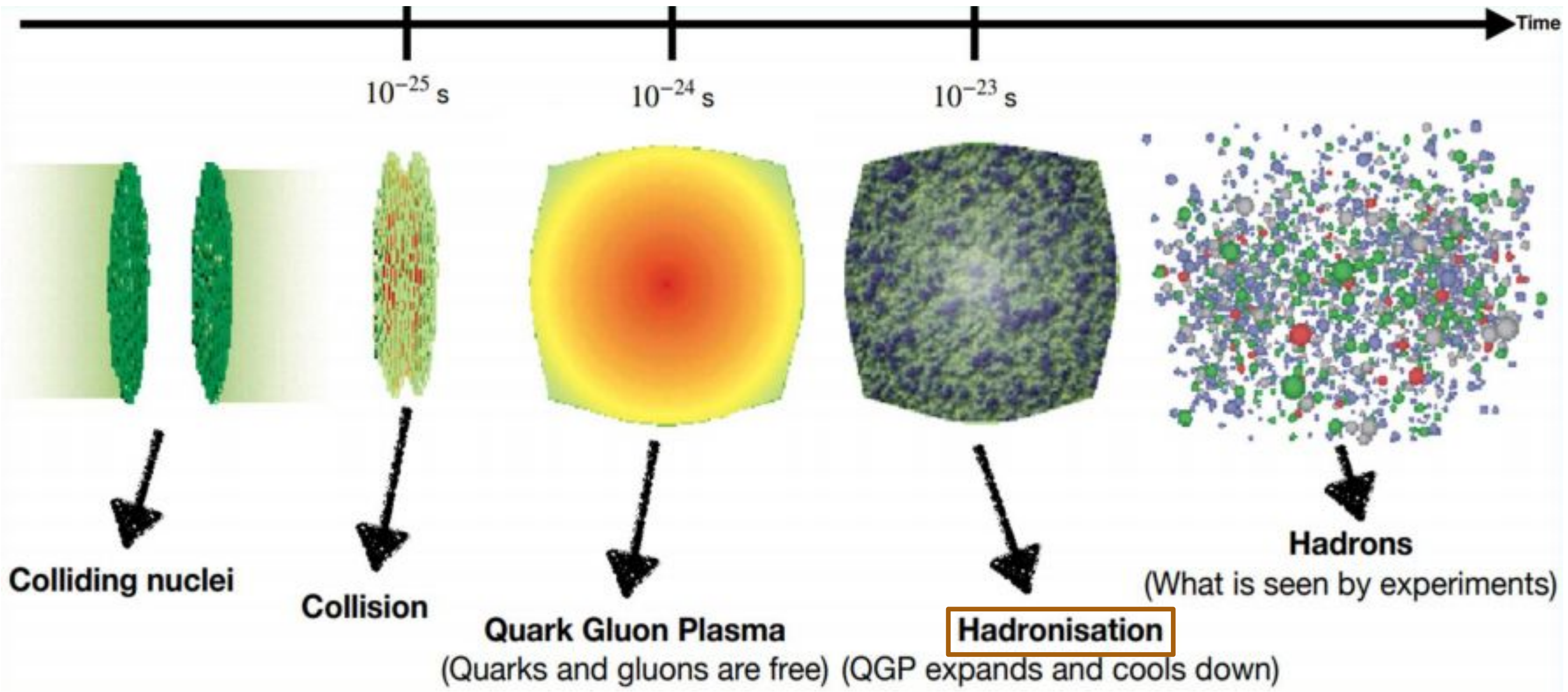
- Believed to have existed just after the Big Bang ($\lesssim 1\ \mu s$) and inside neutron stars

- Can be reproduced in **heavy ion collisions** at LHC



Phase diagram of QGP (Source: CEA)

Heavy ion collisions



Aim to study the **hadronisation process** of quarks & **the effect of presence of QGP** on the process

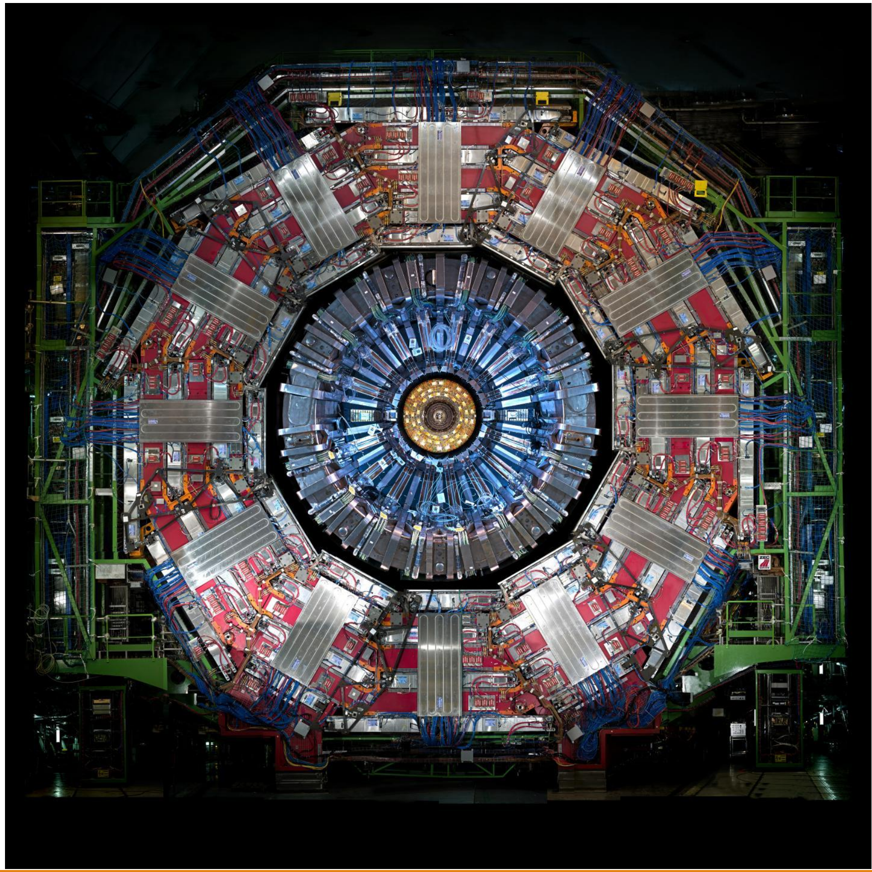
Compact Muon Solenoid (CMS)

- **A general-purpose particle physics detector at the LHC**

- designed to study pp collisions and also with unique capabilities to study heavy ion collisions

- heavy ion collisions normally take place towards the end of the year, upcoming this November!

The analysis is based on the pp 5 TeV dataset collected by CMS in 2017



B mesons, probe of QGP

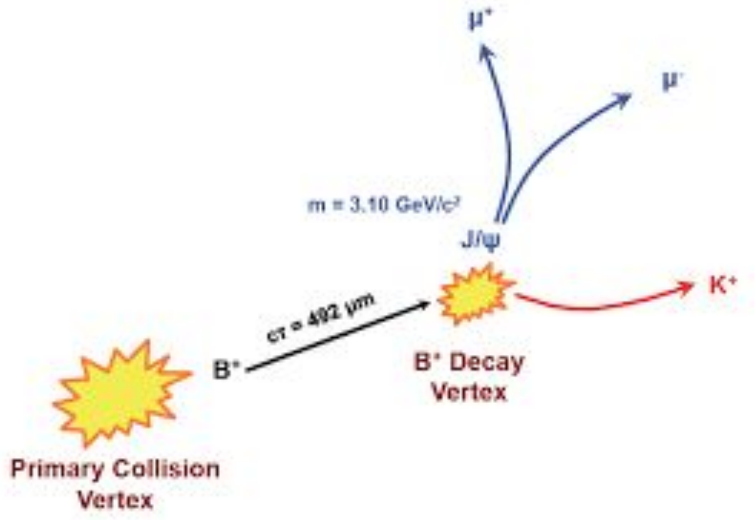
Particle	Symbol	Composition	Charge
Charged B meson	$\mathbf{B^+}$	$\mathbf{u\bar{b}}$	+1
Neutral B meson	$\mathbf{B^0}$	$\mathbf{d\bar{b}}$	0
Strange B meson	$\mathbf{B_S^0}$	$\mathbf{s\bar{b}}$	0
Charmed B meson	$\mathbf{B_C^+}$	$\mathbf{c\bar{b}}$	+1

- Formed from **hadronisation of b quarks**

- We explore the following $\mathbf{B^0_s}$ **and** $\mathbf{B^+}$ decay channels:

$$B_S^0 \rightarrow J/\psi\ \phi \rightarrow \mu^+\mu^-K^+K^-$$
$$B^+ \rightarrow J/\psi\ K^+ \rightarrow \mu^+\mu^-K^+$$

- Detect and measure particles at **the end of the decay chain**



Why B mesons?

- **Longer life time** □ larger displacement □ can be distinguished

- **Massive** enough □ Negligible thermal production

Differential Cross Section

$$\frac{d\sigma}{dy} = \frac{1}{\epsilon L B} \boxed{\frac{dN_S}{dy}}$$

σ: Cross section

ϵ: Efficiency x Acceptance of the detector (obtained from MC simulation)

L: luminosity ($L = 302.3\ \mathrm{pb}^{-1}$)

B: Branching fraction of B meson decay (from PDG)

N_S: Signal Yield (number of signal events obtained from fit to data)

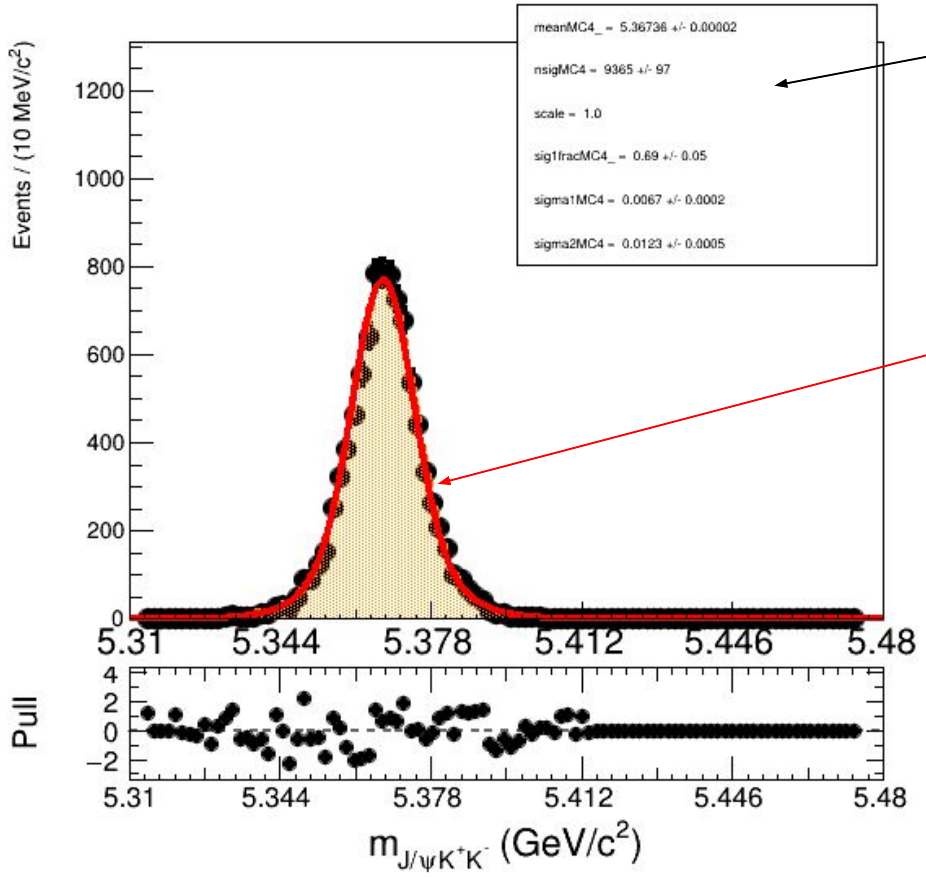
Fitting the data: $\mathbf{B^0_s}$

(Fit using Extended Unbinned Maximum Likelihood method)

Fit to Monte Carlo (MC)

Nominal Model = **Signal** (Double gaussian)

$$l(m) = N_s\left(\alpha \cdot \text{gauss}_1(m\ ;\ \mu\ ,\ \ \sigma_1) + (1-\alpha) \cdot \text{gauss}_2\ (m\ ;\ \mu\ ,\ \ \sigma_2)\right)$$



Parameters

Double gaussian signal

Parameters:

nsig (N_S): number of signal events

mean (μ): the centre position of the peak

sigma# (σ): the width of each gaussian

sig1frac (α): the weight of the first gaussian

Fitting procedure:

1. Fit signal-only MC sample to extract signal shape parameters
2. Fit the data sample constraining the signal shape parameters from MC (next slide)

Fit to data

$$\frac{d\sigma}{d(p_T, y, Mult)} = \frac{1}{\epsilon LB} \frac{dN_S}{d(p_T, y, Mult)}$$

Nominal Model = **Signal** (Double gaussian) + **Background** (Exponential):

$$l(m\ ) = \ N_s\big(\alpha \cdot \mathrm{gauss}_1(m\ ;\ \mu\ \ , s \cdot \sigma_1) + (1 - \alpha) \cdot \mathrm{gauss}_2\ (m\ ;\ \mu\ \ , s \cdot \sigma_2)\big) + N_B \exp(\lambda m\ \ )$$

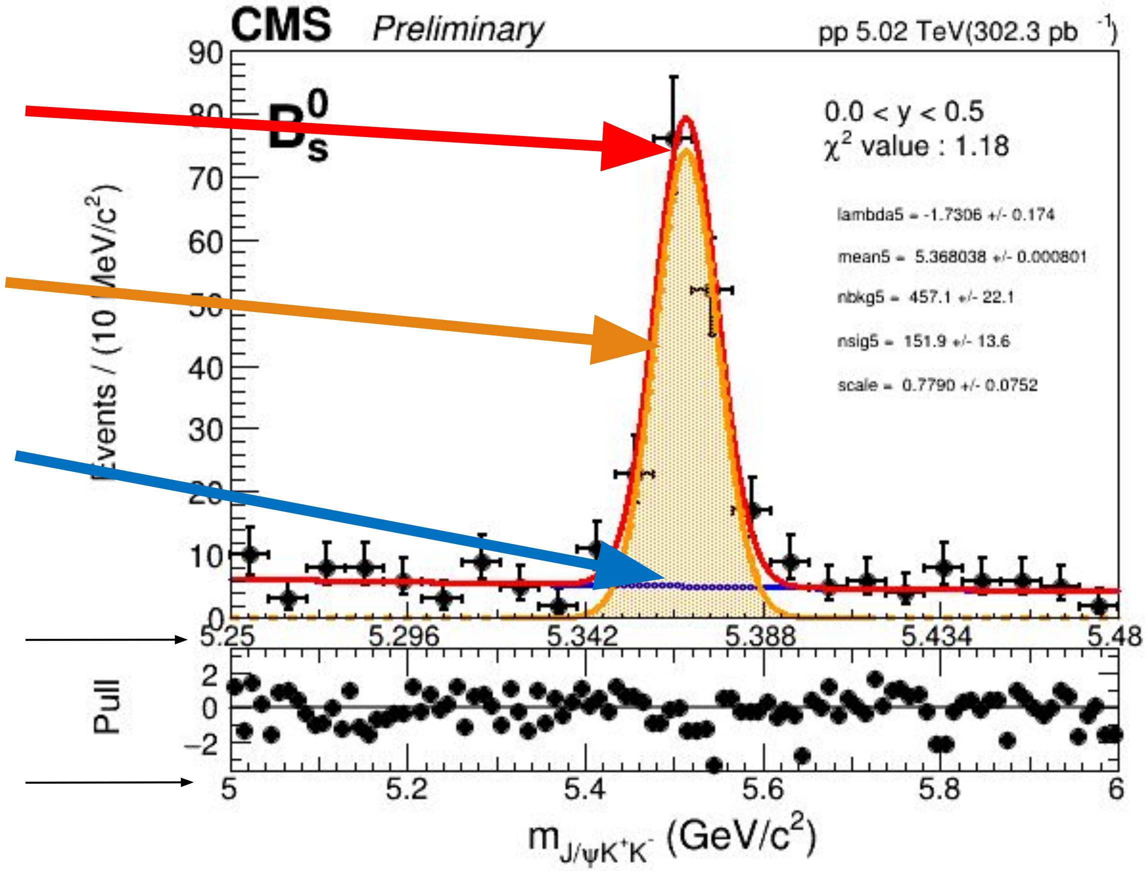
Signal + Background

Signal

Background

Zoomed on the peak

Fitting range (5-6 GeV)



lambda: exponential decay constant of the background (λ)

mean: the position of the peak (μ)

