Quark-Gluon Plasma

B mesons as novel probes of QGP

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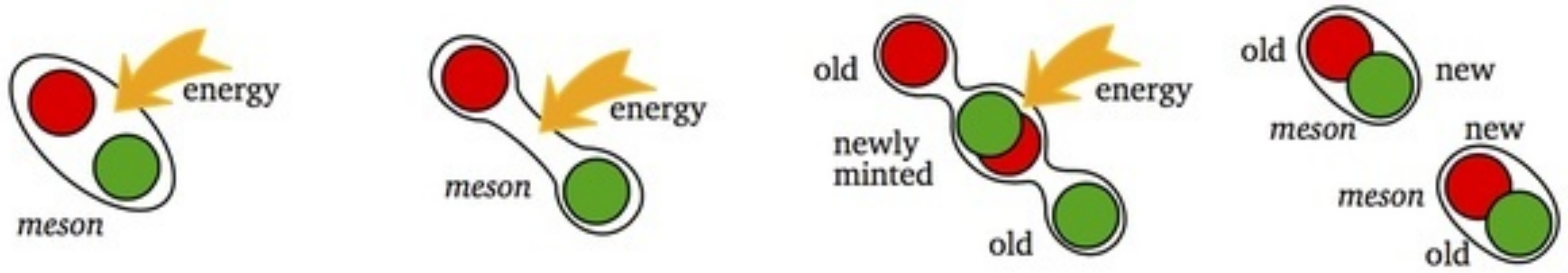
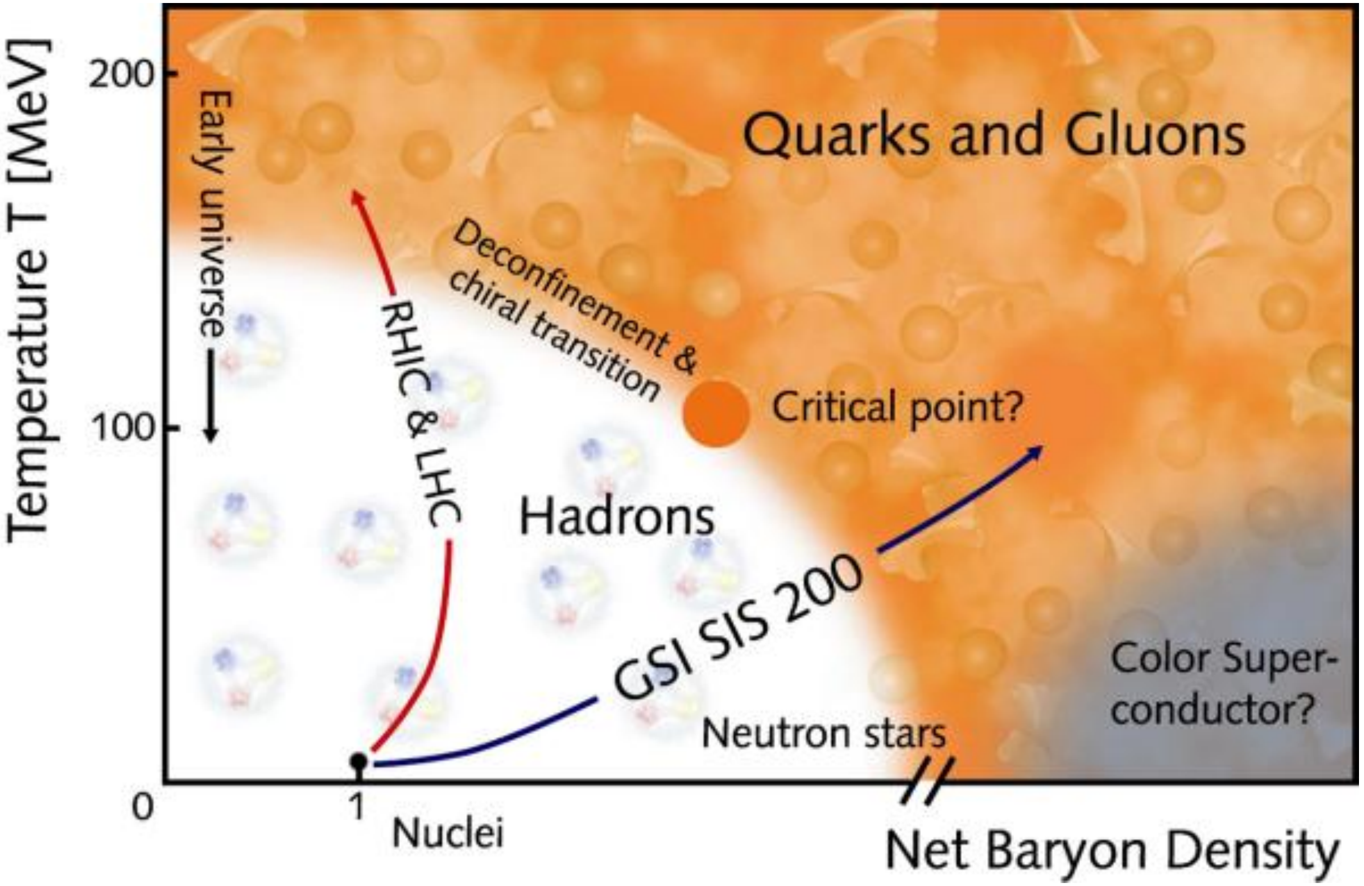
Quarks

- Quarks do not stay alone
- They tend to join other quarks and form hadrons
- This is called **hadronization** and it happens due to the strong nuclear interaction



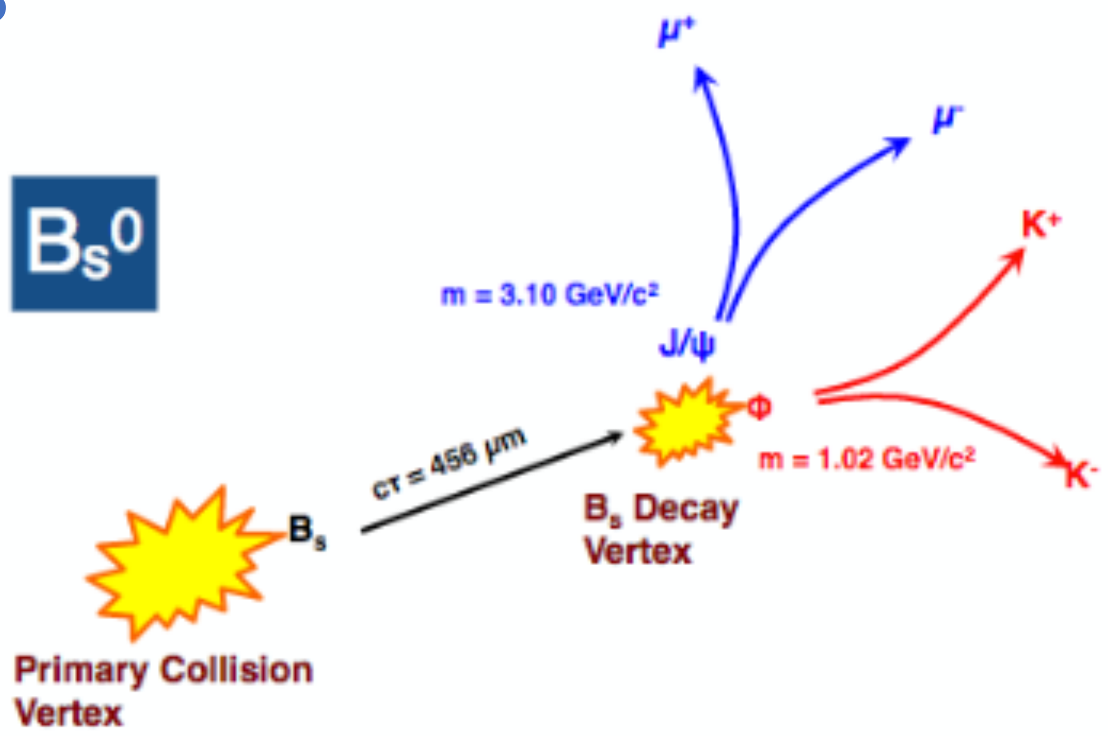
QGP

- Quantum chromodynamis (QCD) predicts that under extreme conditions of temperature and/or density the **Quark-Gluon Plasma (QGP)** is formed.
- **QGP** is a state of matter formed by deconfined quarks and gluons
- Heavy ion collisions like Pb-Pb allow us to recreate the QGP



B mesons in Pb-Pb collisions

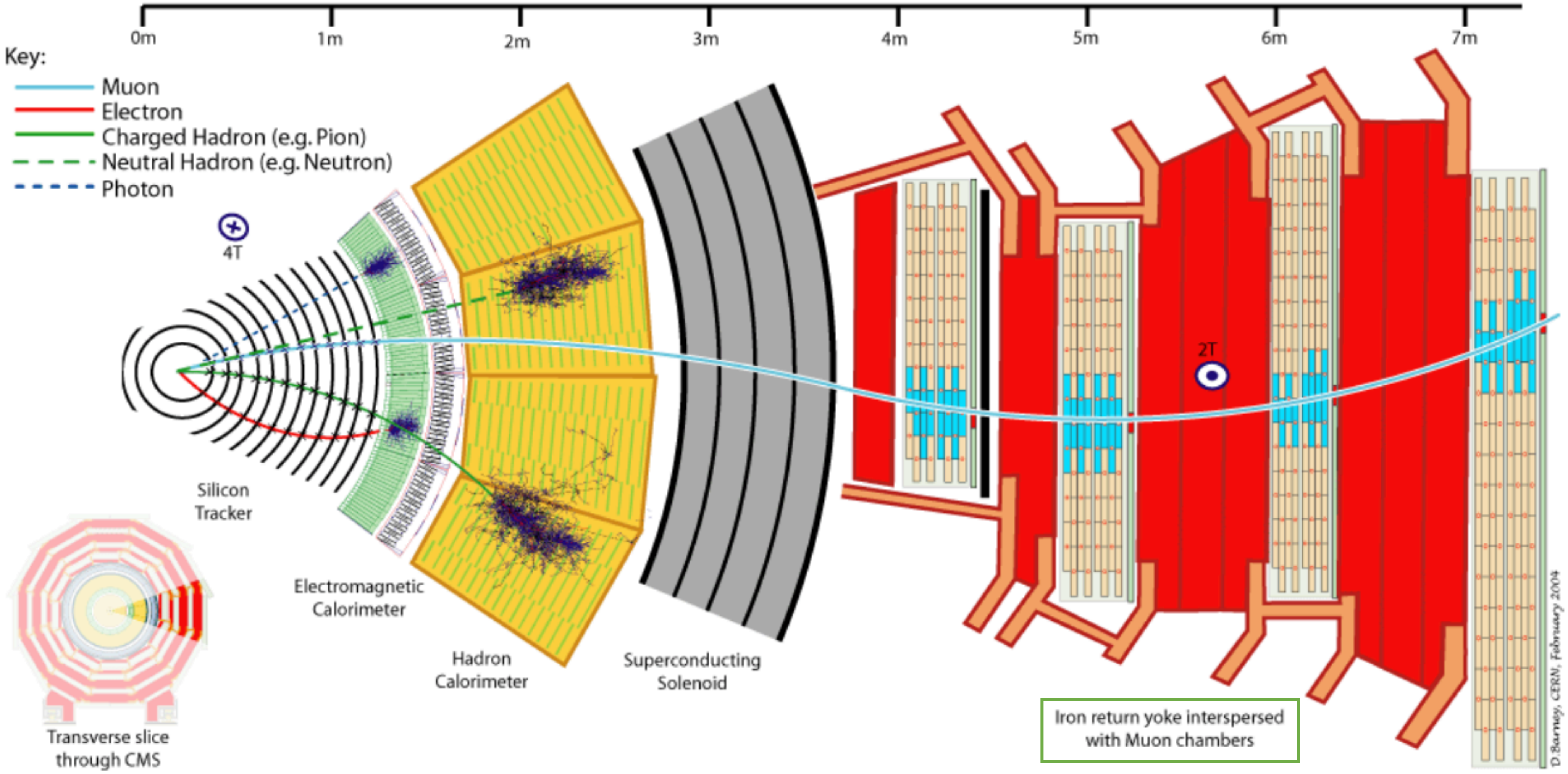
- In p-p collisions ("vacuum"), b quarks hadronise into B hadrons, e.g. **B⁺**(bu), **B$_s$**(bs), **B$_C$**(bc), ...
- What if hadronization happens in a QGP medium?
- Our goal is to measure the cross-section of B mesons in Pb-Pb collisions and study how the QGP affects hadronization
- CMS is the only experiment in which B mesons have been reconstructed through their full decays