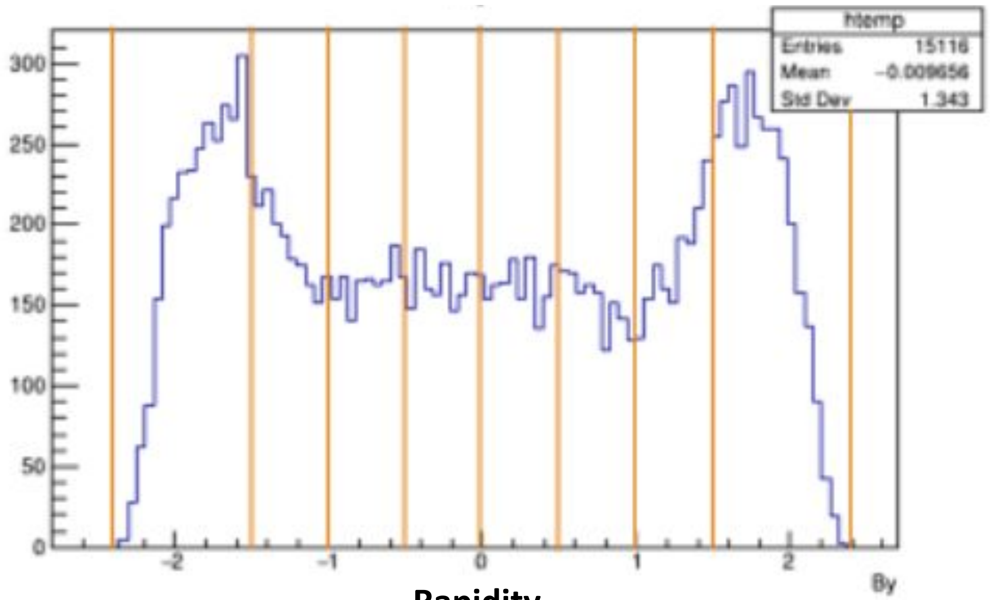
nsig: number of signal events in data (N_S)

nbkg: number of background events in data
Scale: The ratio of the width of the peak compared to that of the Monte Carlo simulation (N_B)

scale: the factor before the width of the peak (s)

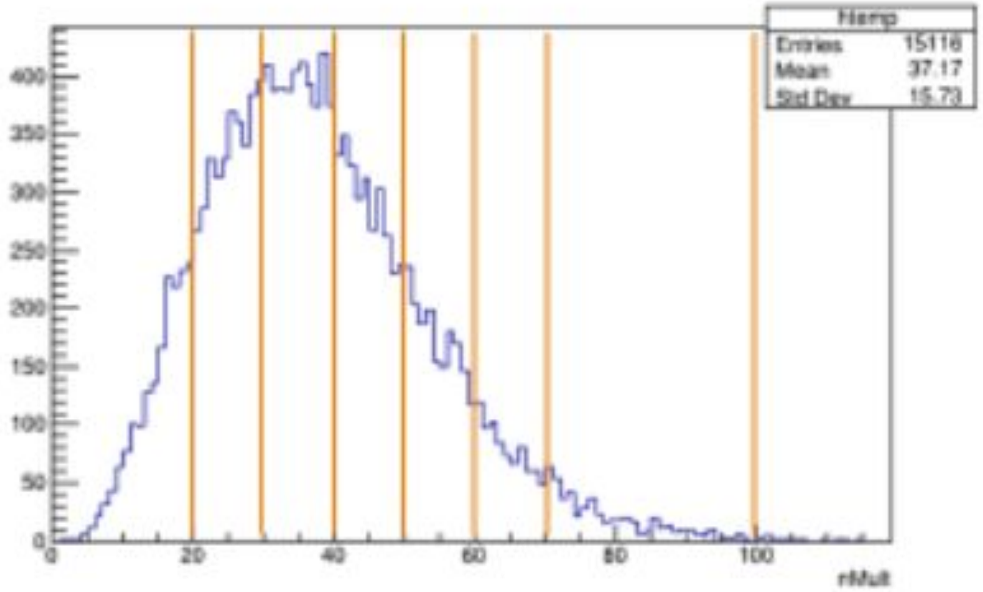
χ^2 Value (normalised): Quality of the fit test result

Binning of Rapidity and Multiplicity



Rapidity

Boundaries of bins: {-2.4, -1.5, -1.0, -0.5, 0.0, 0.5, 1.0, 1.5, 2.4}

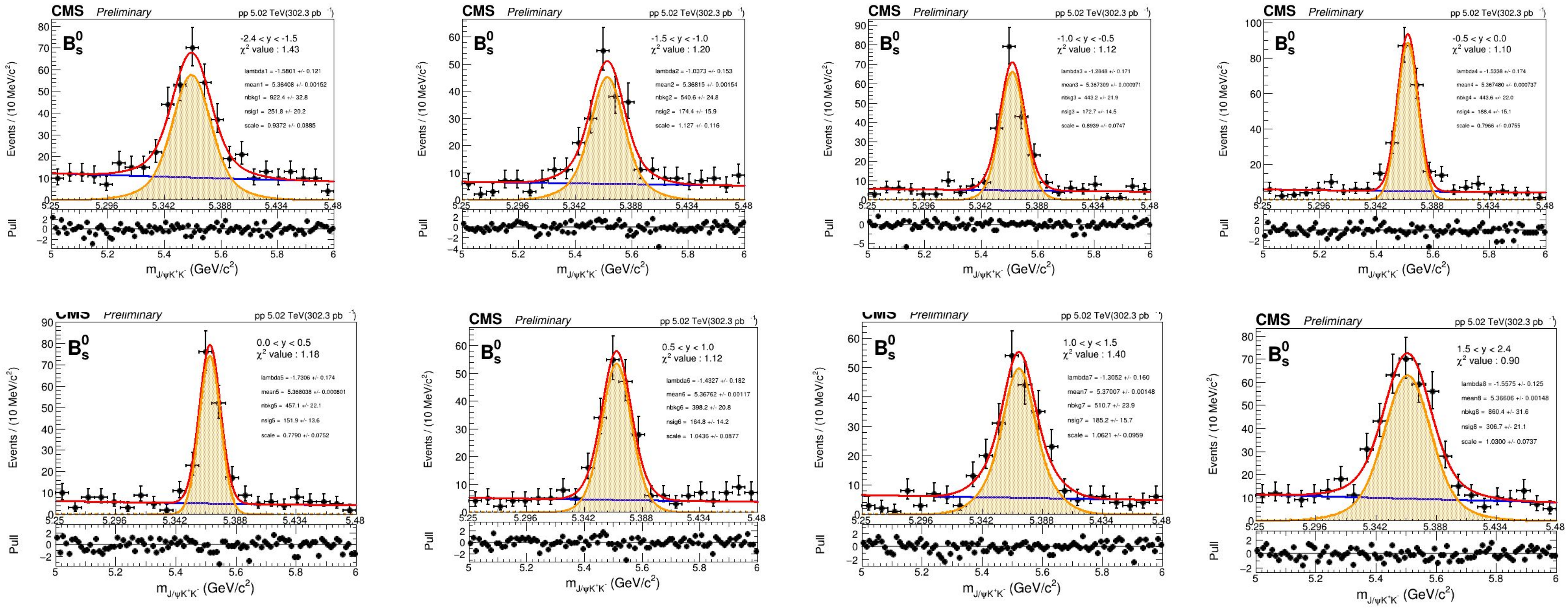


Multiplicity

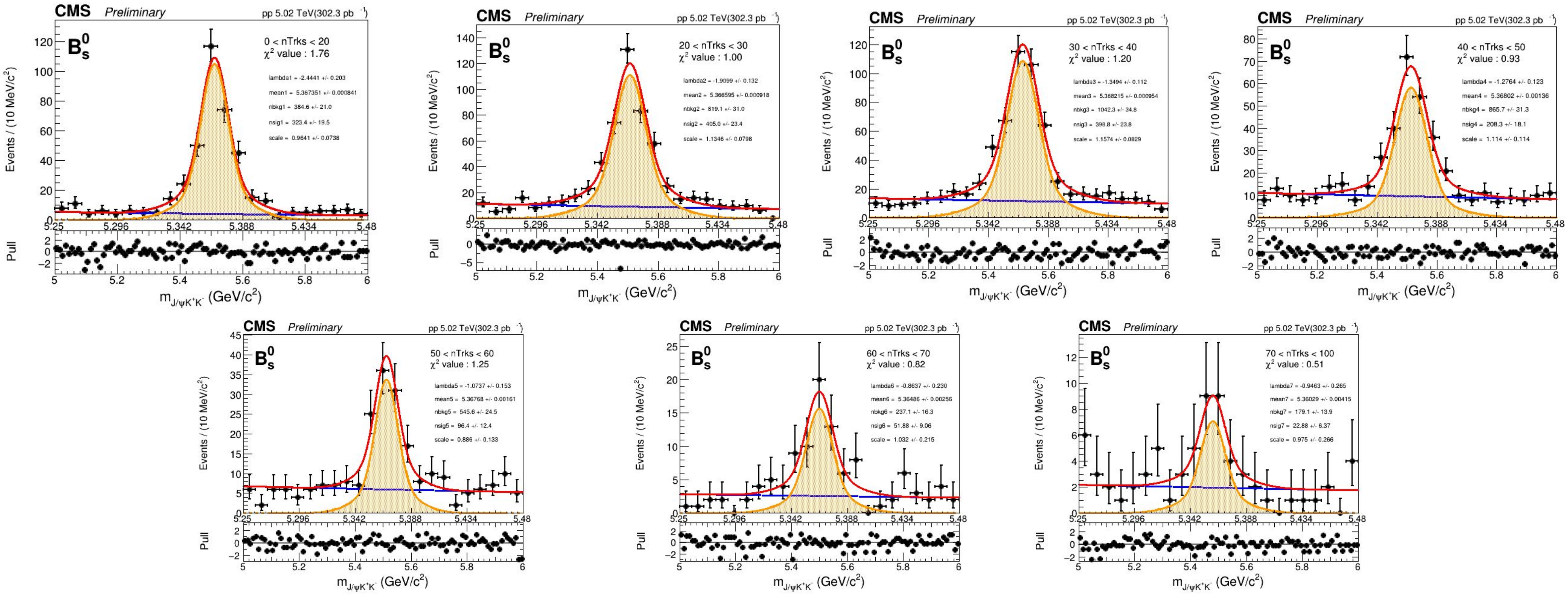
Boundaries of bins: {0, 20, 30, 40, 50, 60, 70, 100}

Next, we perform the fits in each of these bins

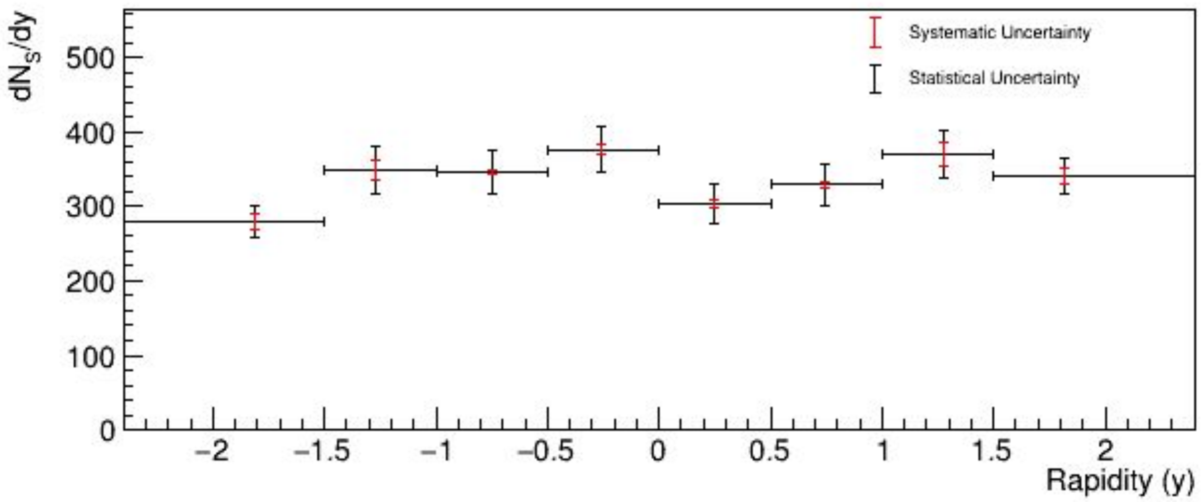
Nominal B_s^0 Mass Fit Results versus Rapidity

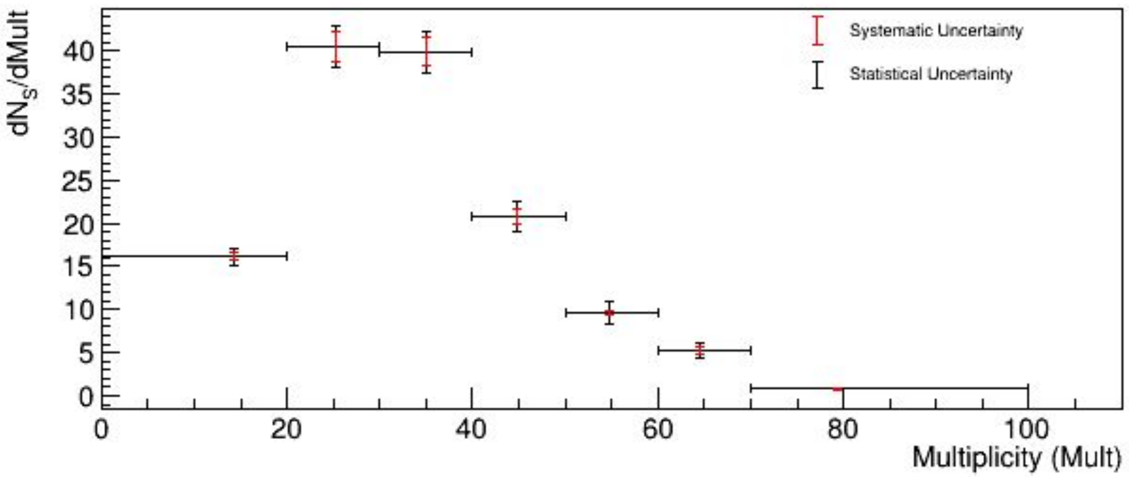


Nominal B_s^0 Mass Fit Results versus Multiplicity



Differential results





Fitting the data: **B^+**

(Fit using Extended Unbinned Maximum Likelihood method)

$$\frac{d\sigma}{d(p_T, y, Mult)} = \frac{1}{\epsilon LB} \frac{dN_S}{d(p_T, y, Mult)}$$

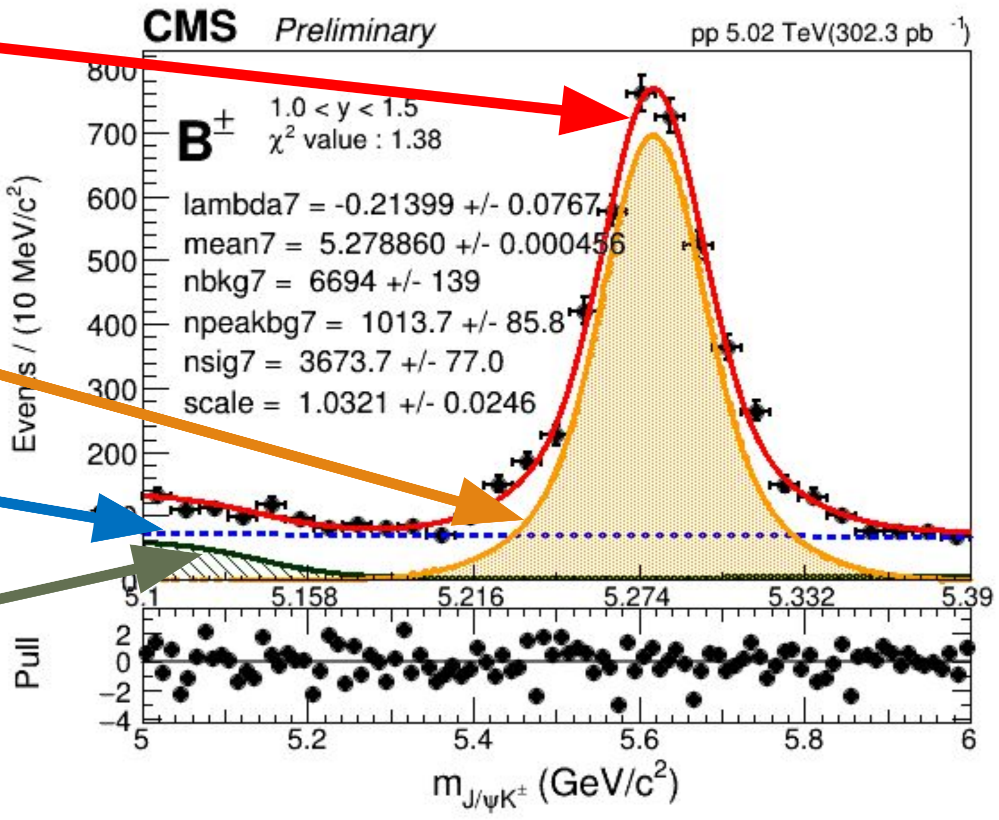
Yield Extraction (B^+)

Signal + Background

Signal

Combinatorial Background

Partially reconstructed decays



lambda: exponential decay constant of the background (λ)

mean: the position of the peak

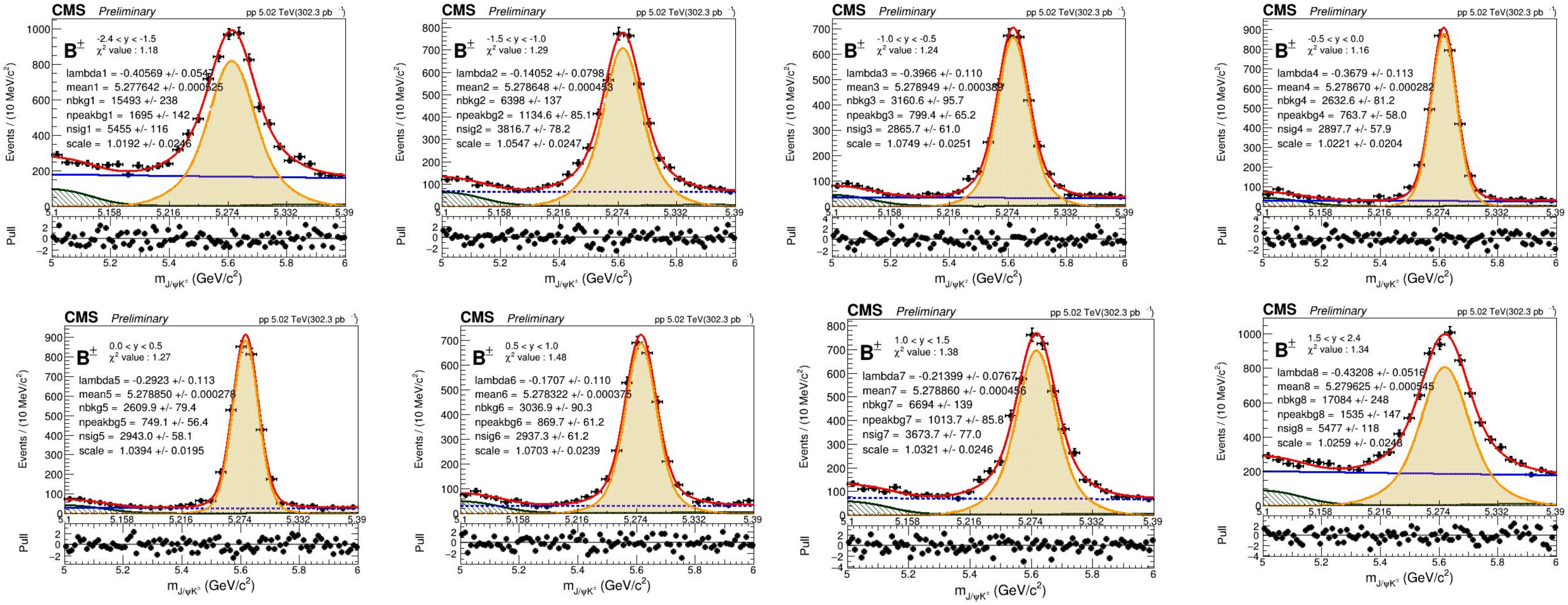
nsig: number of signal events in data (N_S)

nbkg: number of background events in data
Scale: The ratio of the width of the peak compared to that of the Monte Carlo simulation (N_B)

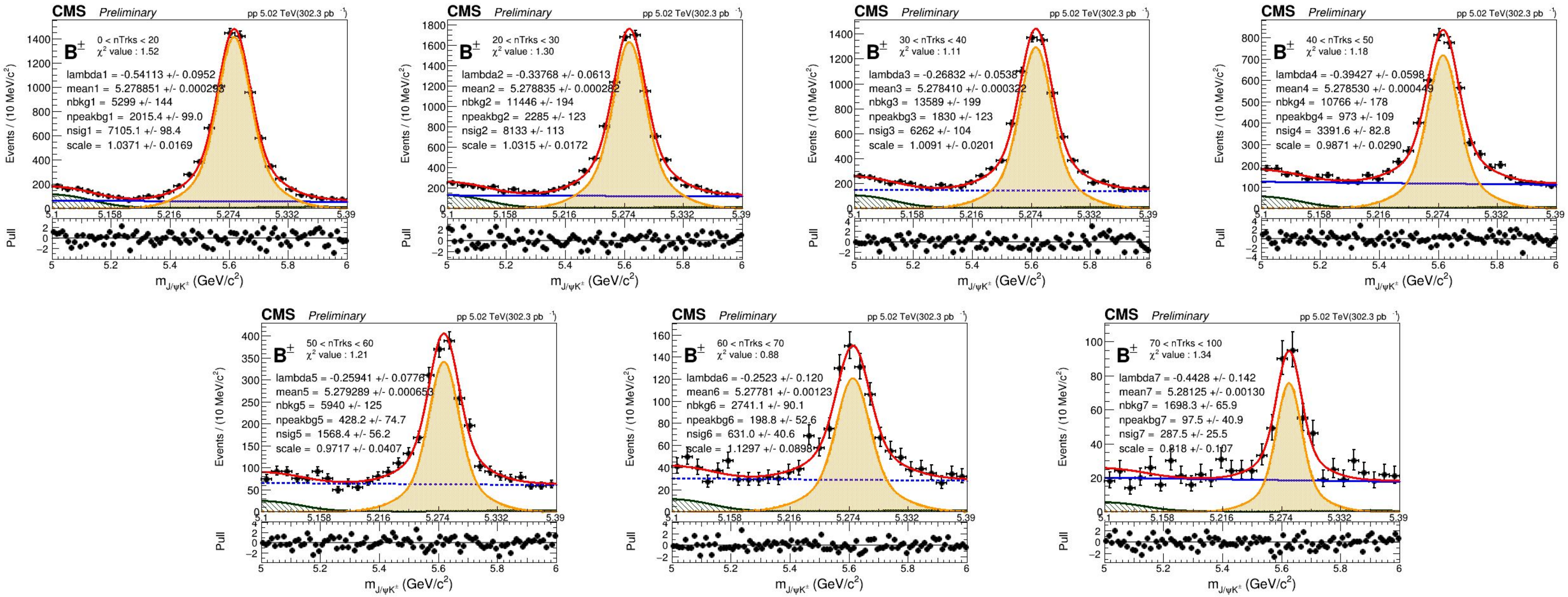
Npeakbg: number of events in partially reconstructed decays

χ^2 Value: Quality of the fit test result

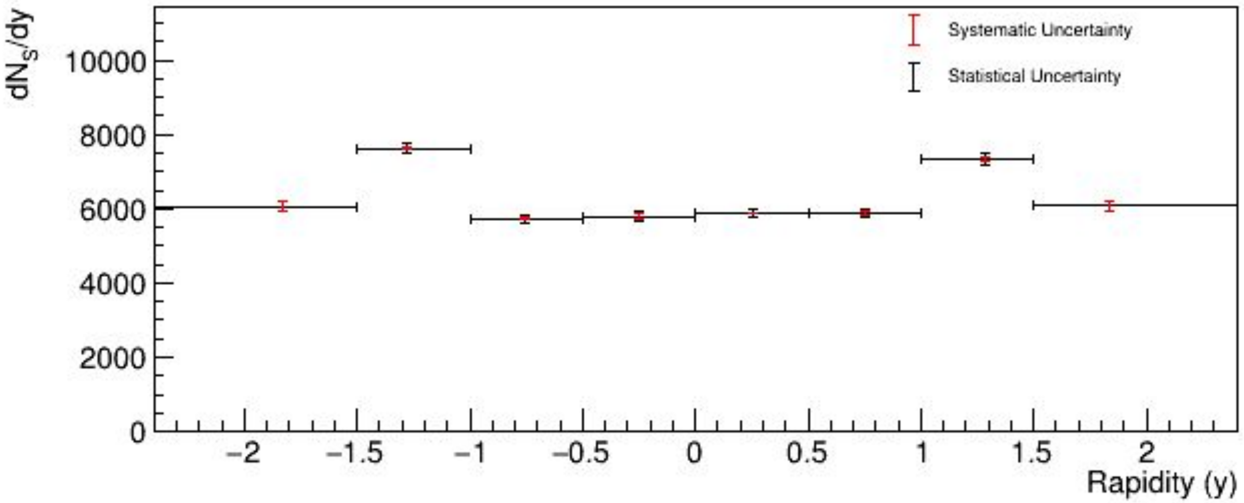
Nominal B^+ Mass Fit Results versus Rapidity

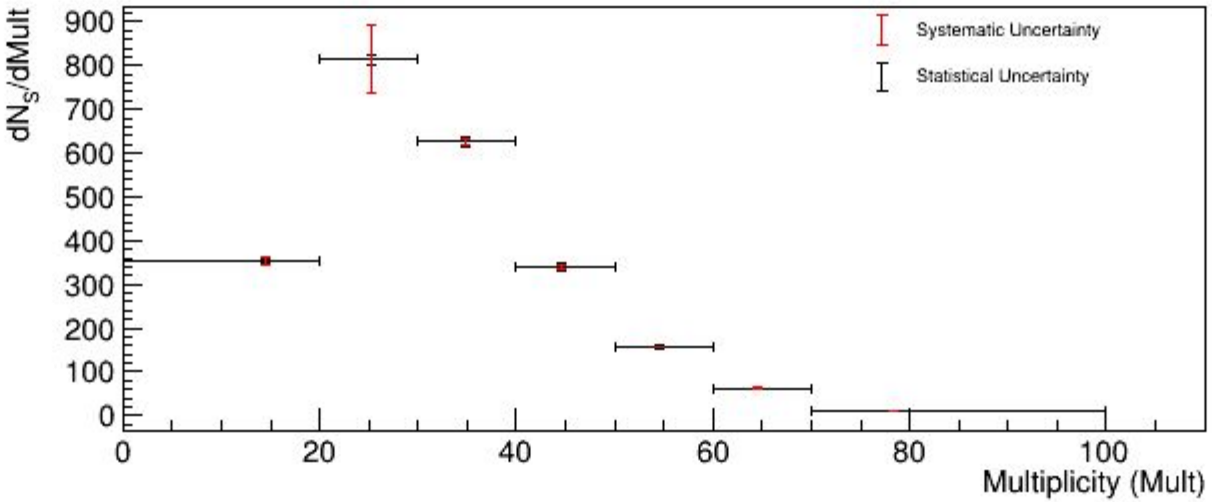


Nominal B^+ Mass Fit Results versus Multiplicity



Differential results





pp->B+X production cross section versus B mesons rapidity and event multiplicity

Systematic uncertainties

Systematic variations

Signal

Nominal signal model: Double Gaussian

Variations:

- Triple Gaussian
- Fixed mean
- CB + Gaussian
- Double CB (for testing)