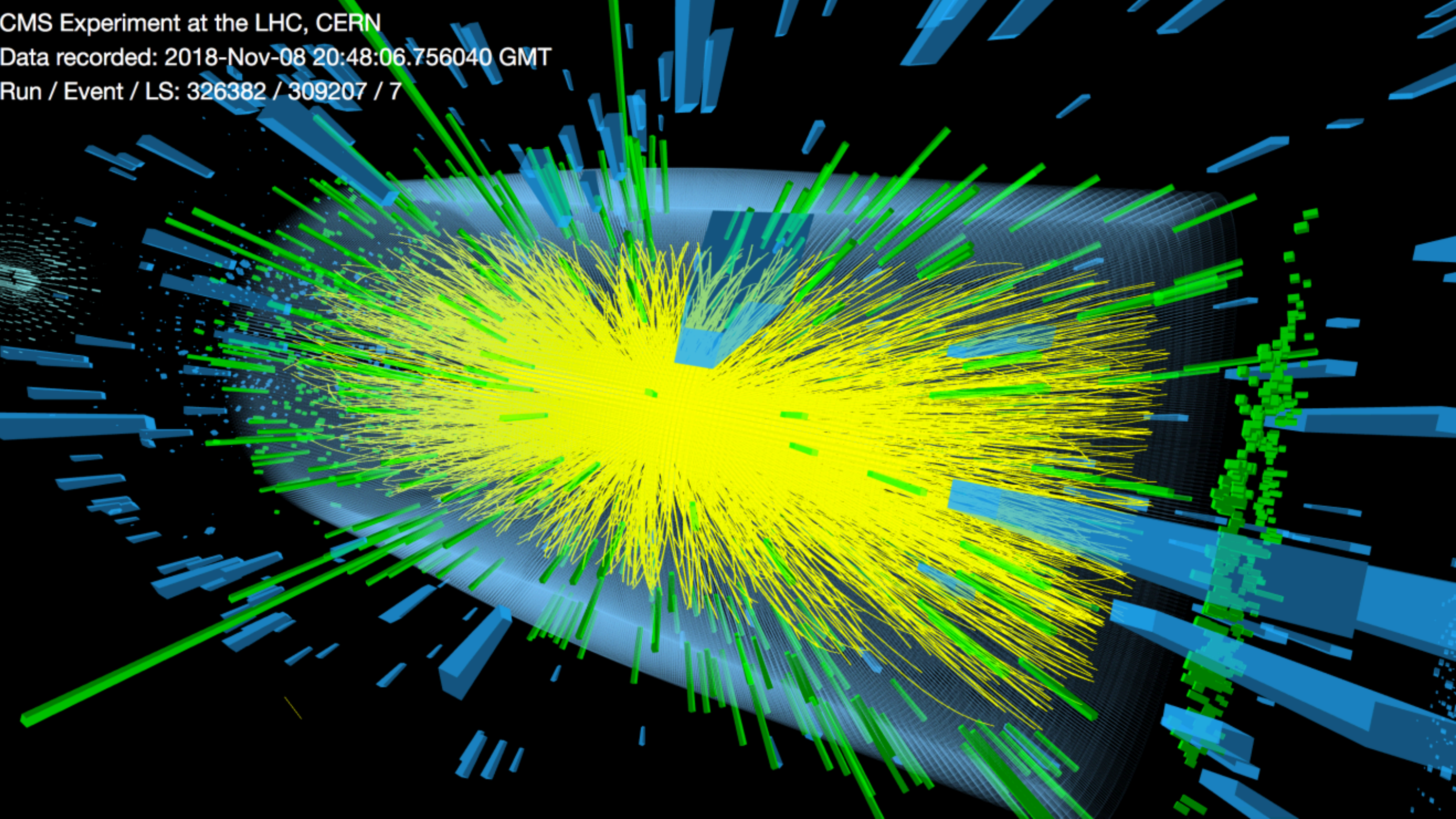


$$B^+ \to J/\Psi(\mu^+\mu^-)K^+$$

$$B_s \to J/\Psi(\mu^+\mu^-)\phi(K^+K^-)$$

Detector


0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February 2004


CMS Experiment at the LHC, CERN
Data recorded: 2018-Nov-08 20:48:06.756040 GMT
Run / Event / LS: 326382 / 309207 / 7

Data, MC samples, and signal selection

- Data: **Pb-Pb collisions** collected by CMS
  - last LHC run (November 2018)
  - luminosity = 1.5 nb^{-1}
  - centre of mass energy = 5.02 TeV

- MC simulated by Pythia + Geant

- Signal selection
  - pre-selection: baseline muon and track kinematics and quality
  - BDT discriminant optimized with additional event variables: e.g. vertex fit probability, pointing angle, decay length, impact parameter

B production

B production

- Cross-section:

$$\sigma = \frac{N}{\mathcal{E}\mathcal{A}\mathcal{B}\mathcal{L}}$$

- Signal yield **N**
  - from data
- Efficiency **Ɛ** and acceptance **A**
  - from MC simulation
- Branching fraction **B**
  - from PDG
- Luminosity **L**

Because we use MC (**A** and **Ɛ**), it is critical to **validate** it:
i.e. to ensure that MC correctly describes the data.

B signal extraction, N

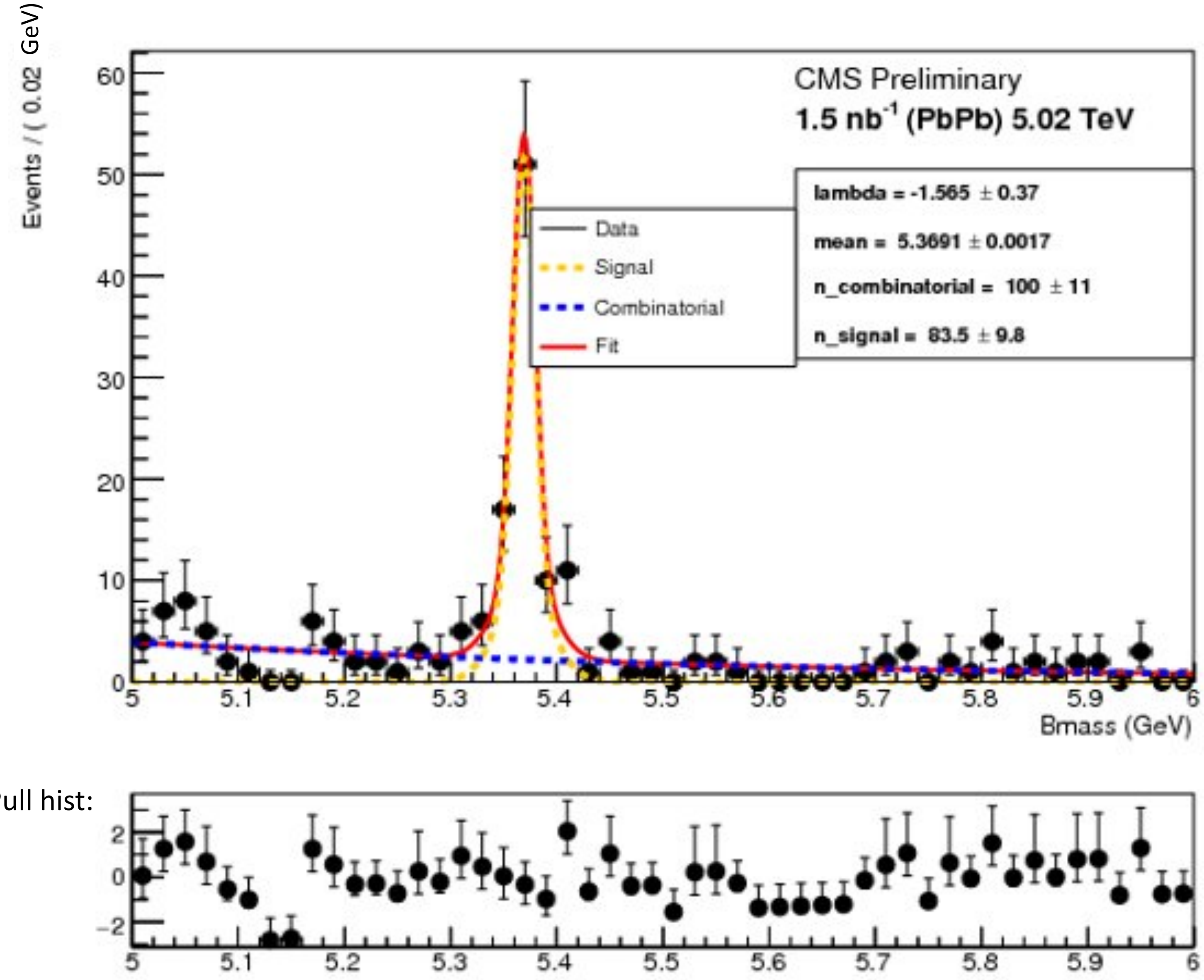
B signal extraction

- Signal yield **N** extracted by fitting the data
- Extended unbinned maximum likelihood fit (RooFit)
  - Signal model: sum of 2 gaussians
  - Combinatorial background model: exponential

$$L(m) = N_S\big(\alpha\,.\,G(\sigma_1,\mu) + (1-\alpha)\,.\,G(\sigma_2,\mu)\big) + N_{CB}\big(Exp(\lambda)\big)$$