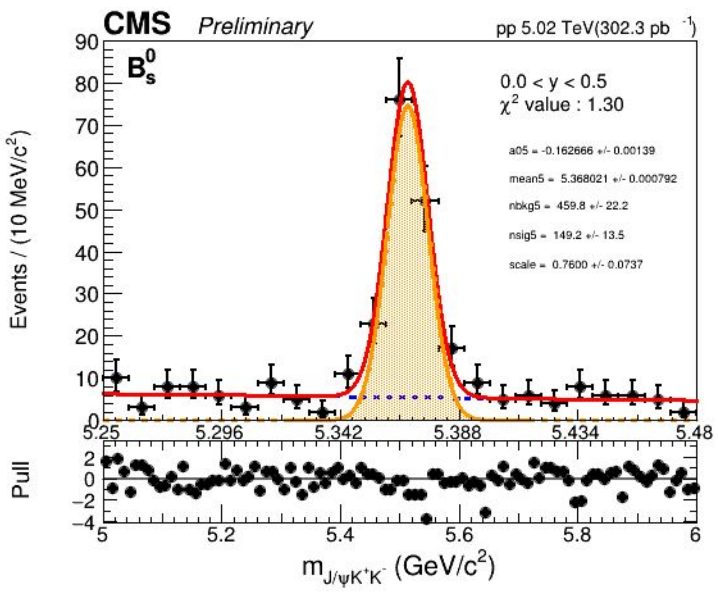
Background

Nominal signal model: Exponential

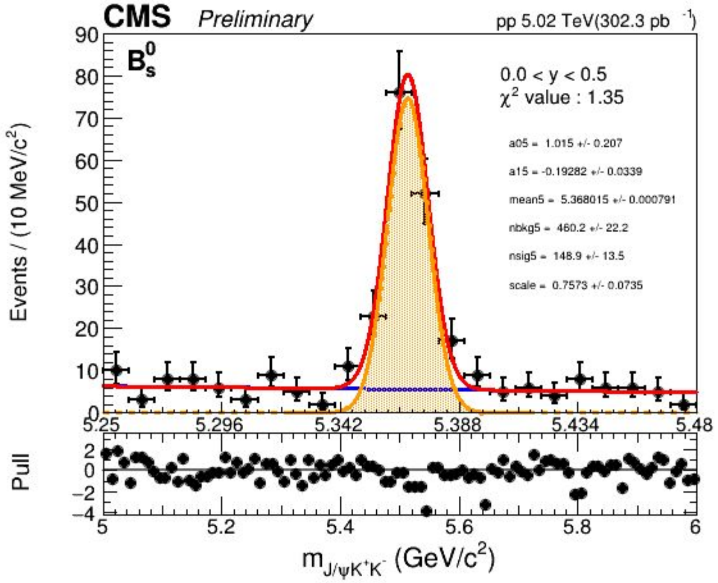
Variations:

- Linear
- Second order polynomial
- Mass range

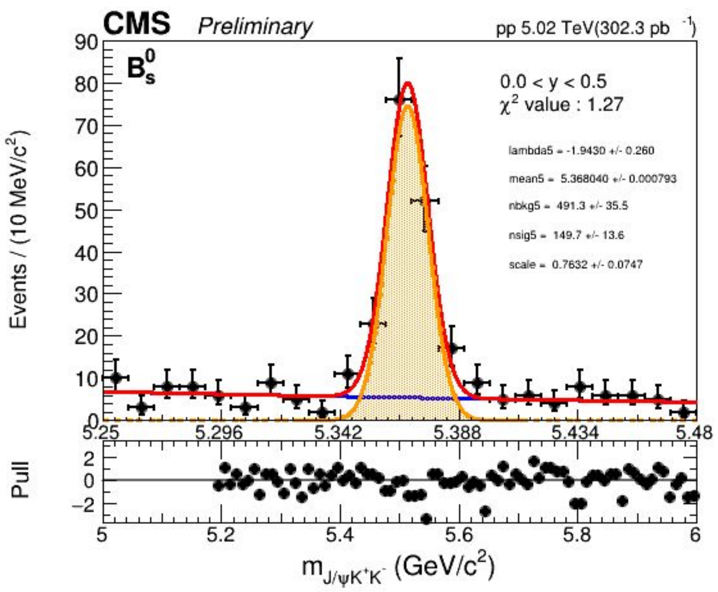
Background modeling variations



Linear



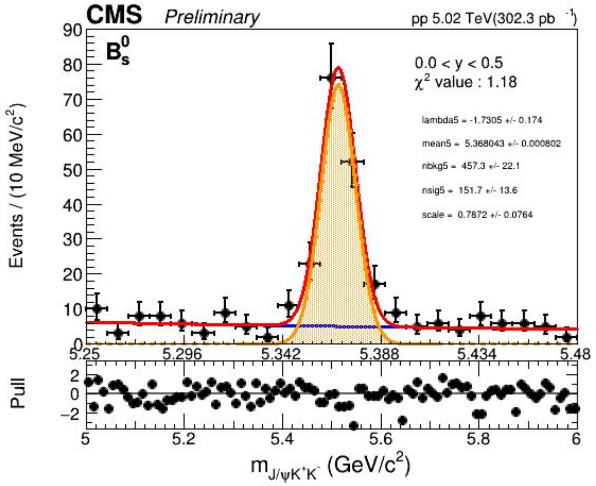
Second Order Polynomial



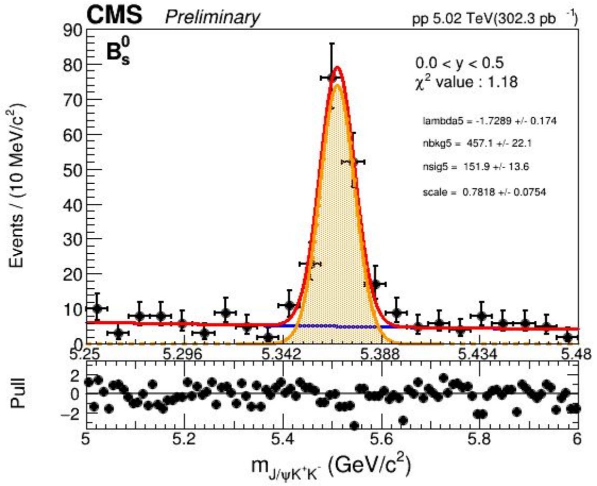
Mass range

(Examples from rapidity fits)

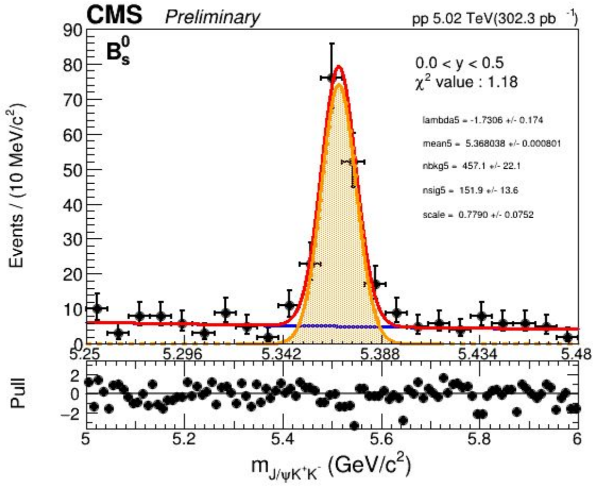
Signal modeling variations



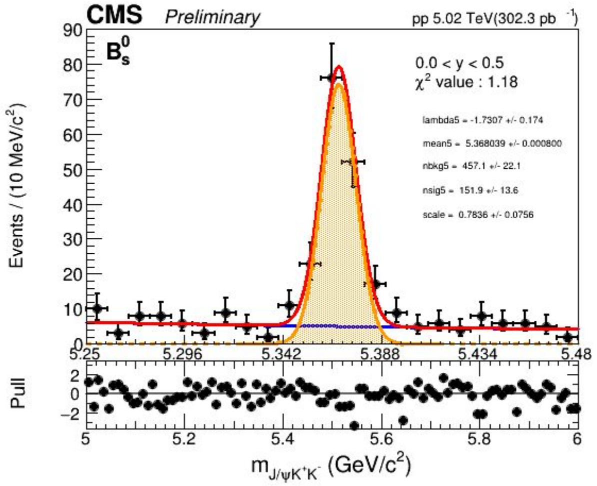
Triple Gaussian



Fixed mean



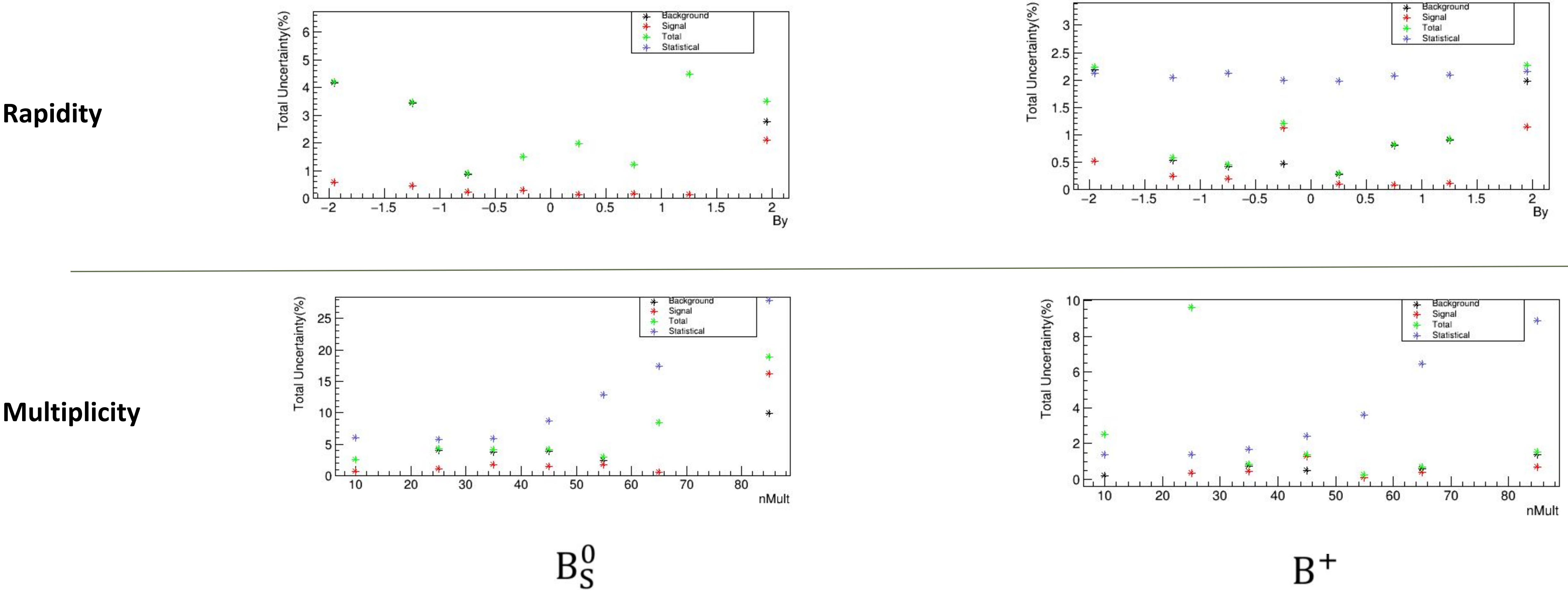
Crystal Ball + Gaussian



Double Crystal Ball

(Examples from rapidity fits)

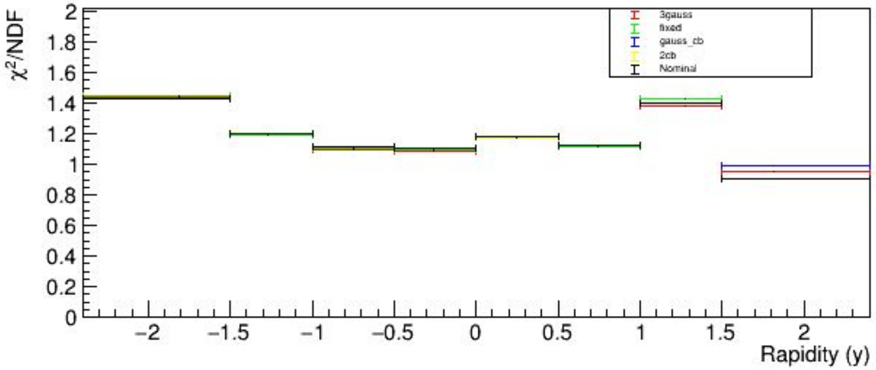
Systematics

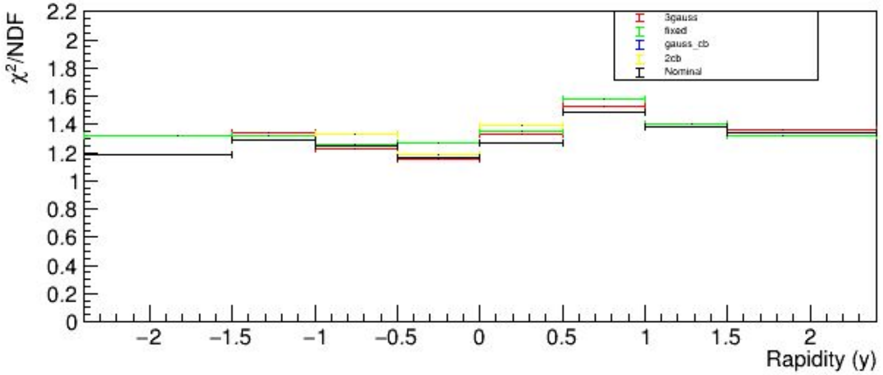


Quality of fits

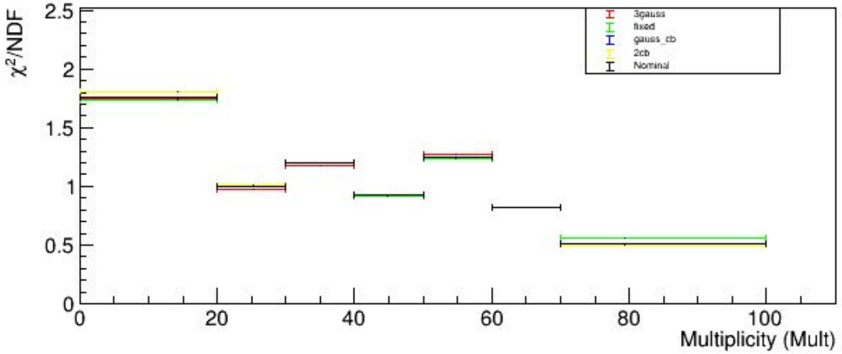
Signal Variations Fit Quality test

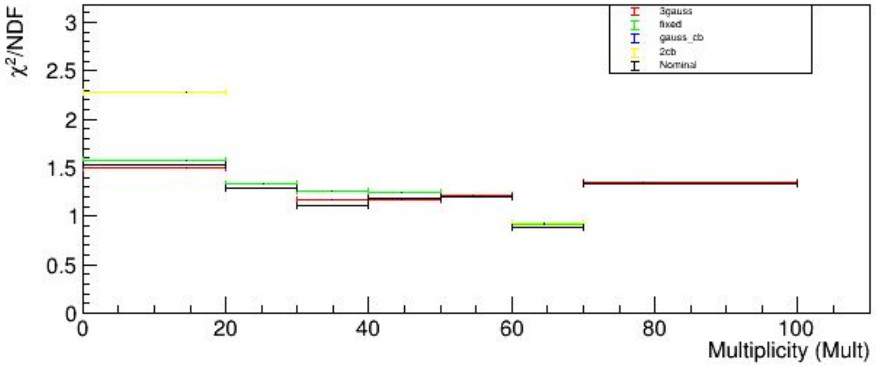
Rapidity





Multiplicity

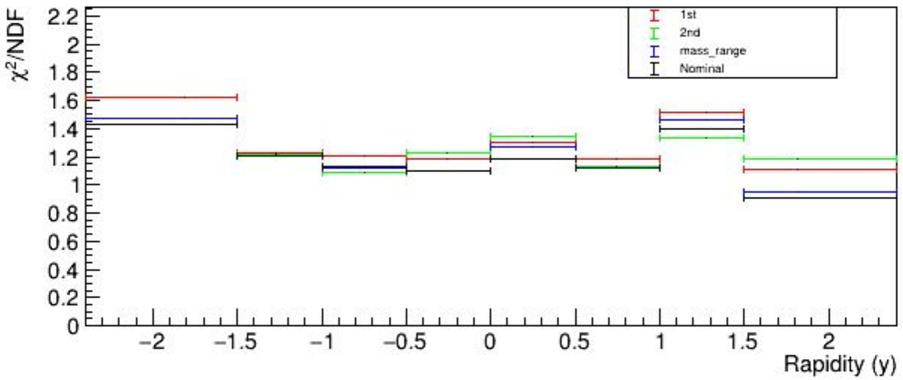


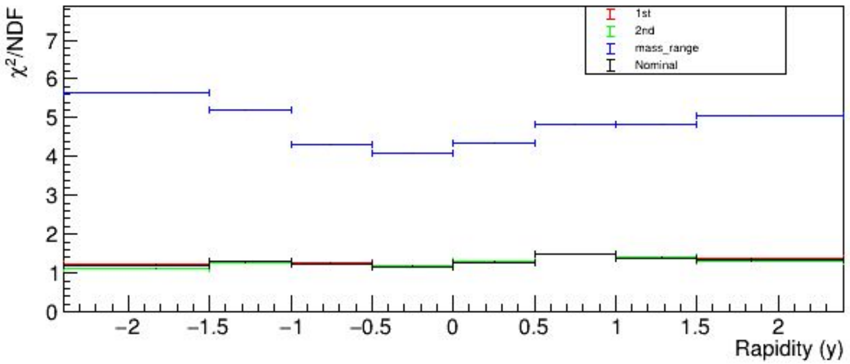


B_s^0 B^+

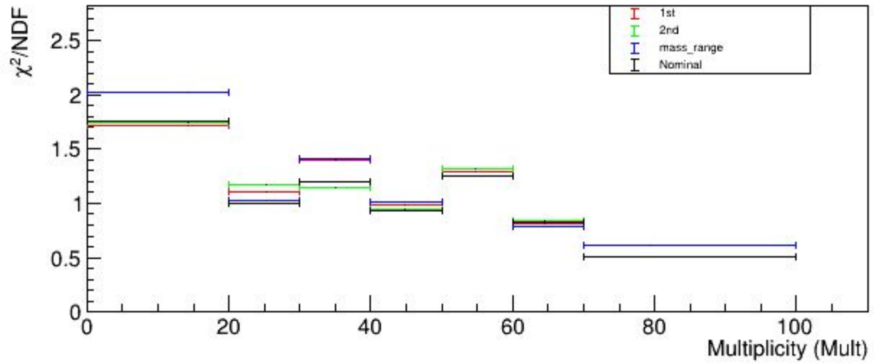
Background Variations Fit Quality test

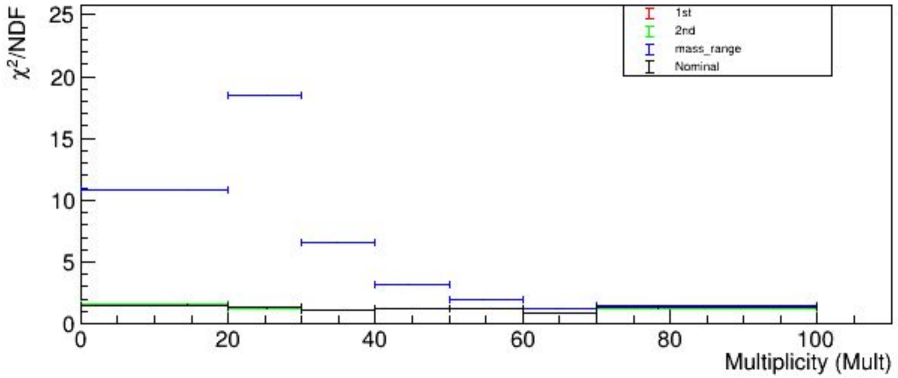
Rapidity





Multiplicity

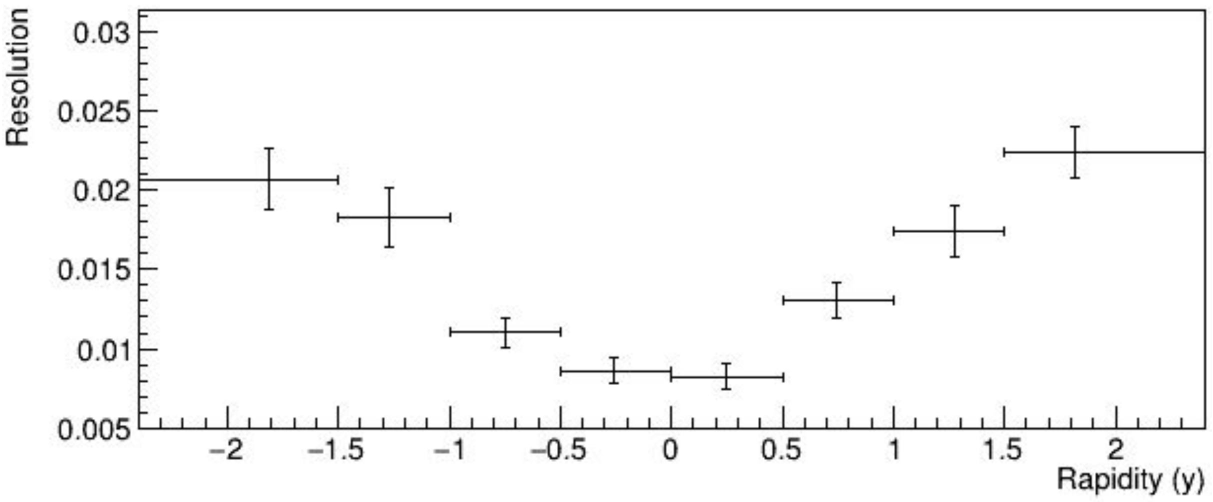




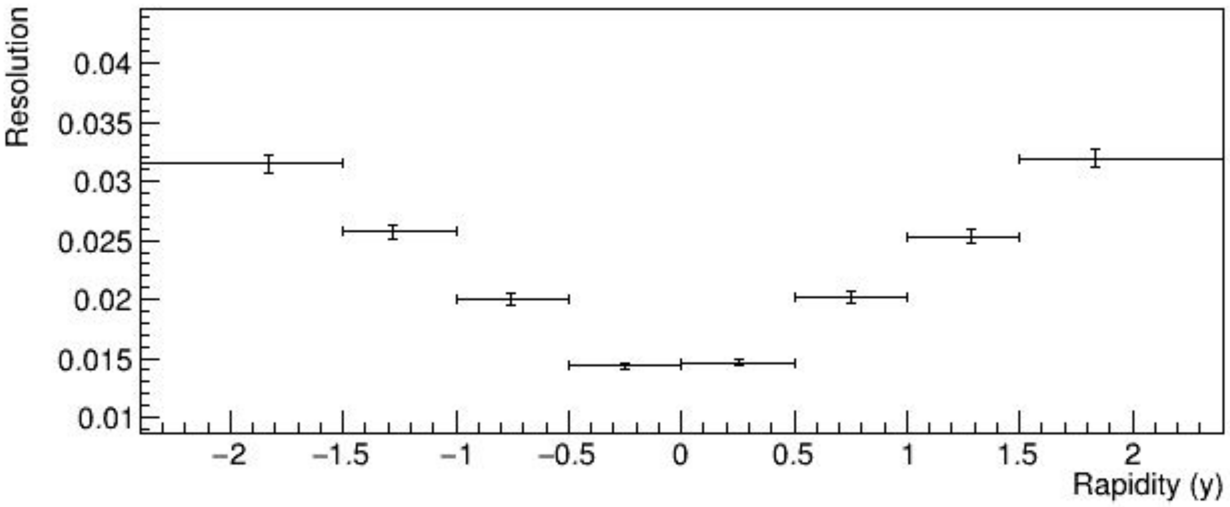
B_s^0 B^+

Stability analysis

Mass Resolution (versus Rapidity)



B_S^0



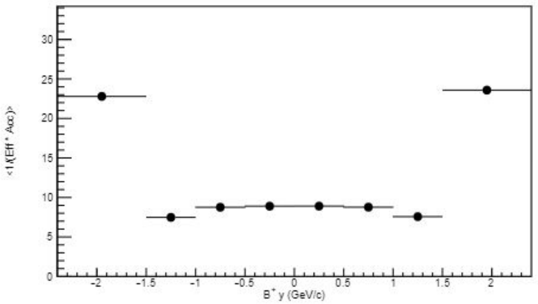
B^+

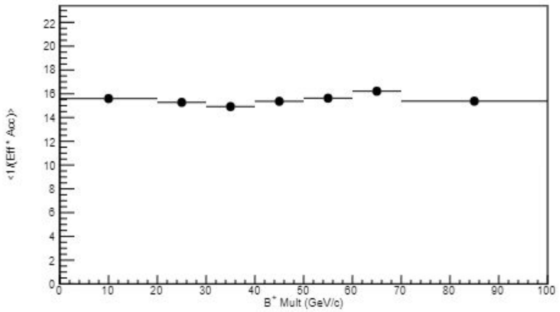
The detector resolution is optimal in the central region (small |y|) and degrades towards the forward region (large |y|), as expected

Cross section Results

Computation of cross section

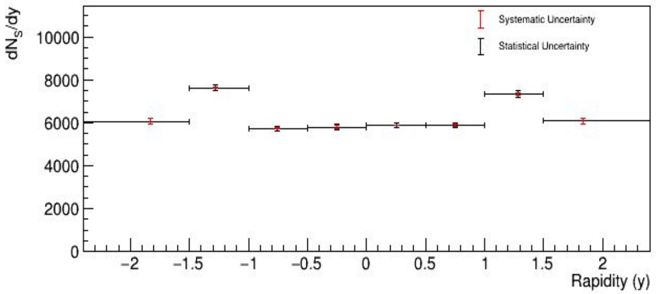
Efficiencies

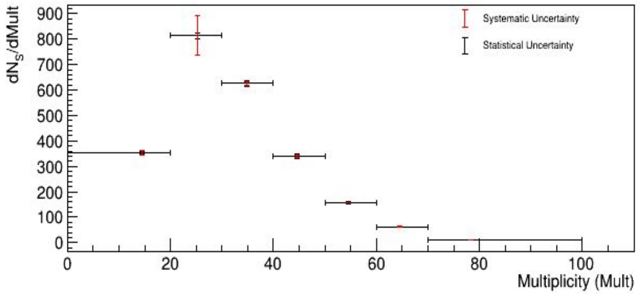




$$\frac{d\sigma}{dy} = \frac{1}{\epsilon L B}\frac{dN_S}{dy}$$

Raw yields





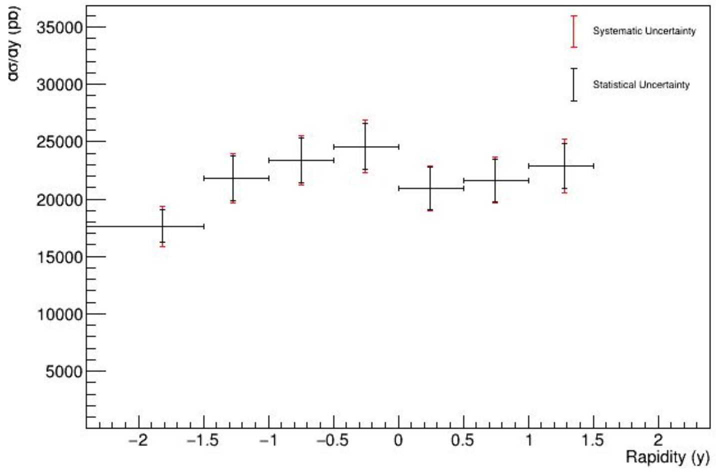
$L = 302.3 \pm 1.9\% \text{ pb}^{-1}$

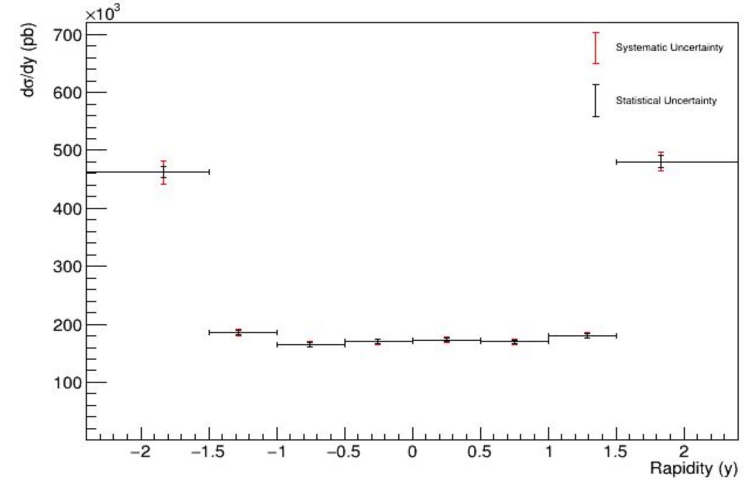
$B = 1.020 \pm 0.019 \times 10^{-3}$

Cross section

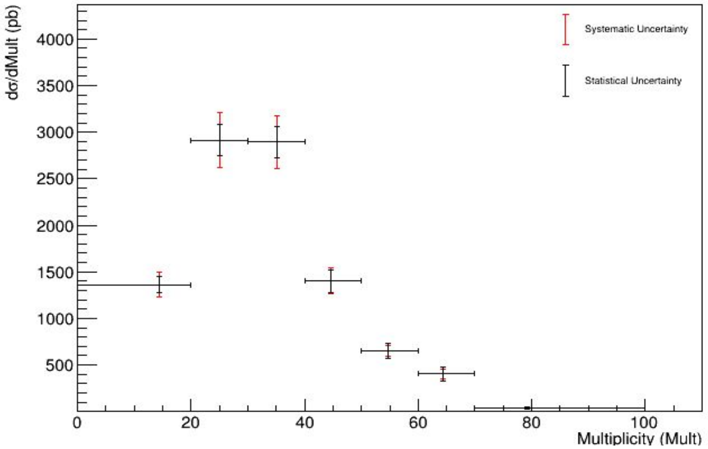
B_s^0 B^+

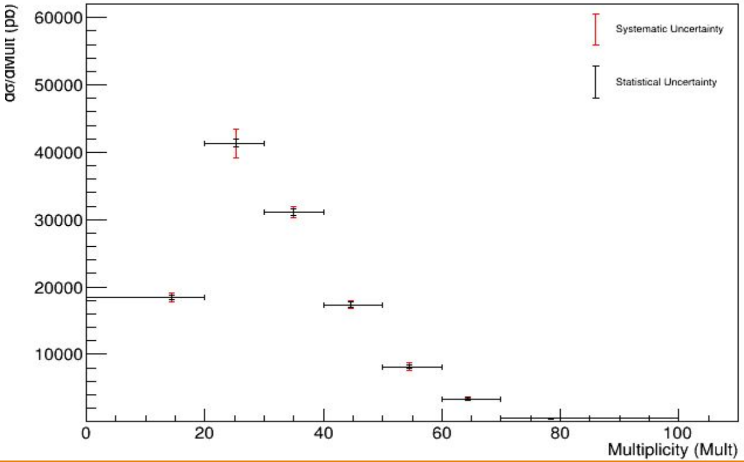
Rapidity





Multiplicity





Summary

Summary

- We have analysed the pp data collected by CMS at 5 TeV
- We have measured the differential production cross sections for B^0_s and B^+ mesons
- As function of meson (y) and collision (mult) observables that had not been studied before
- Including detailed study of systematic uncertainties

The work also involved

- Implementing and carrying out a large number (~600) of fits to MC and data
- Verify their quality, via chi2 and pull calculations
- Verify parameter and resolution stability across bins

Next steps

- Finalize measurement of **the cross sections for B^0_s and B^+ mesons**
- Compare our results with the theory prediction
- Use obtained results to determine:
    - Ratio of cross sections in pp collisions **B^0_s/B^+** (quark hadronisation process)
    - Ratio of cross sections in **pp and PbPb collisions**, $R_{AA} \propto \sigma_{PbPb}/\sigma_{pp}$ (properties of QGP)
- We have been reporting regularly at the CMS Heavy Ion working group meetings
- We are documenting our work on a CMS Analysis Note

Thank you for your attention!