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

B_s signal extraction

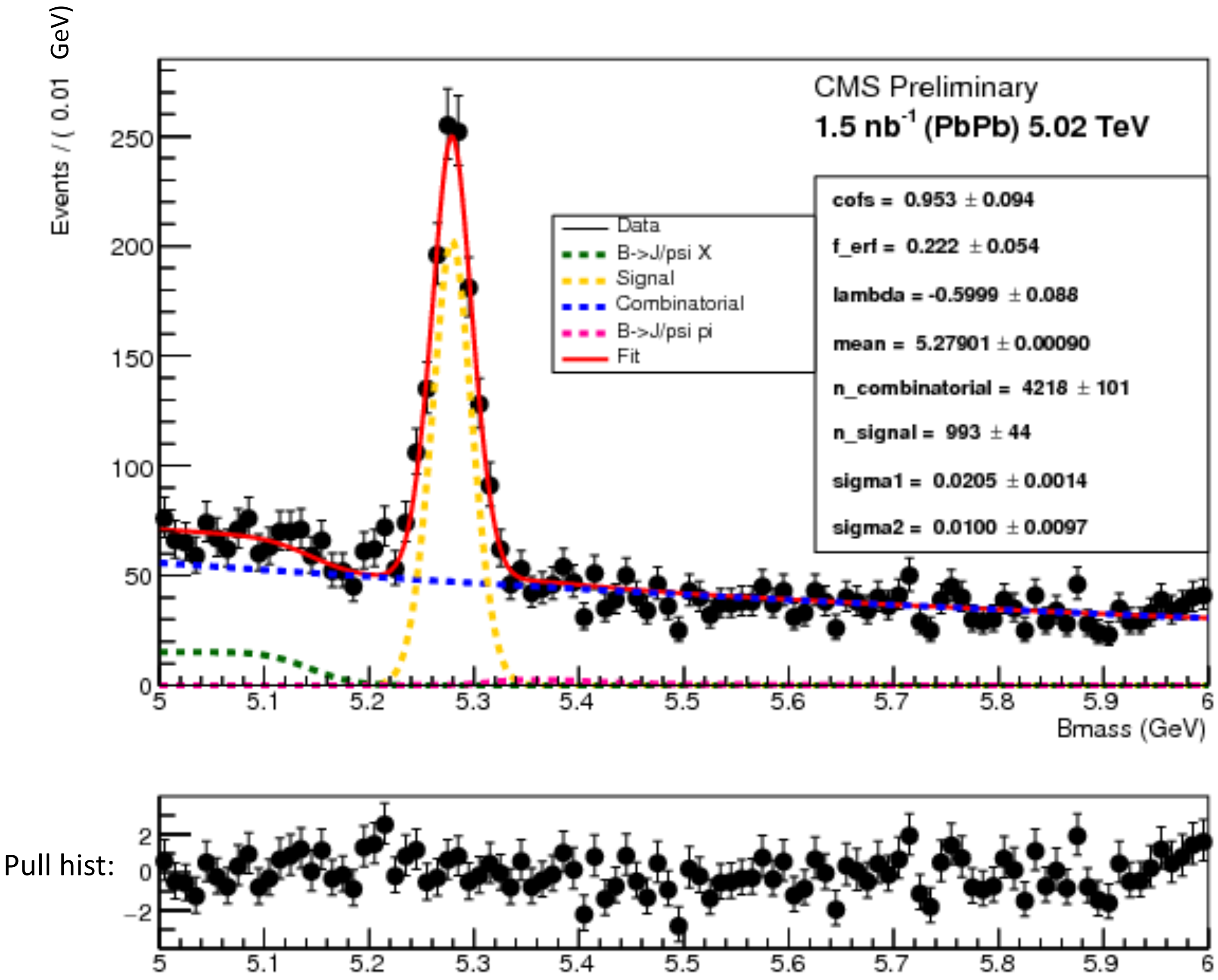


Pull hist:

$$\underline{N_S\left(\alpha\,.\,G(\sigma_1,\mu)+(1-\alpha)\,.\,G(\sigma_2,\mu)\right)}$$

$$+\underline{N_{CB}\left(Exp(\lambda)\right)}+$$

B^+ signal extraction



$$N_S\left(\alpha \,.\, G(\sigma_1, \mu) + (1-\alpha) \,.\, G(\sigma_2, \mu)\right)$$

$$+N_{CB}\left(Exp(\lambda)\right)+$$

$$+N_{erf}\left(Erf(sh, sc)\right)+$$

$$N_{jpp}(fixed)$$

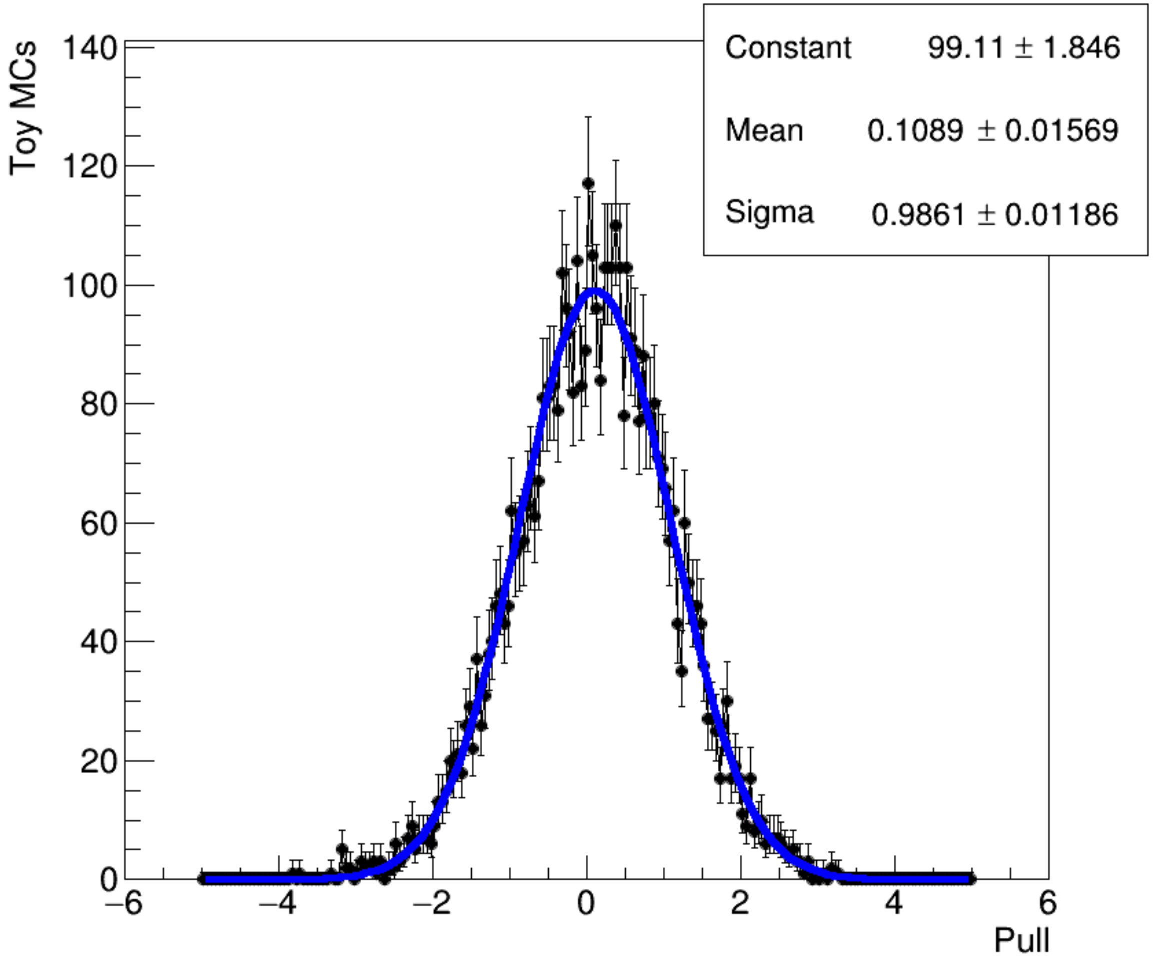
$$B_S^0 \to J/\psi\ K^+K^-$$

$$B \to J/\psi\ \pi$$

Fit validation

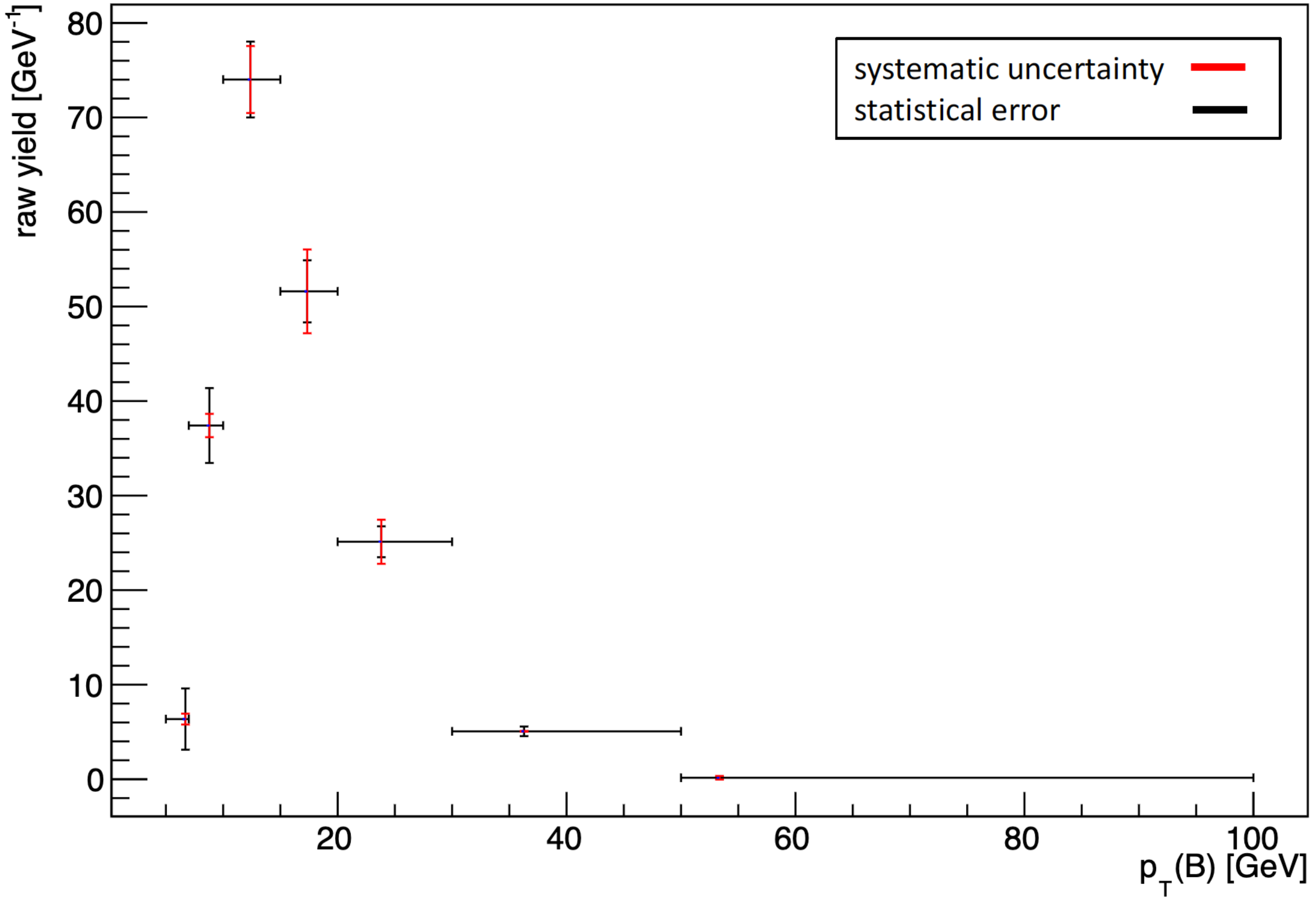
- To **validate the fit** (i.e. verify its ability to correctly extract the parameters).
- We generate 5000 toy MCs (events being generated following the fit's PDF), fit them and retrieve their input parameters.
  - pull distribution: should be a gaussian curve with mean = 0 and sigma = 1

$$\text{Pull} = \frac{N_i - N_{mean}}{\sigma}$$



Differential yield and systematics

B^+ meson

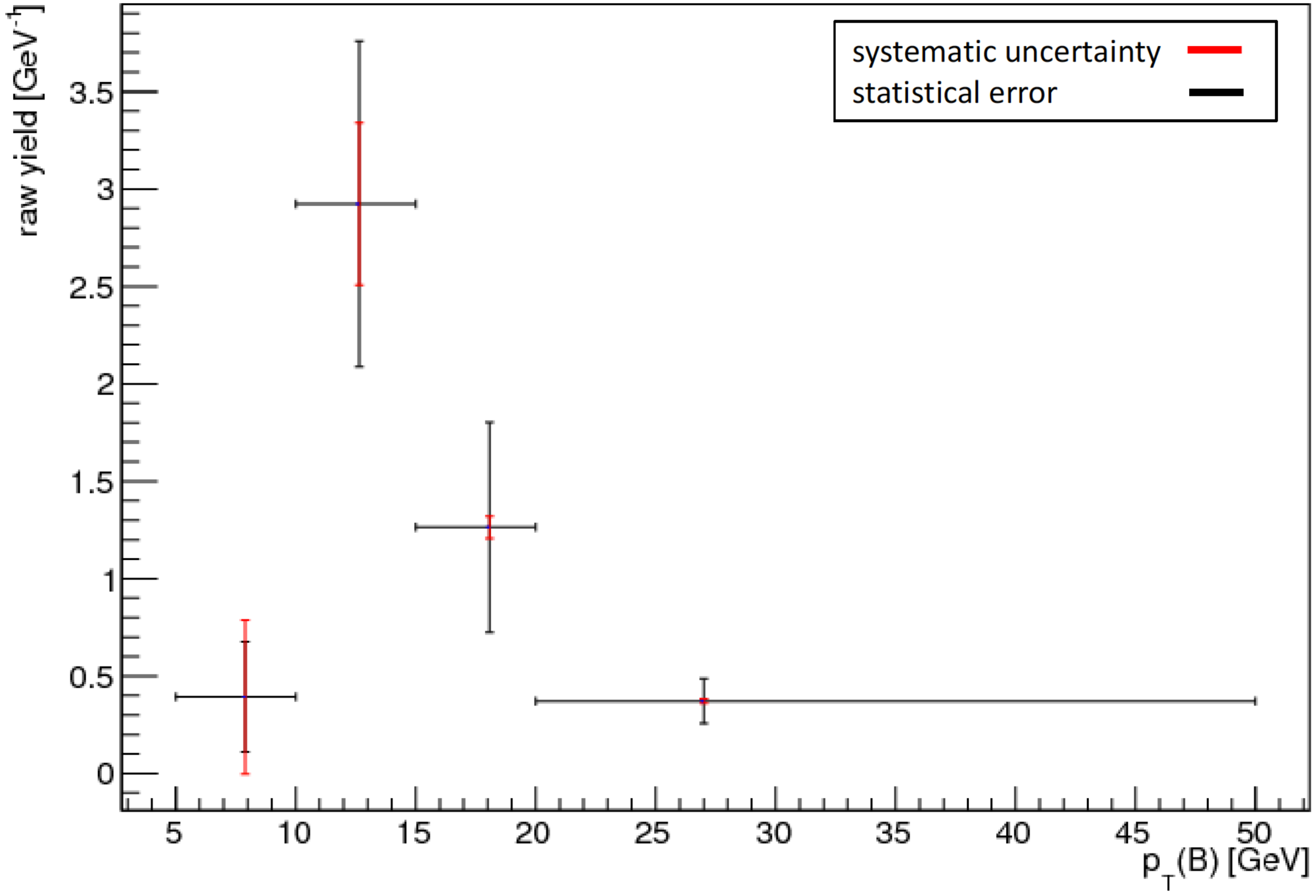


- We repeat the fit by splitting the data in pT bins.
- We evaluate the systematic uncertainty by pdf variation, varying:
  - signal pdf
  - background pdf
  - fit range

Bins (GeV)	p_T	N_{signal}	**Statistical error (+/-)**	**Systematic uncertainty (+/-)**
5-7	6.70422	6.35808	3.23988	0.574439
7-10	8.80085	37.4122	3.96142	1.23235
10-15	12.3866	74.0124	4.01438	3.54562
15-20	17.3456	51.6057	3.2833	4.43056
20-30	23.8173	25.117	1.6365	2.33201
30-50	36.2883	5.06199	0.507416	0.0324111
50-100	53.3649	0.152899	0.0543959	0.186233

Differential yield and systematics

B_s meson



Bins (GeV)	p_T	N_{signal}	**Statistical error (+/-)**	**Systematic uncertainty (+/-)**
5-10	7.90338	0.392302	0.283052	0.394663
10-15	12.6422	2.92439	0.835797	0.416504
15-20	18.0687	1.26369	0.538784	0.056602
20-50	27.0028	0.371153	0.114931	0.0118273

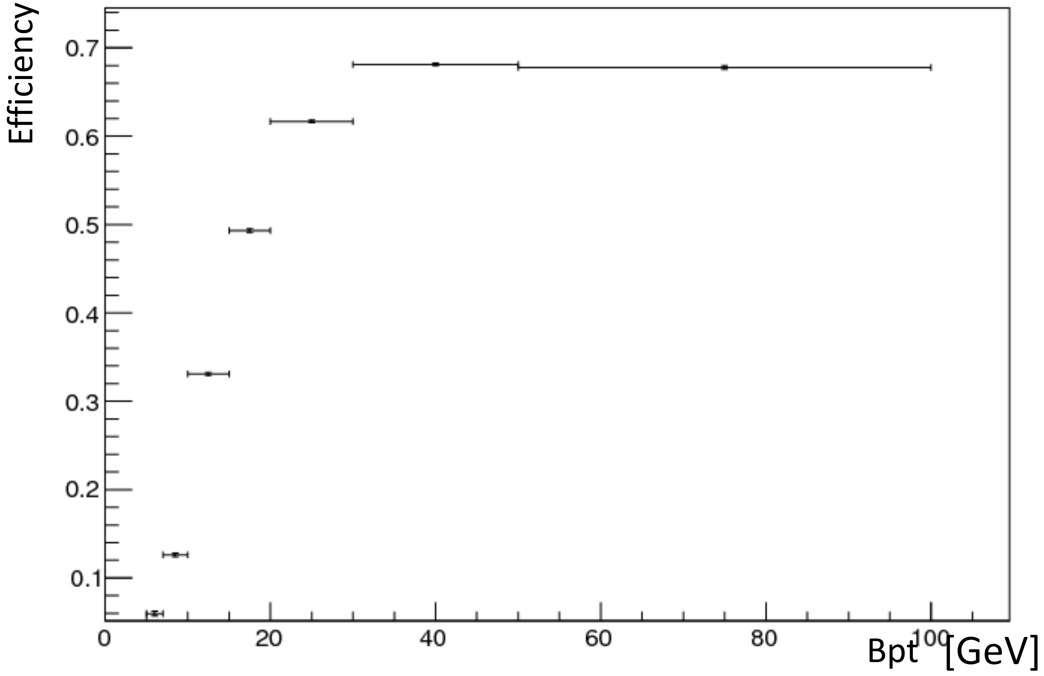
Efficiency, ε

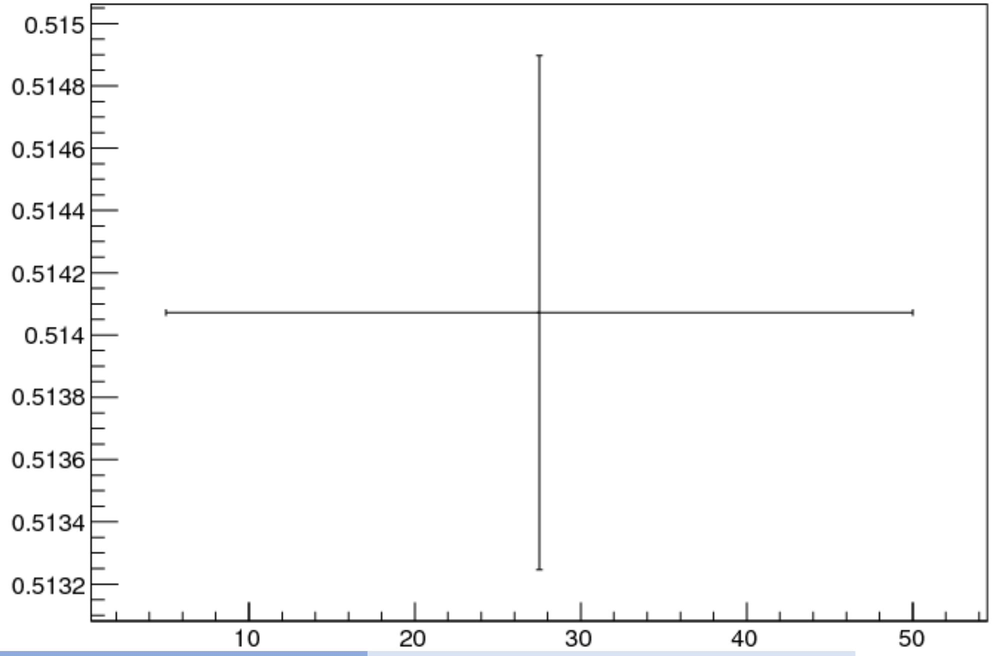
Efficiency

- Efficiency measures the amount of lost signal

$$\epsilon = \frac{\text{events with cuts}}{\text{events without cuts}}$$

- Determined from MC simulation -> so it is crucial to validate signal MC against data
- For that we must remove background from data – implemented 2 methods:
    - Sideband subtraction
    - SPlot