Backup

Nuclear Modification Factor (R_{AA})

$$R_{AA} \propto \frac{\left(\frac{d\sigma}{dp_T}\right)_{PbPb}}{\left(\frac{d\sigma}{dp_T}\right)_{pp}}$$

- PbPb: lead-lead collision producing QGP
- pp: proton-proton collision not producing QGP

Compare them

Unbinned Extended Maximum likelihood

$$\mathcal{L}(m_i, \vec{\lambda}) = \prod_{i=1}^{N} \ell(m_i) \times \frac{e^{-N} N^{N_{obs}}}{N_{obs}!}$$

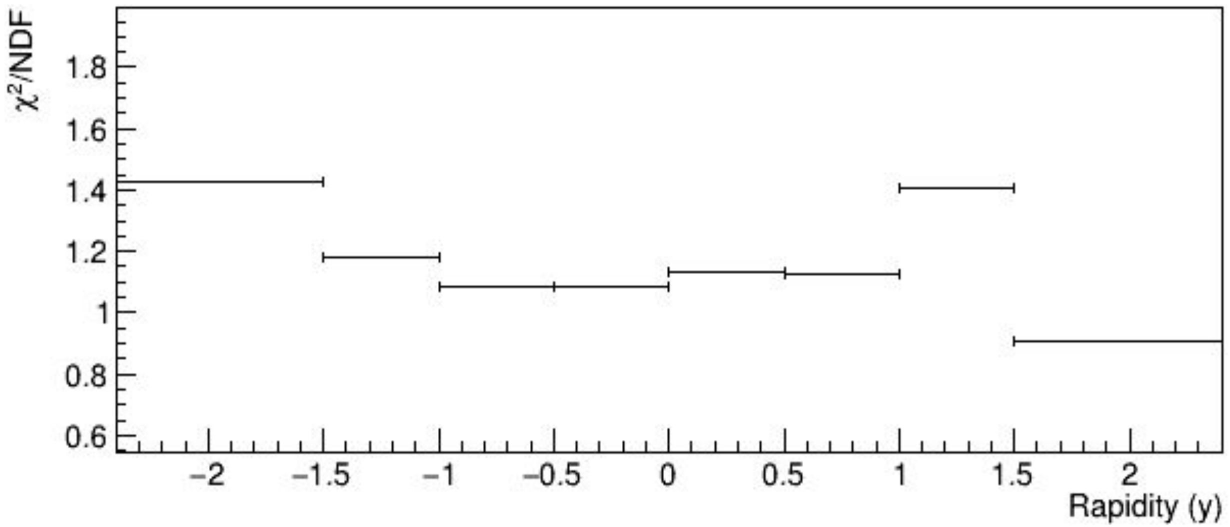
$\boldsymbol{\ell}$: model, a probability distribution function (pdf), (weighted) sum of a signal pdf (double gaussian) and a background (exponential) pdf

$\boldsymbol{N}$: actual total number of total events

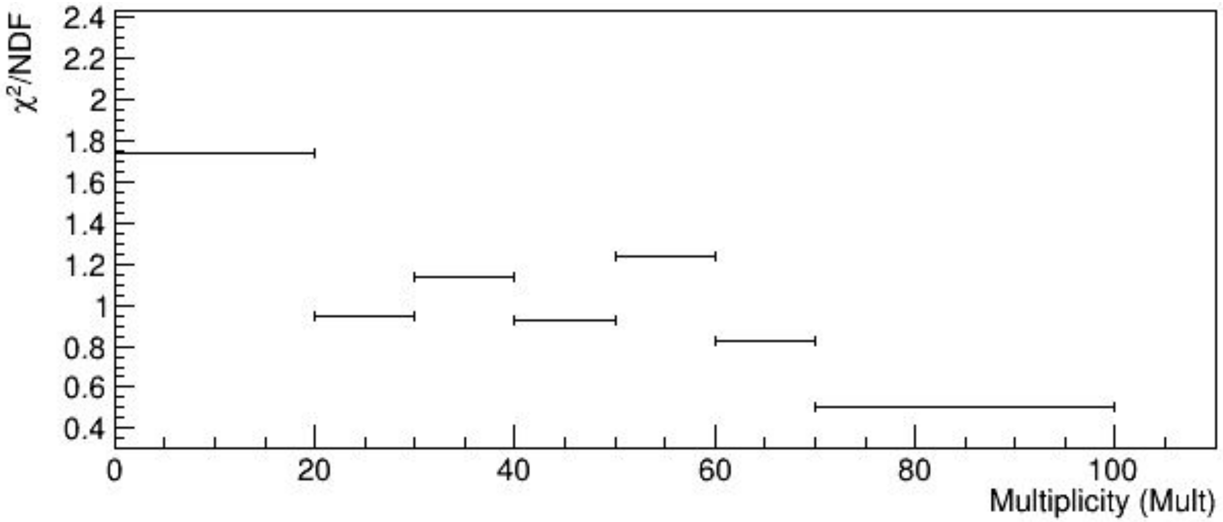
$\boldsymbol{N_{obs}}$: estimated total number

$\vec{\boldsymbol{\lambda}}$: array of parameters

Fit quality test (normalised χ^2)