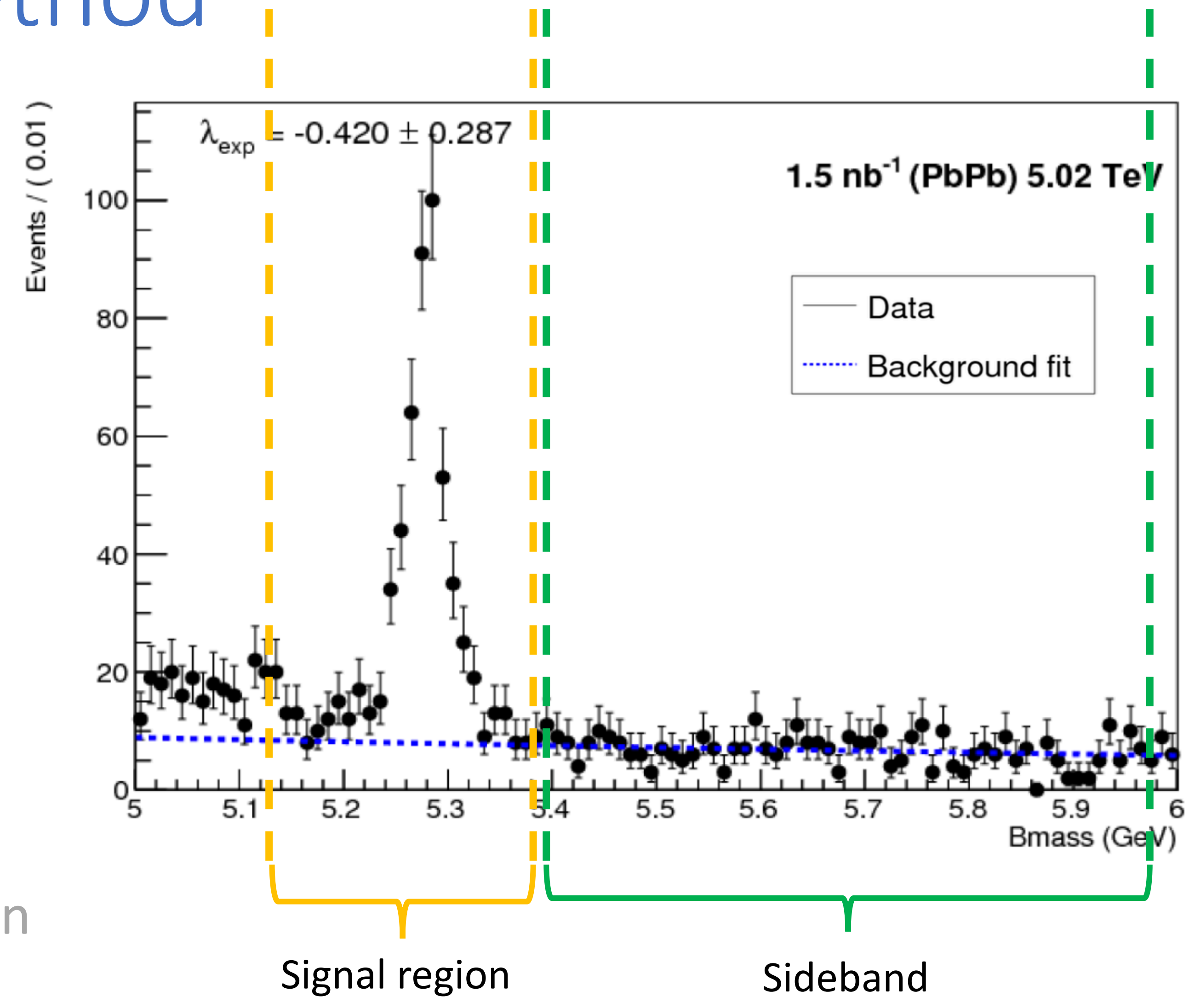


Sideband Subtraction Method

- Use invariant mass for discriminating signal from background
- Define two regions:
  - Signal region (S + B)
  - Sideband region (B)
- Signal distribution for a variable V:

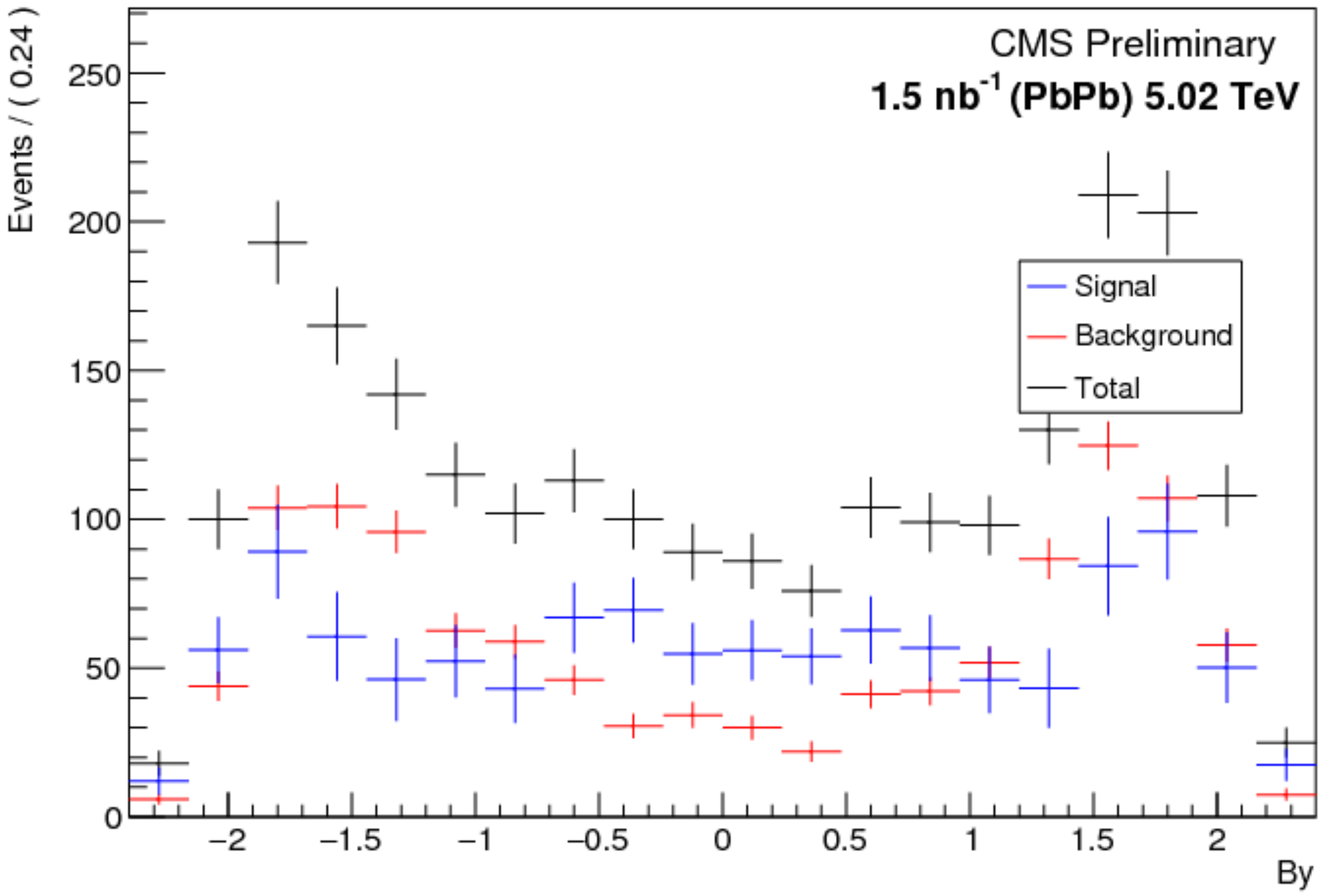
$$V_S = V_{S+B} - \alpha . V_B$$

- Determine the subtraction factor α:
  - $\alpha = P/R$
  - P: integral of background fit in signal region
  - R: integral of background fit in sideband



Note: variable V assumed to be independent from mass

Sideband subtraction results



SPlot method

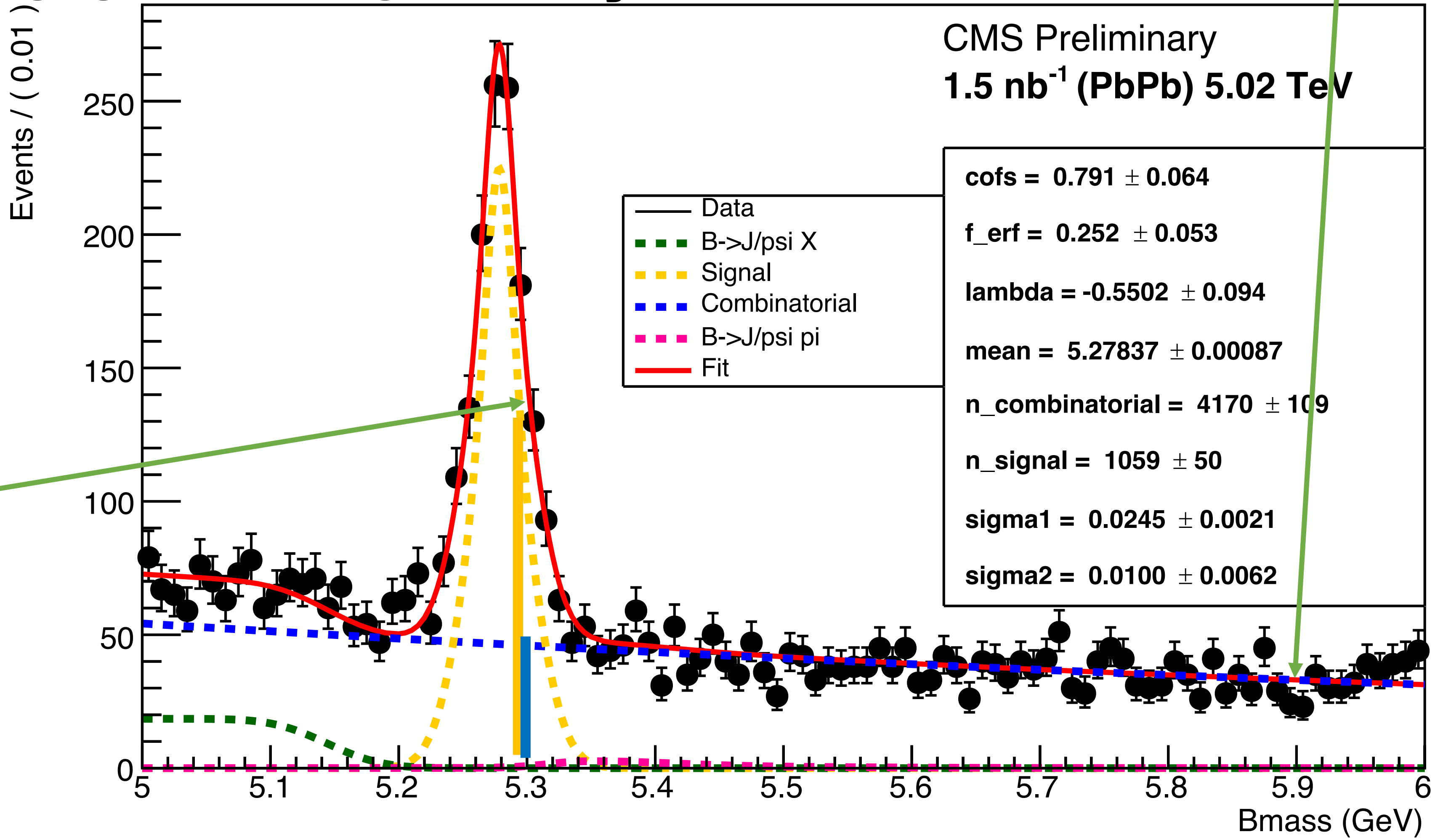
- SPlot method is likelihood based.
- Each event has two weights (extracted from likelihood):
    1. Probability of belonging to the signal, $\mathbf{W_S}$
    2. Probability of belonging to the background, $\mathbf{W_B}$

- Signal distribution for an (independent) variable V is a data distribution where each bin is multiplied by its $\mathbf{W_S}$

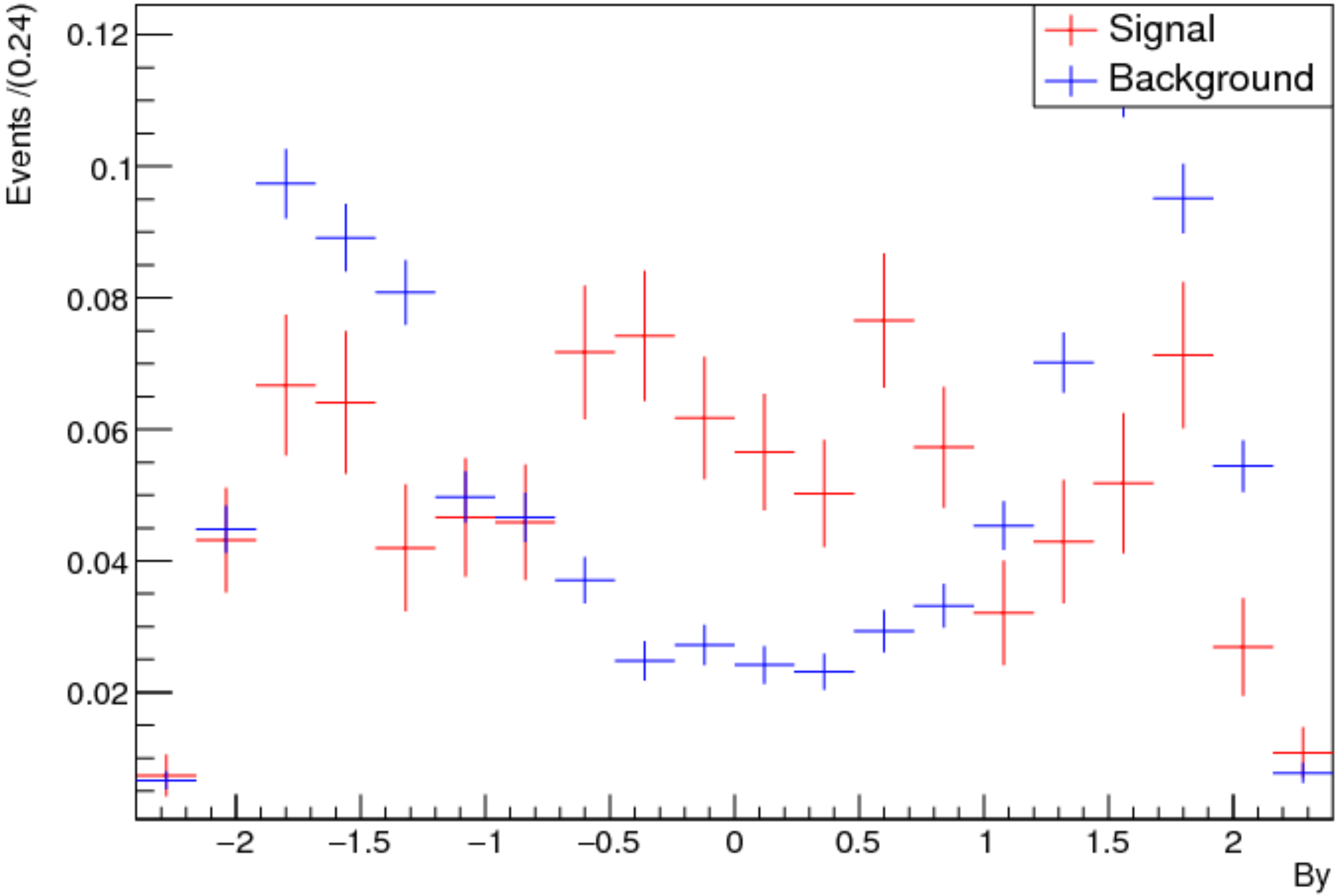
W_S

W_B

$W_B = 1$
$W_S = 0$

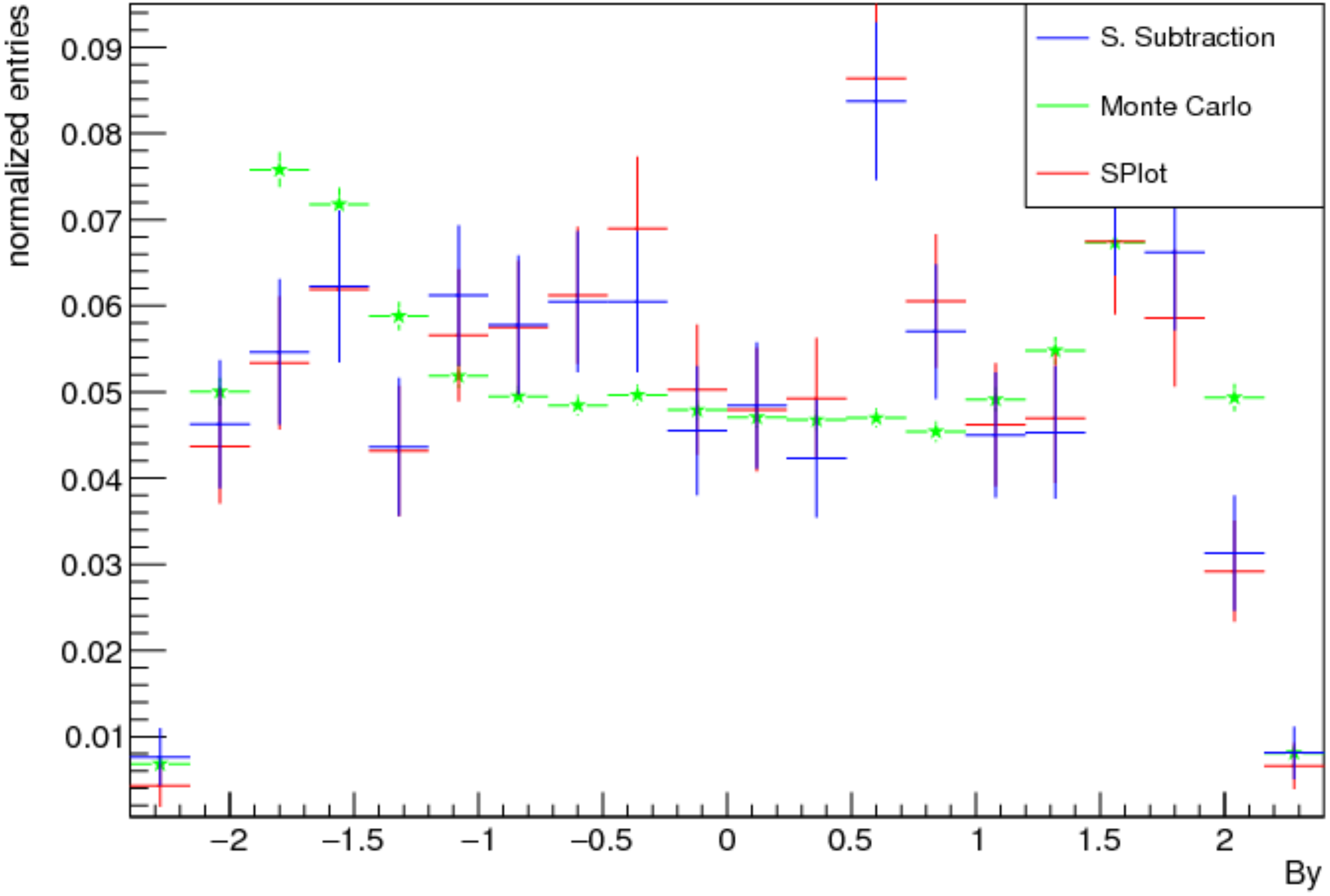


SPlot results



Comparison: sideband vs splot vs mc

- SPlot is more robust than sideband subtraction because it uses information from a full likelihood fit
- MC is reasonably similar to the data
- *However...*



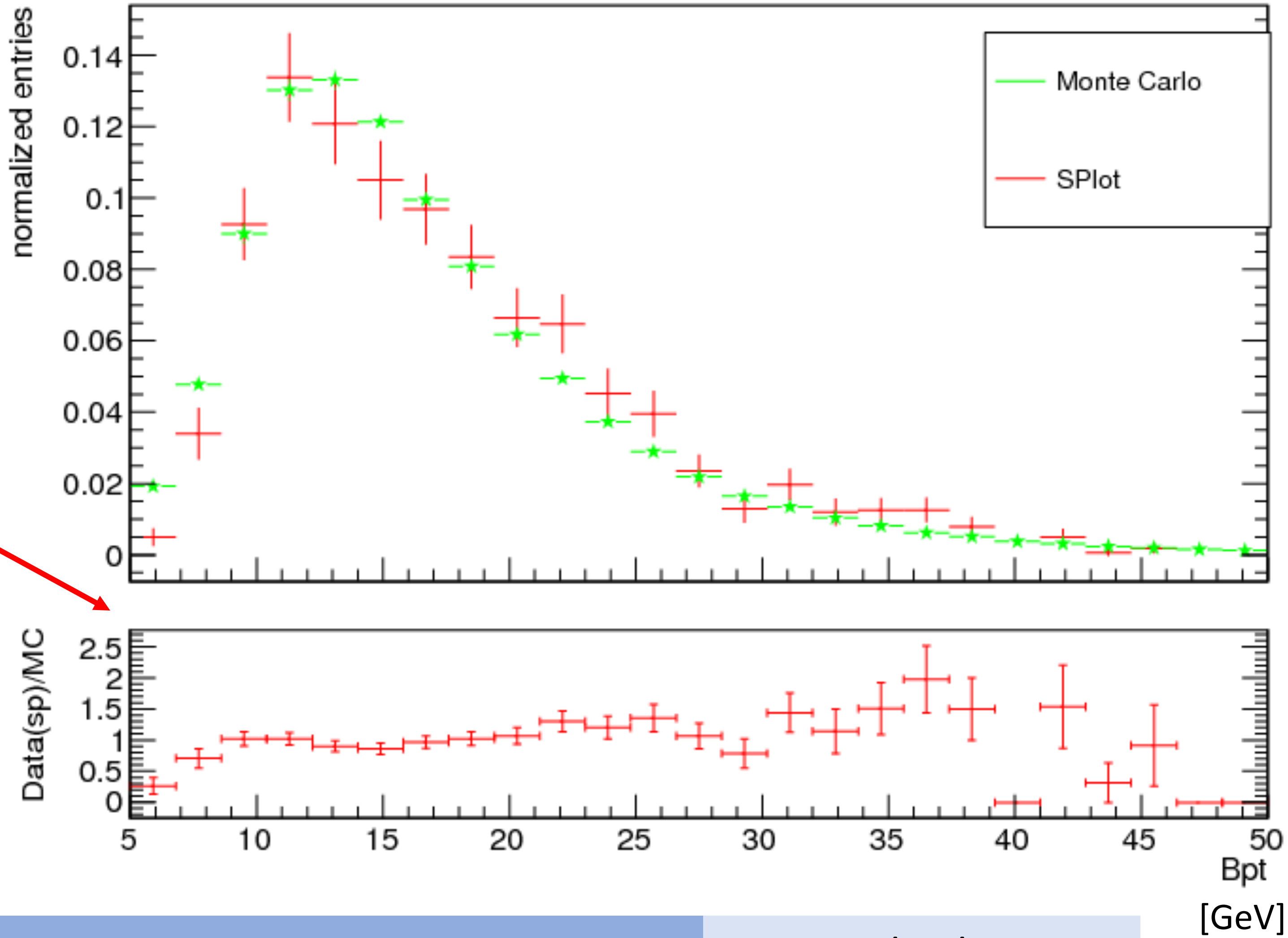
Efficiency systematics

- Effect of disagreement between MC and data on our results is quantified by efficiency systematic error