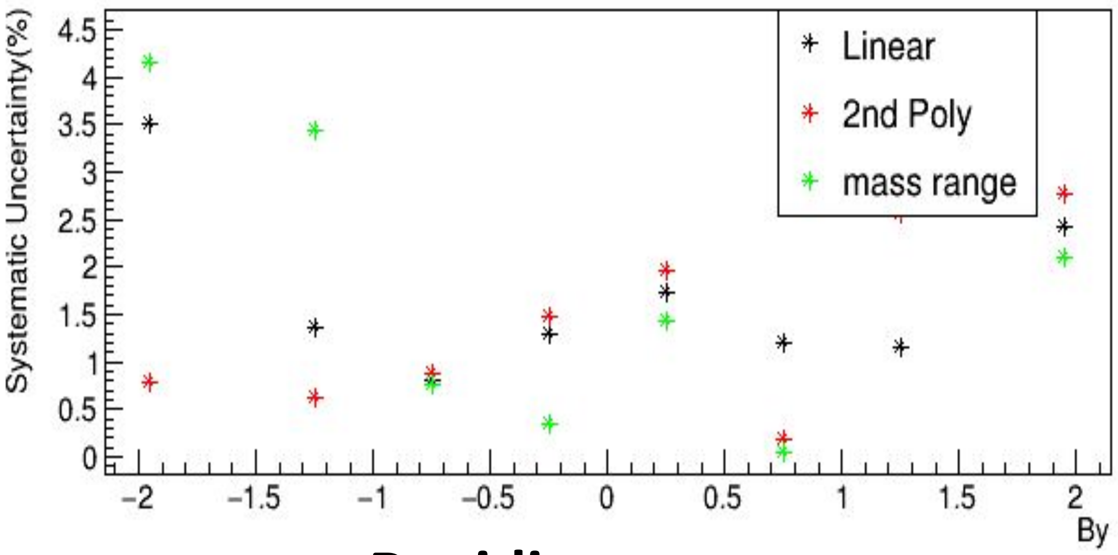


Rapidity

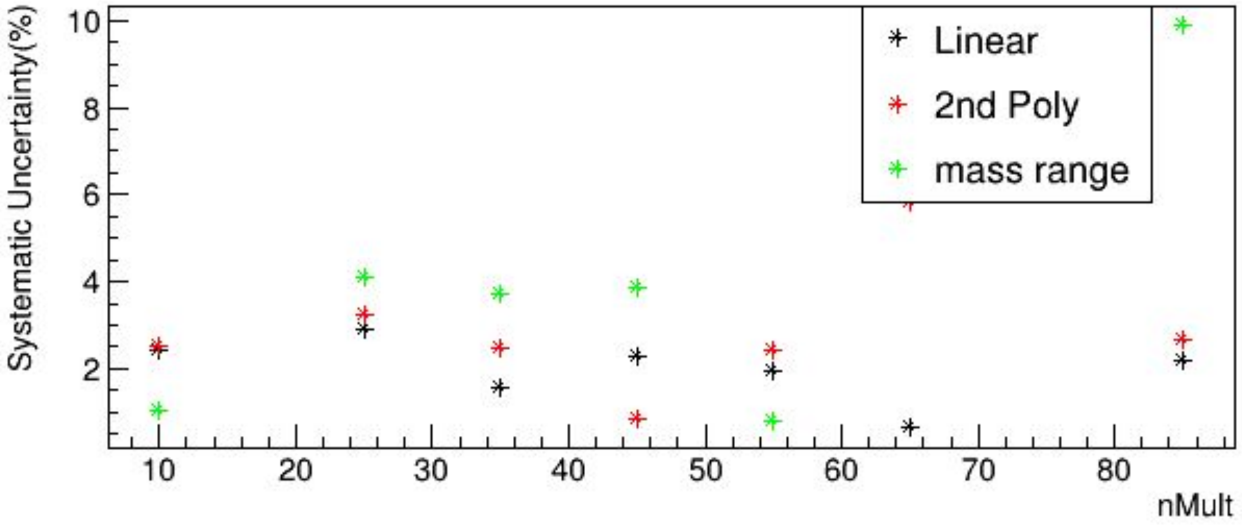


Multiplicity

Background systematics

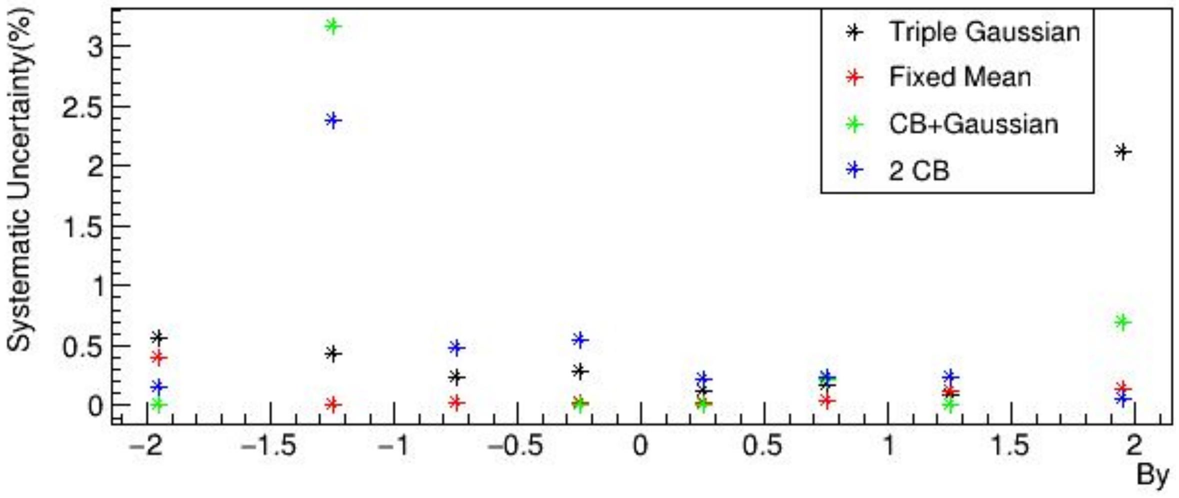


Rapidity

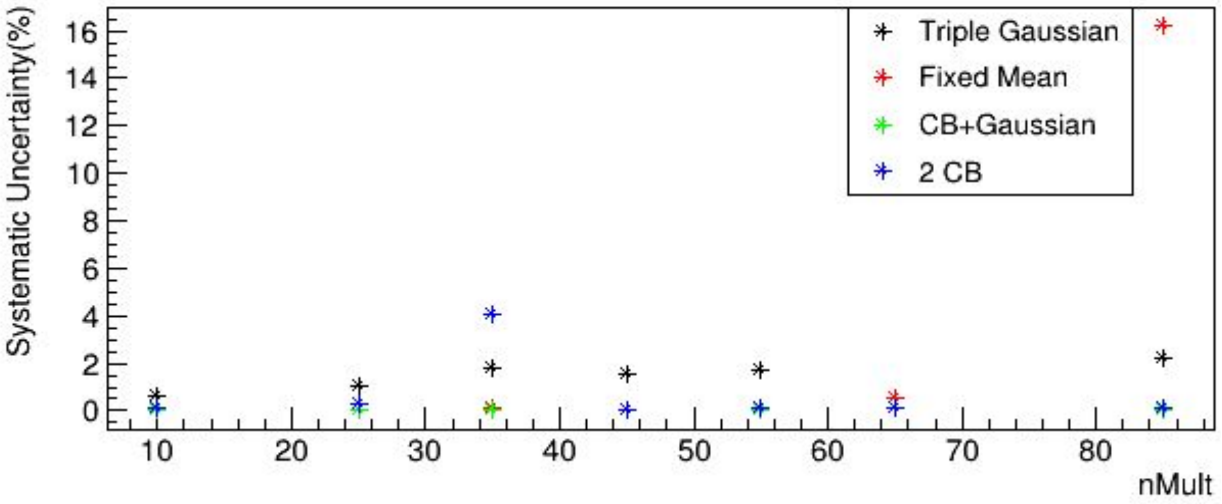


Multiplicity

Signal Systematics

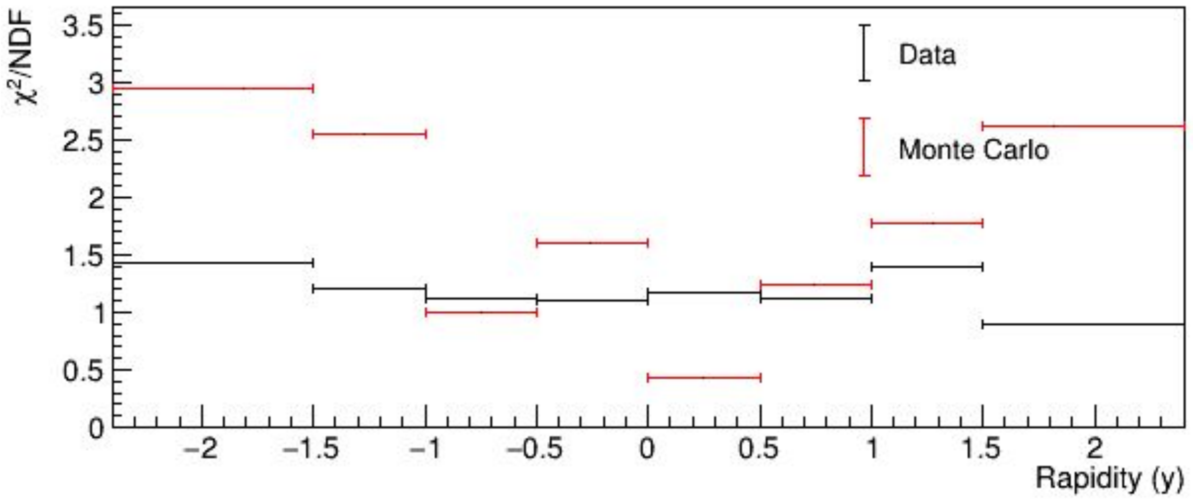


Rapidity

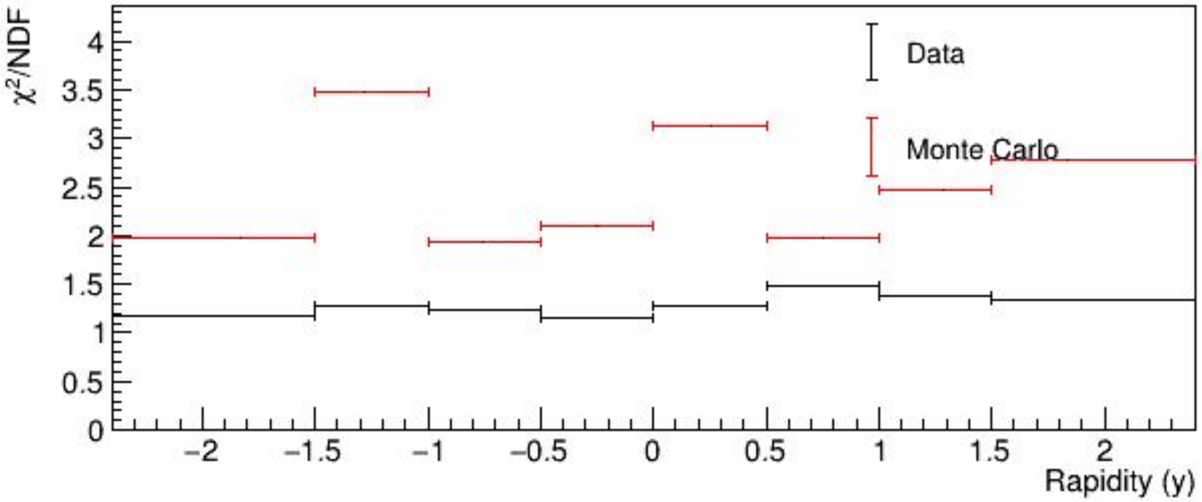


Multiplicity

Fit Quality test (Rapidity)

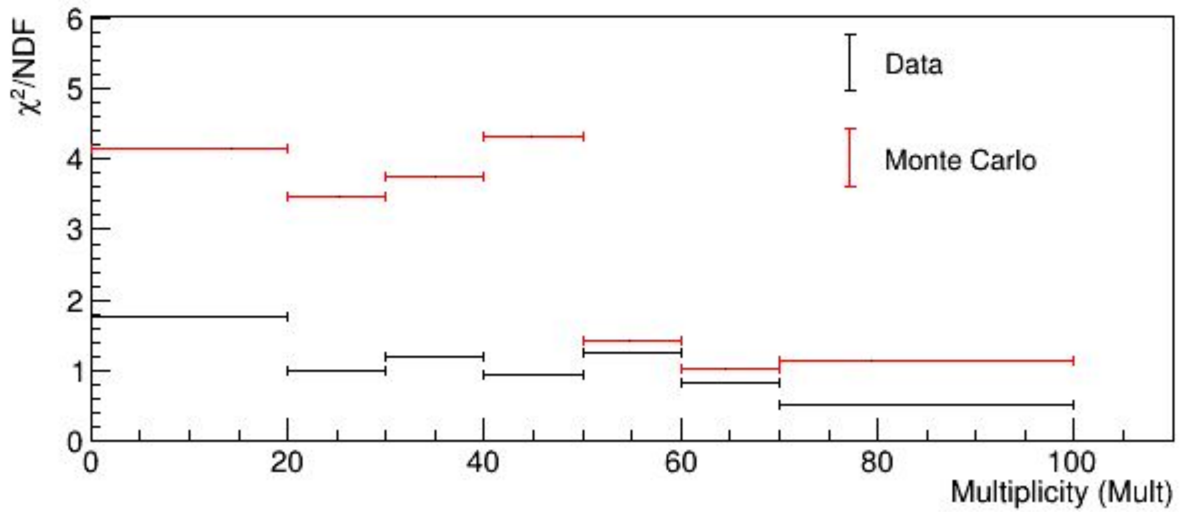


B_S^0

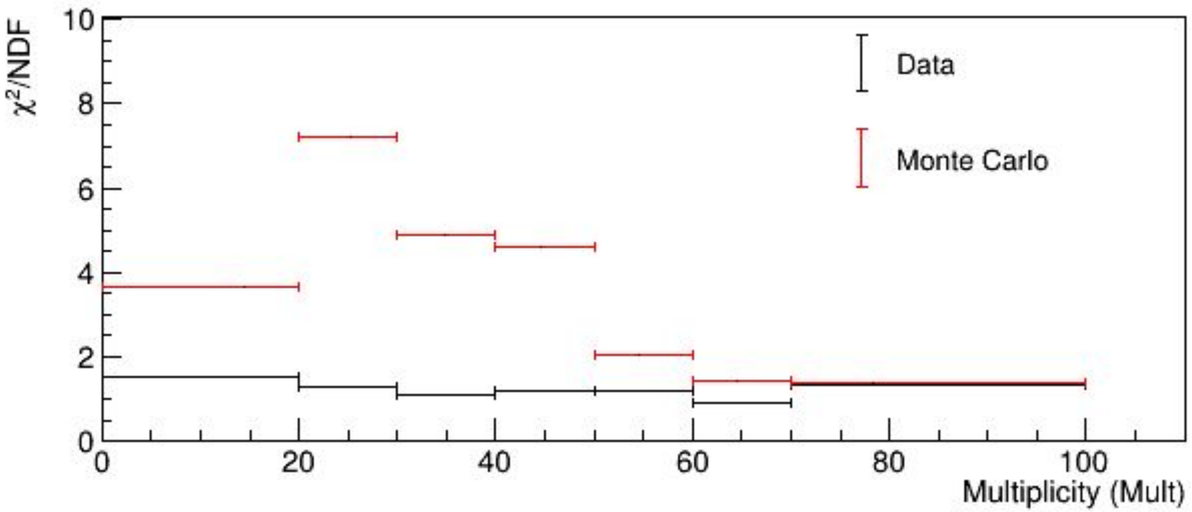


B^+

Fit Quality test (Multiplicity)

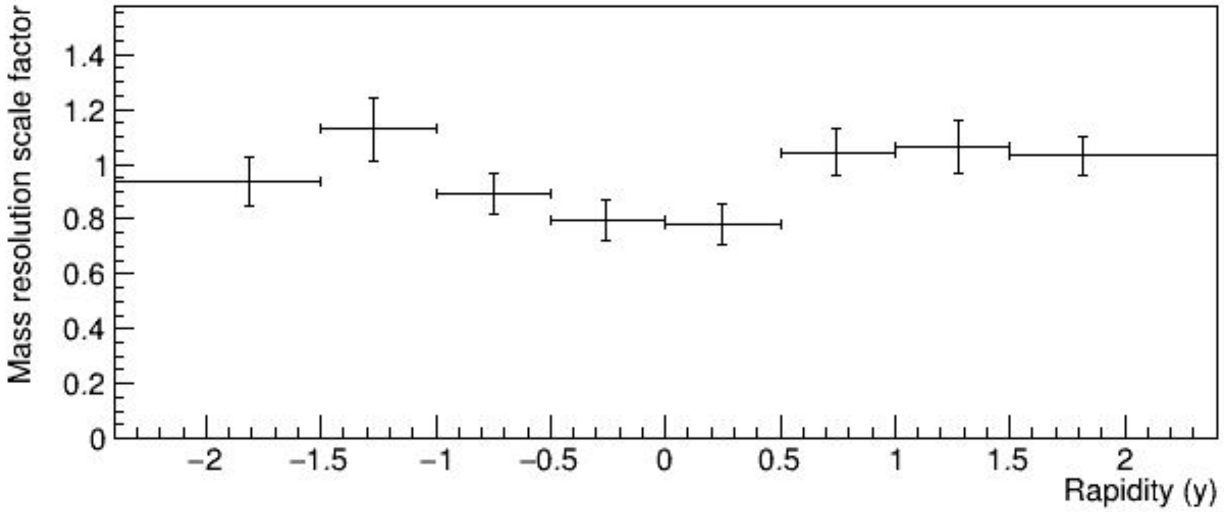


B_S^0

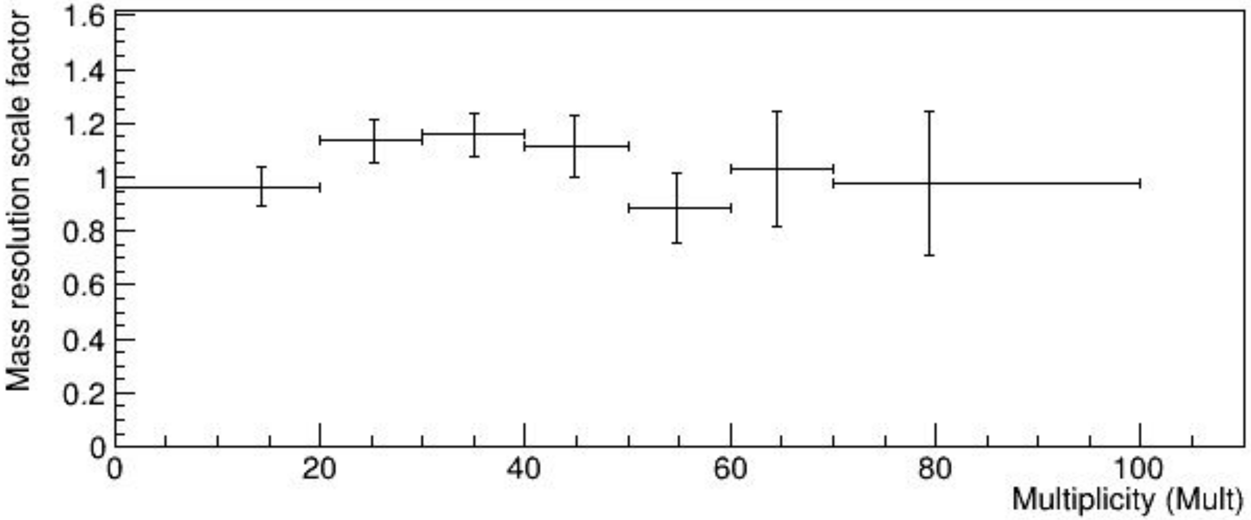


B^+

Resolution scale

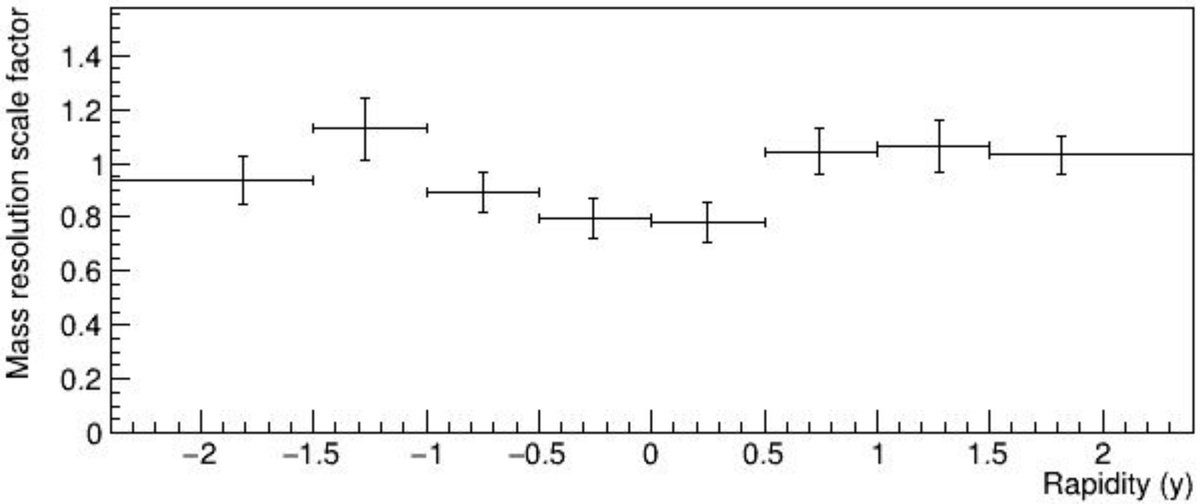


Rapidity

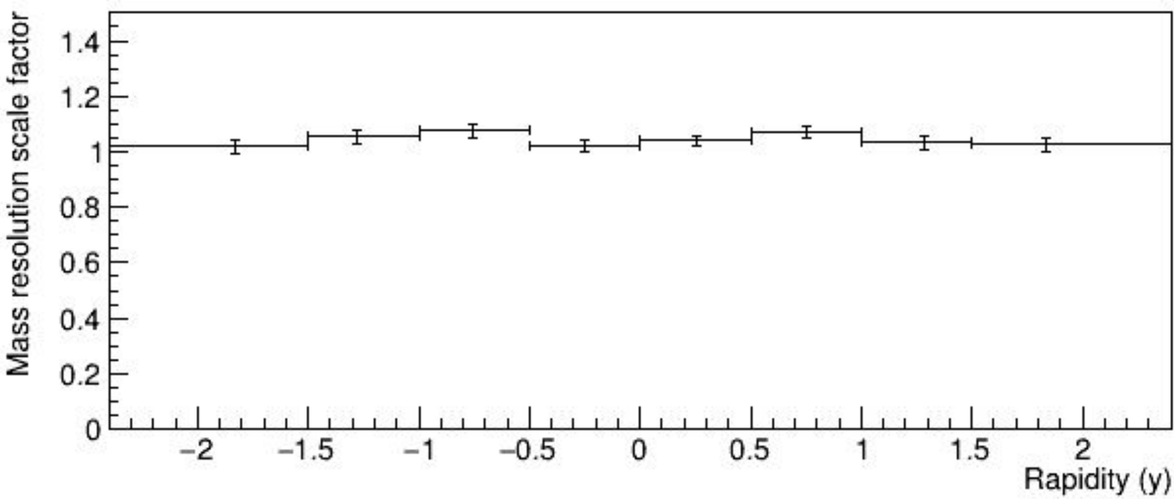


Multiplicity

Resolution scale (Rapidity)

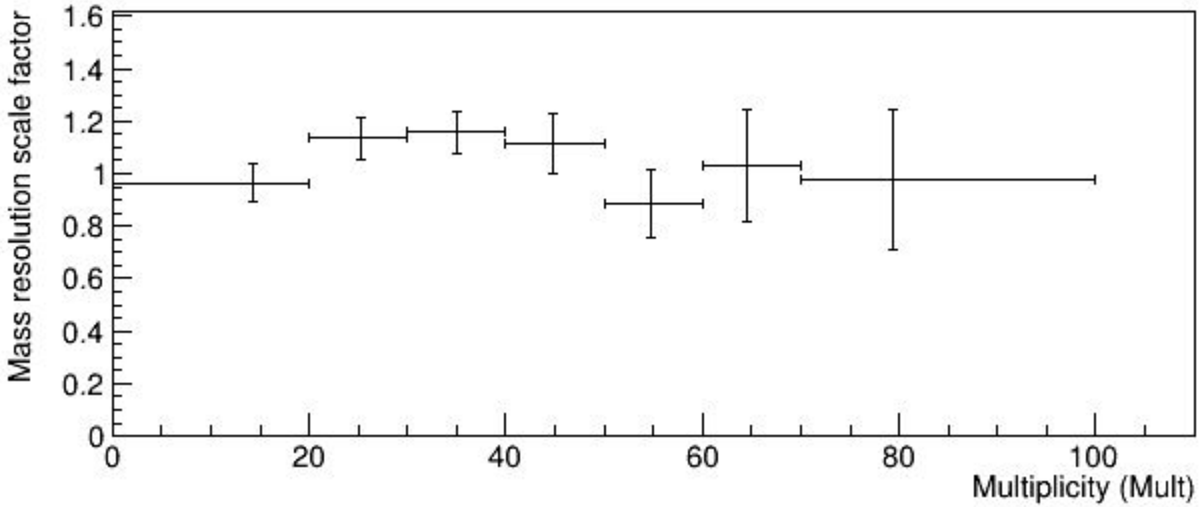


B_s^0

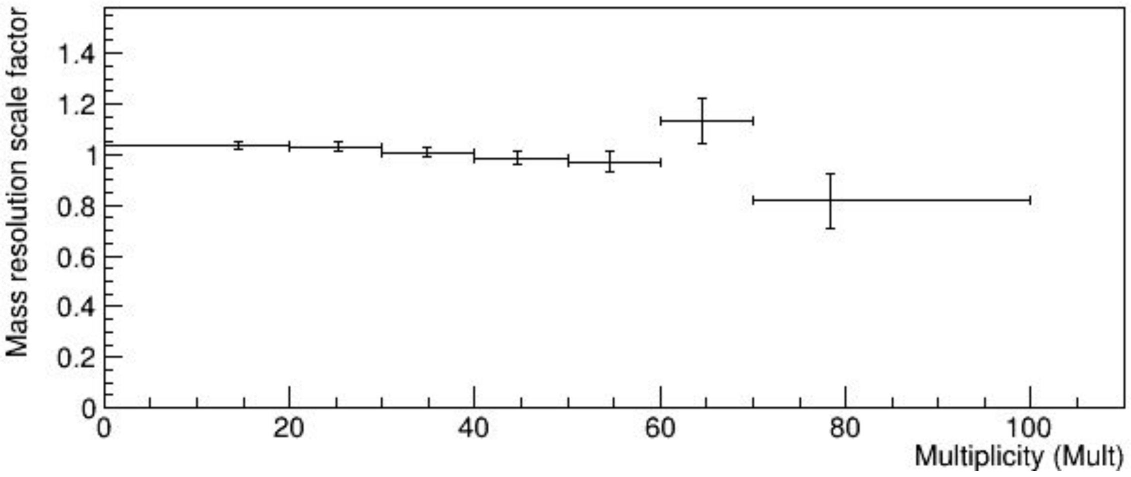


B^+

Resolution scale (Multiplicity)

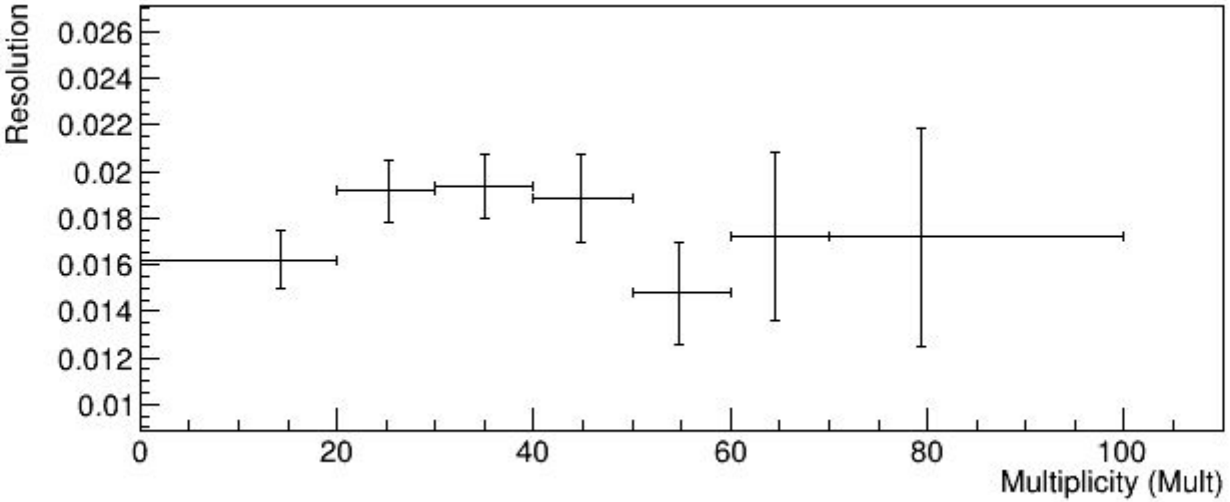


B_S^0

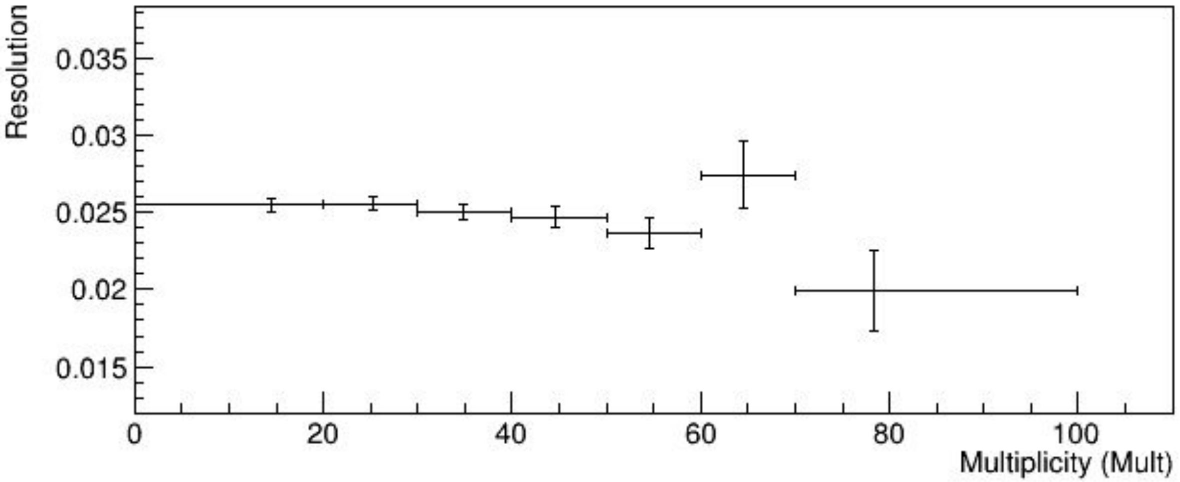


B^+

Mass Resolution (Multiplicity)

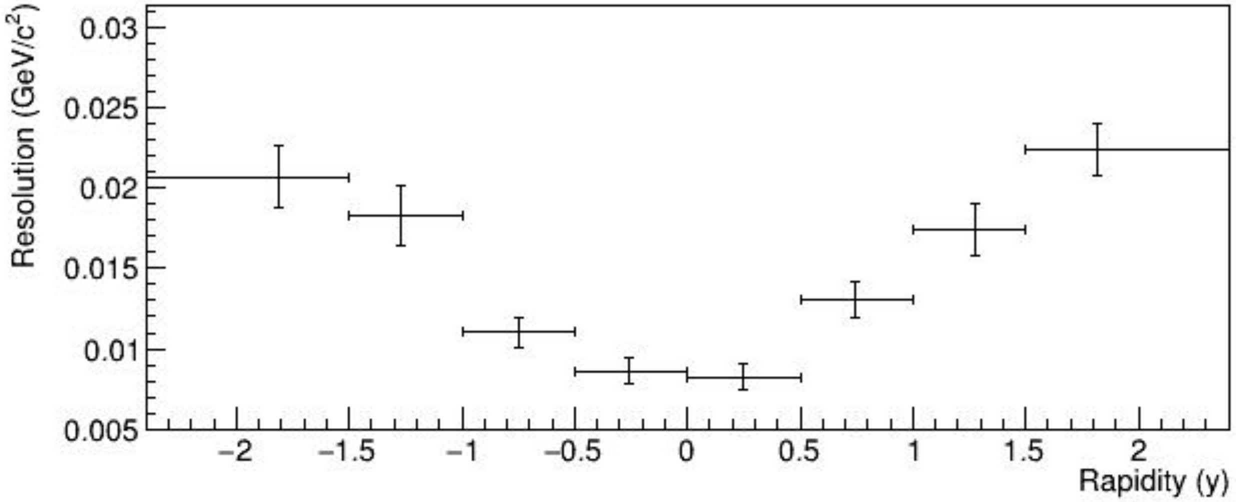


B_S^0

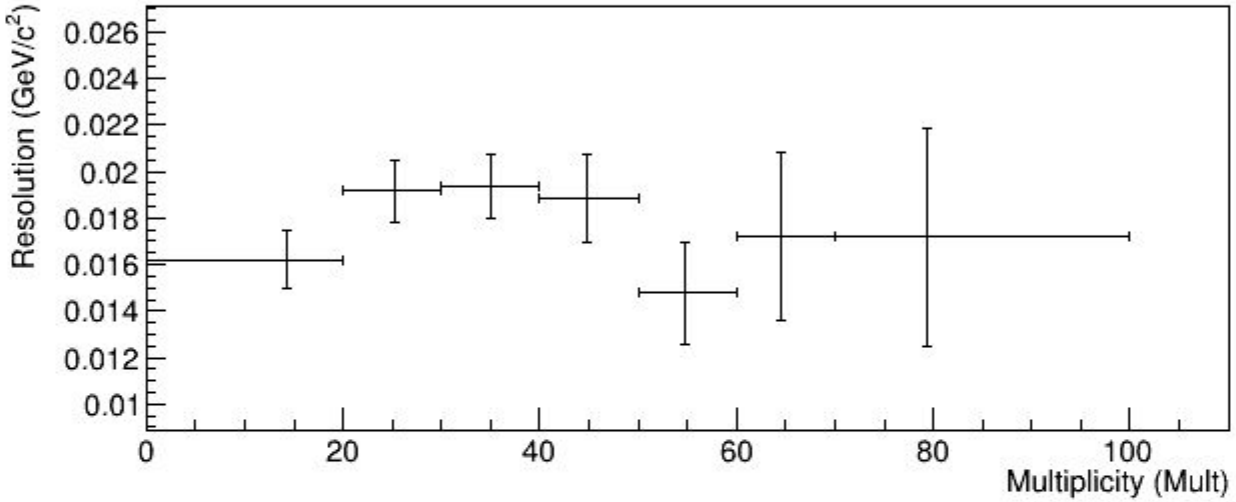


B^+

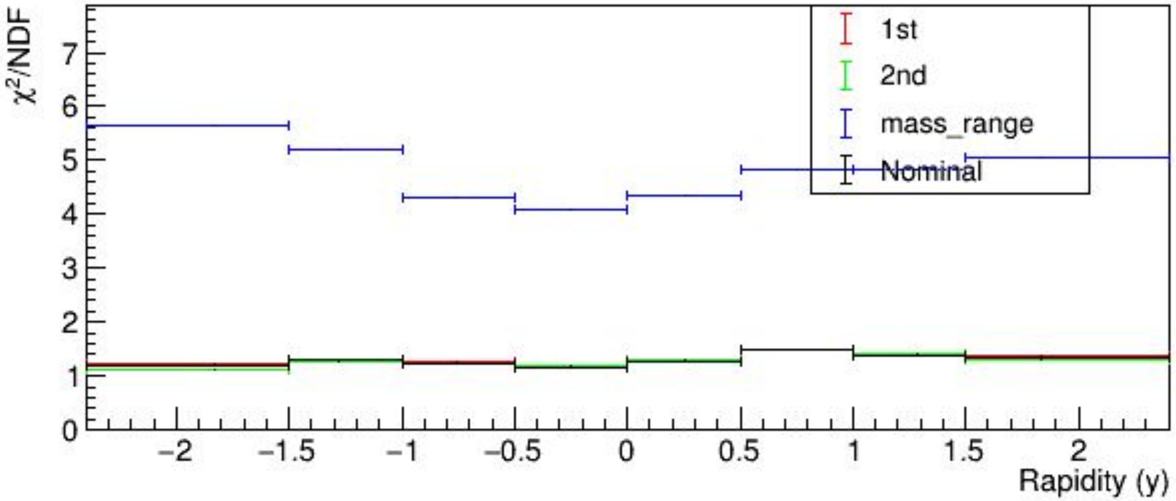
Mass Resolution



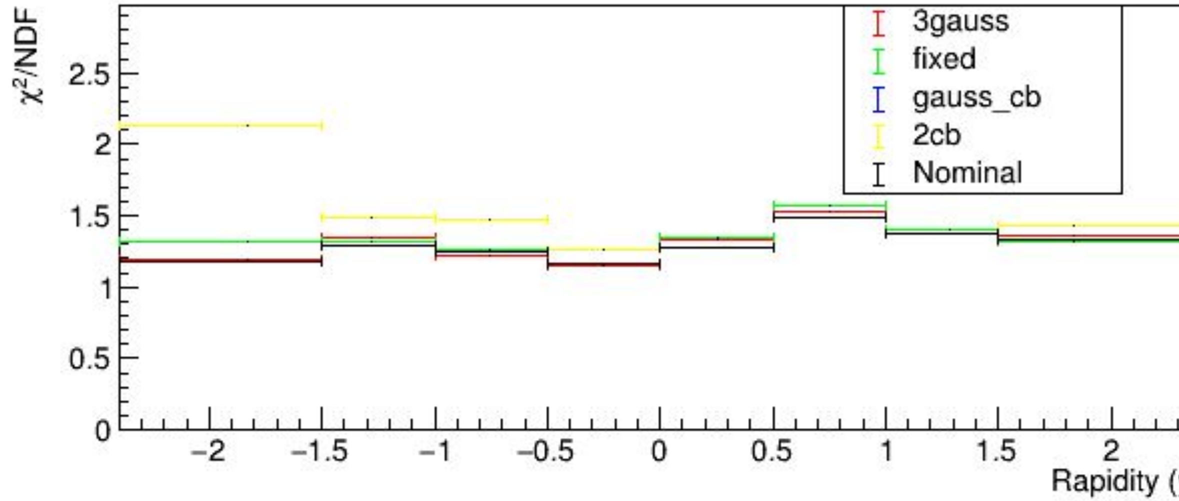
Rapidity



Multiplicity



χ^2/NDF
1st
2nd
mass_range
Nominal
Rapidity (y)



χ^2/NDF
3gauss
fixed
gauss_cb
2cb
Nominal

Summary

y: 64 data fits + 40 MC fits
mult: 56 data fits + 36 MC fits
pt: 56 data fits + 36 MC fits

Now a total number of 288 fits for B_s^0

y: 64 data fits + 40 MC fits
mult: 56 data fits + 36 MC fits
pt: 56 data fits + 36 MC fits

Gave 12 talks:

6 in CMS Spectra and Heavy Flavour meeting: 21st July. 28th July, 4th August, 18th August, 25th August, 1st September

6 in LIP CMS meetings: 27th July, 3rd August, 10th August, 17th August, 23rd August, 31th August