$$\Delta = \frac{\epsilon^1 - \epsilon^0}{\epsilon^0}$$

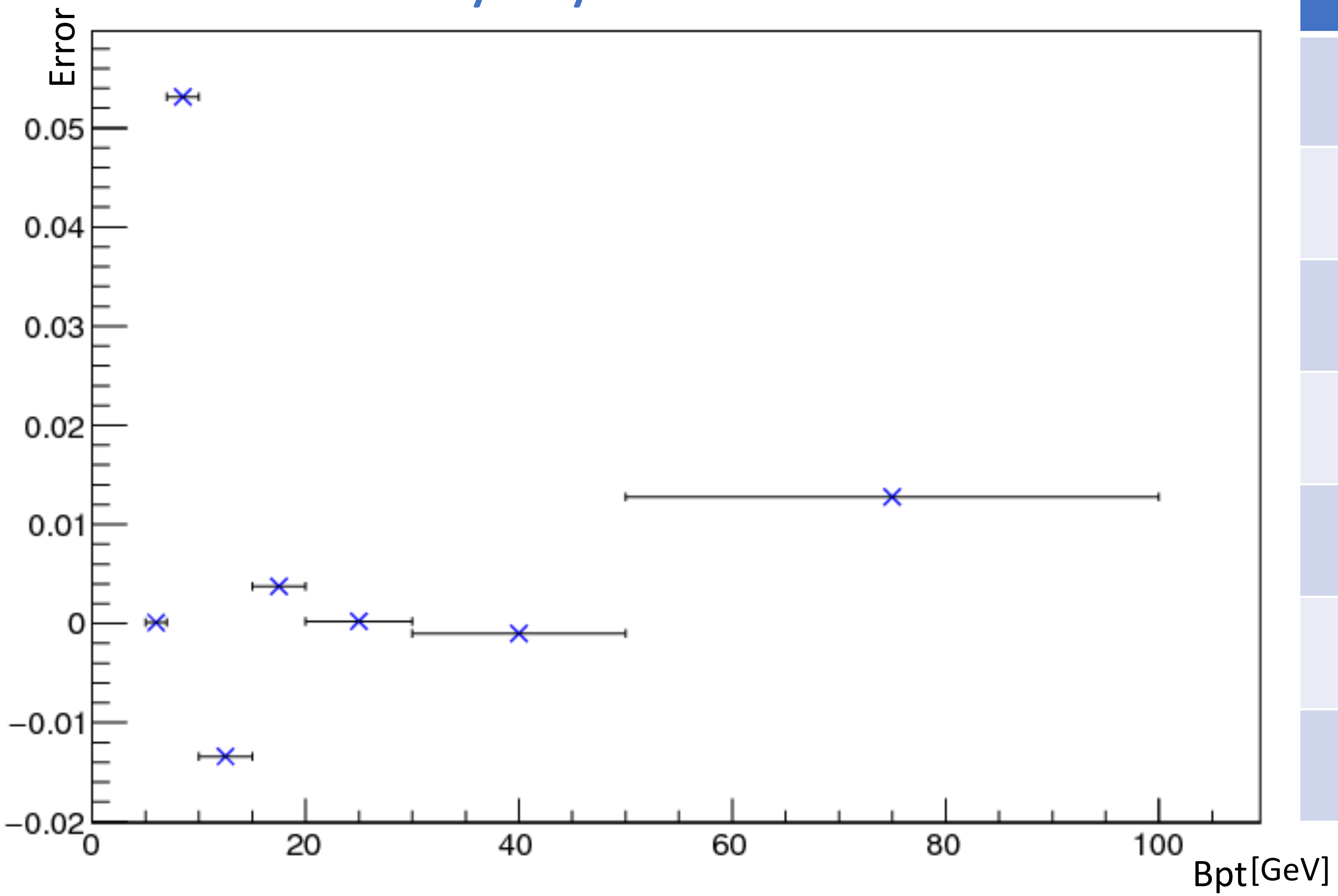
ϵ^0: Nominal efficiency (calculated with MC)

ϵ^1: Efficiency calculated with weighted MC



- MC weights are given by data/MC ratio

Efficiency systematics



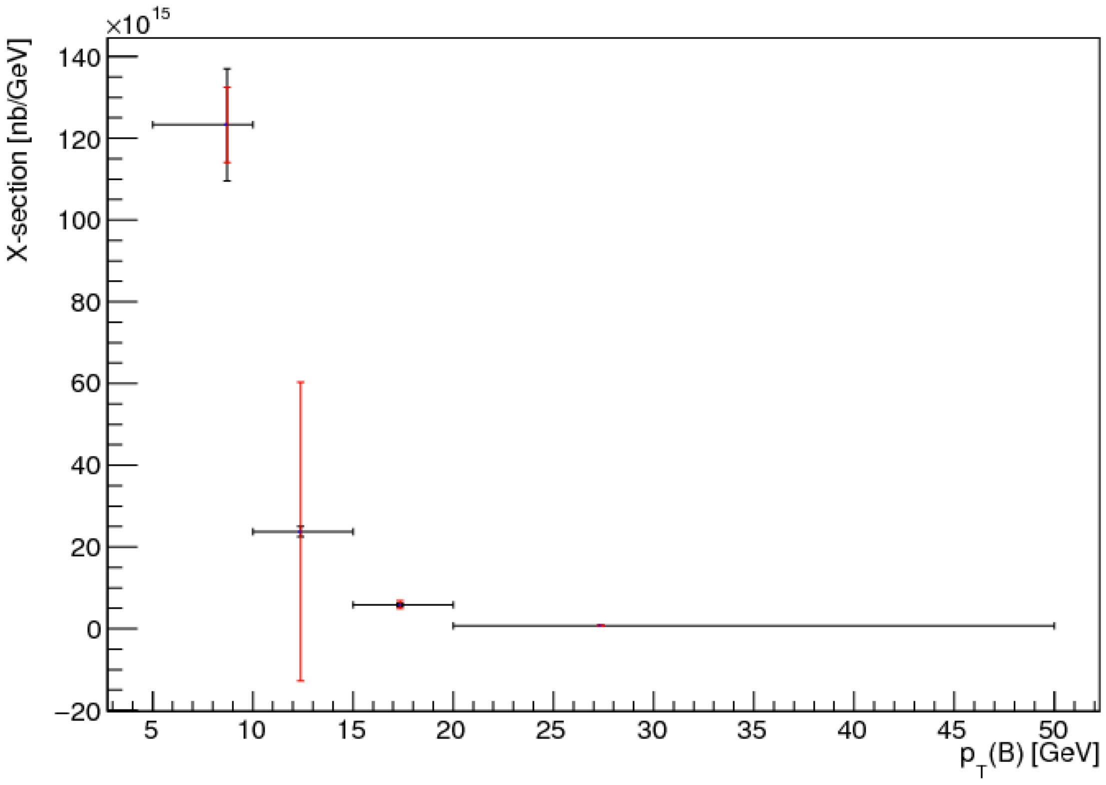
p_T (GeV)	Rel. Error (%)
5-7	0.01
7-10	5.31
10-15	-1.34
15-20	0.37
20-30	0.02
30-50	-0.10
50-100	1.28

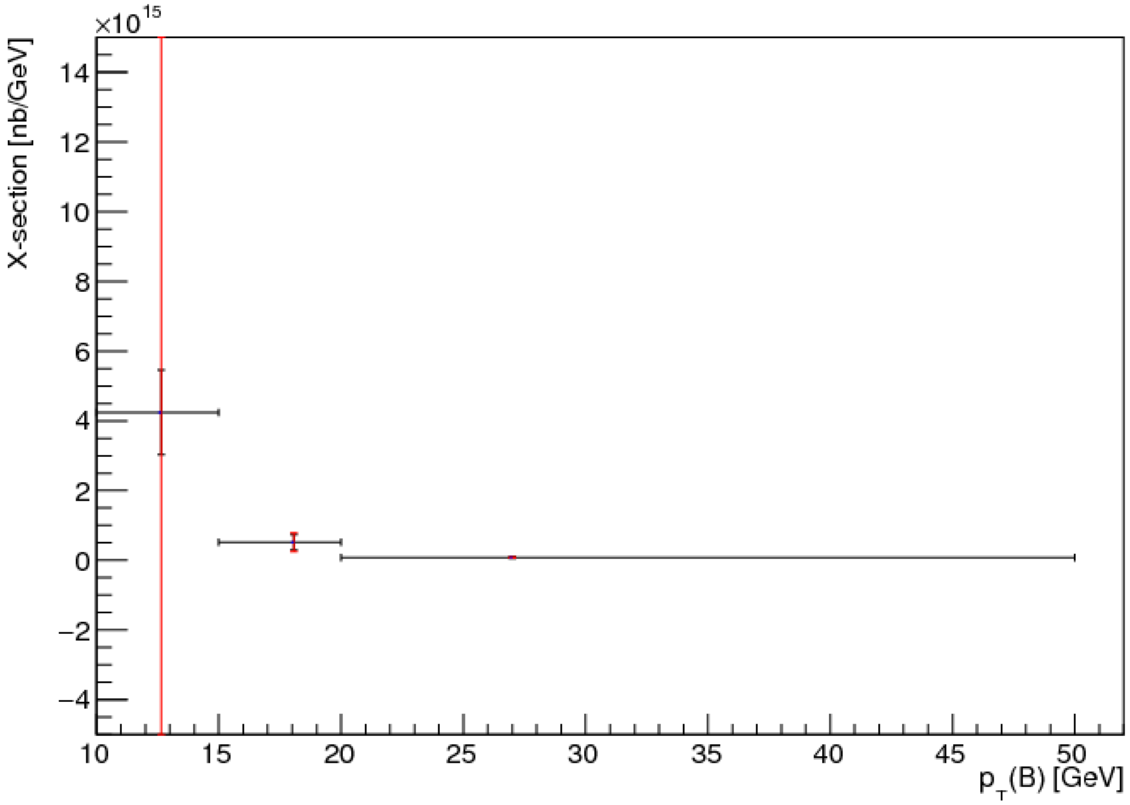
Cross-section

Cross-section

$$\sigma = \frac{N}{\mathcal{E}\mathcal{A}\mathcal{B}\mathcal{L}}$$

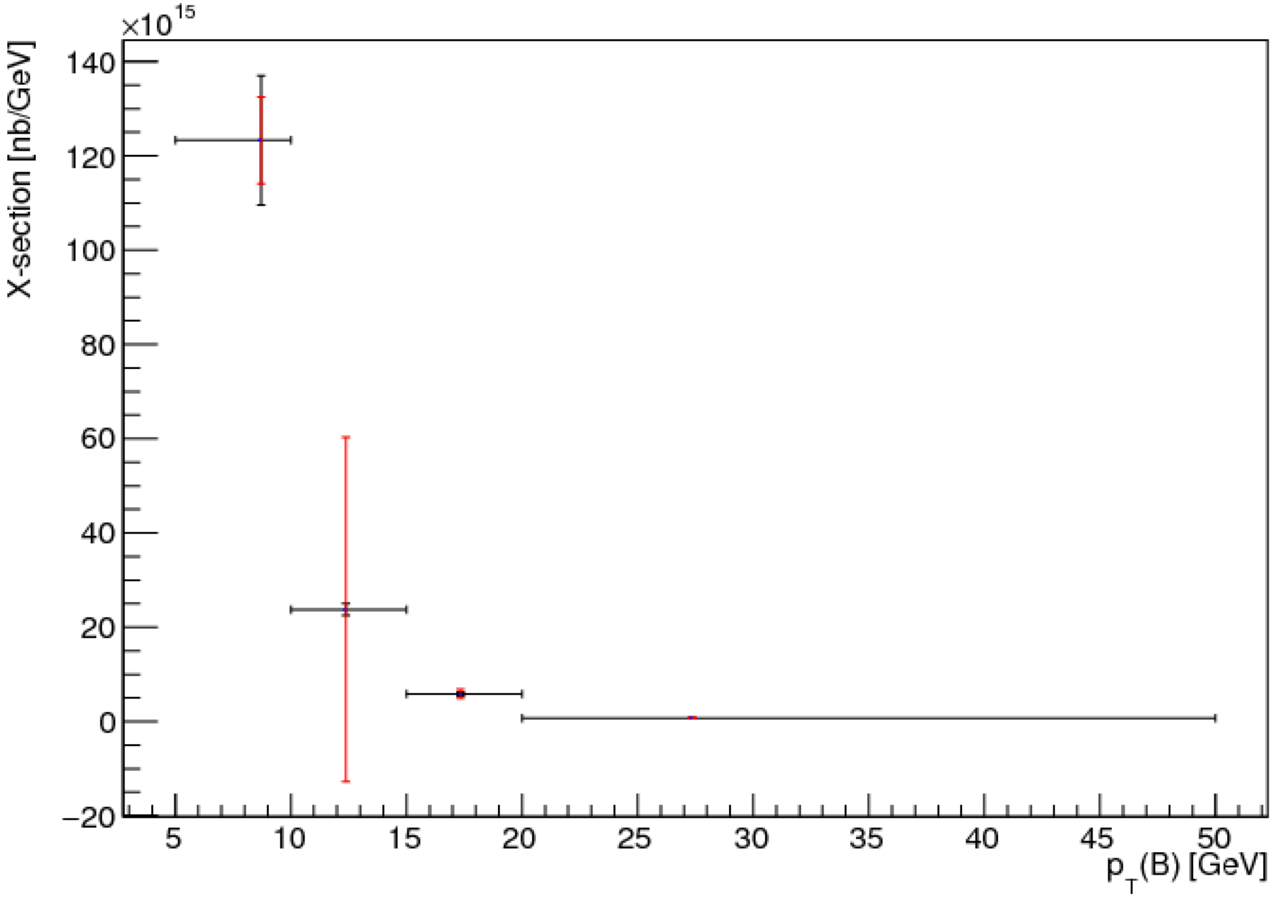
- **N** from fit
- **ε** and **A** from MC
- **B** from PDG
- **L** = 1.5 nb^{-1}





Cross-section

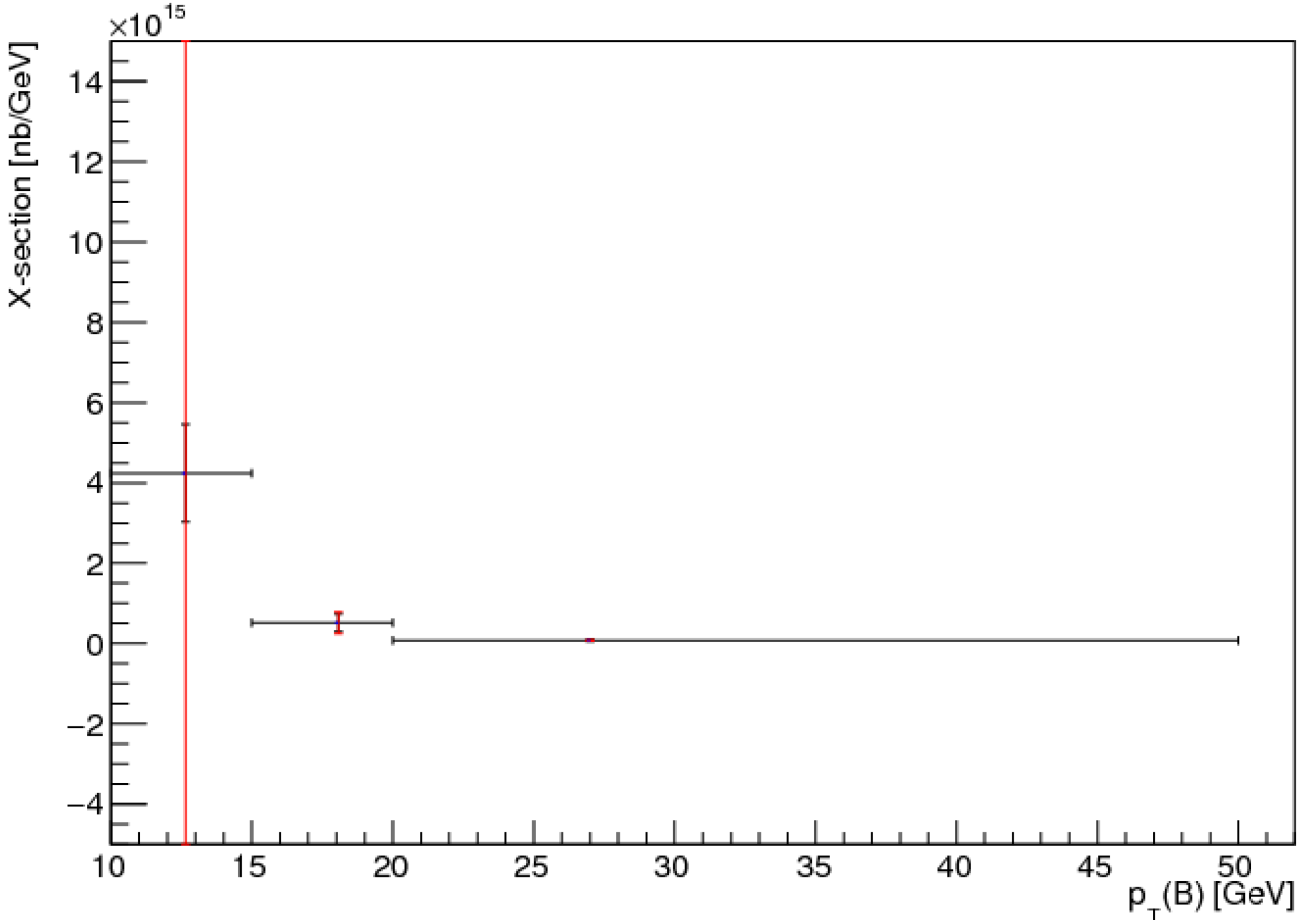
B^+ meson



Bin (GeV)	**X-section (nb/GeV)**	**Systematic uncertainty (+/-)**	**Statistical error (+/-)**
5-10	1.23297e+17	9.18916e+15	1.3736e+16
10-15	2.37764e+16	3.64892e+16	1.28976e+15
15-20	5.85321e+15	9.54505e+14	3.72444e+14
20-50	7.2012e+14	5.97817e+13	3.93007e+13

Cross-section

B_S meson



Bin (GeV)	X-section (nb/GeV)	Systematic uncertainty (+/-)	Statistical error (+/-)
5-10	1.58776e+16	7.46635e+18	1.14559e+16
10-15	4.24098e+15	1.07684e+16	1.21208e+15
15-20	5.19063e+14	2.69032e+14	2.21306e+14
20-50	7.50075e+13	1.20703e+13	2.32267e+13

Conclusions

Conclusions

- We have explored B mesons as novel probes of the QGP with CMS
- B_s meson observed for the first time ever in heavy ion data
- Performed detailed study of MC validation by extracting signal from data
  - implemented the sideband-subtraction and sPlot methods
- Measured differential production cross-sections for B_s and B^+ mesons in Pb-Pb collisions at 5.02 TeV
- Dominant uncertainties:
  - B_s: affected by reduced statistics (more data required from LHC to improve results)
  - B^+: affected by discrepancies between data and MC

Possible next steps

- Continue contributing to ongoing CMS analysis.

1) Solve instabilities found for certain pT bins (Bs).
2) Probe **strangeness enhancement** and **hadronization**:
   i. Calculate the ratio between the Bs and B+ cross-sections in Pb-Pb collisions
3) Probe **energy loss** in the QGP medium:
   i. Measure the production of B mesons also in p-p collisions
   ii. Calculate the nuclear modification factor (RAA)

$$R_{AA} = \frac{1}{< N_{coll} >} \frac{N_{AA}}{N_{pp}}$$

Backup

- In order to plot the fit we used the extended unbinned maximum likelihood: *(**S**: signal; **G:** gaussian; **CB**: combinatorial background; **erf**: error function; **sh**: shift; **sc**: scale; **jpp**: $J/\psi\ \pi$ component;)*

$$\boxed{L(m) = N_S\big(\alpha\,.\,G(\sigma_1,\mu) + (1-\alpha)\,.\,G(\sigma_2,\mu)\big) + N_{CB}\big(Exp(\lambda)\big) + N_{erf}\big(Erf(sh,sc)\big) + N_{jpp}(fixed)}$$

B+

$$\boxed{L(m) = N_S\big(\alpha\,.\,G(\sigma_1,\mu) + (1-\alpha)\,.\,G(\sigma_2,\mu)\big) + N_{CB}\big(Exp(\lambda)\big)}$$

B_S

$$\mathscr{L}(N, \overrightarrow{\lambda}) = \underbrace{\frac{e^{-N} N^{N_{obs}}}{N_{obs}!}}_{\text{Poisson parameter}} \times \prod_{i=1}^{N_{obs}} L(\overrightarrow{m_i}, \overrightarrow{\lambda})$$

$\boldsymbol{N}$: number of expected events (sum of N´s); $\boldsymbol{N_{obs}}$: number of observed events (=$\boldsymbol{N_S}$); $\boldsymbol{L}$: total PDF; $\overrightarrow{\boldsymbol{m_i}}$: vector of invariant mass; $\overrightarrow{\boldsymbol{\lambda}}$: vector of parameters to be estimated (σ_1, μ, λ, etc.)

B+ signal extraction

Fit validation – Systematic error

- The formula for the systematic error of the fit is:

  ε = (pull distribution mean) x (signal yield sigma)

- Using the values from the fit and the fit validation, we get:
- ε = 0.1089 x 50 = 5.445
- This value corresponds approximately to the difference between the fit mean and the parameter distribution mean:

  1059- 1052 = 7

Rapidity

-

y - rapidity ($y = \frac{1}{2} \ln \left(\frac{E - p_z}{E + p_z} \right)$)