Upsilon meson production in p+p collisions measured at STAR

Jakub Češka

Supervisor: Leszek Kosarzewski

Advisor: Jaroslav Bielčík

FJFI ČVUT

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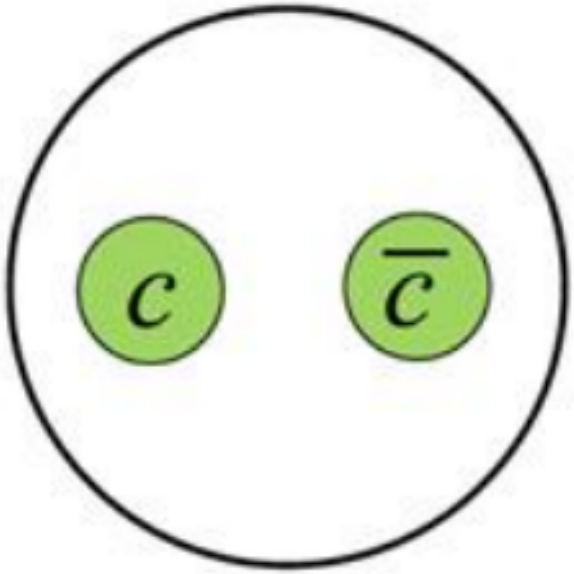
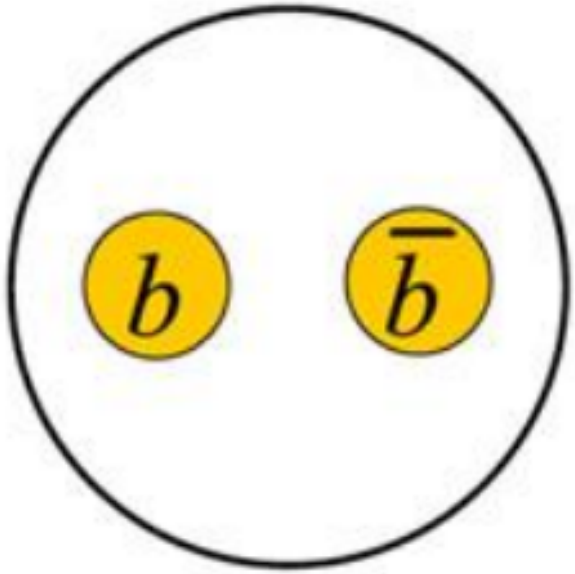

c
$\overline{c}$

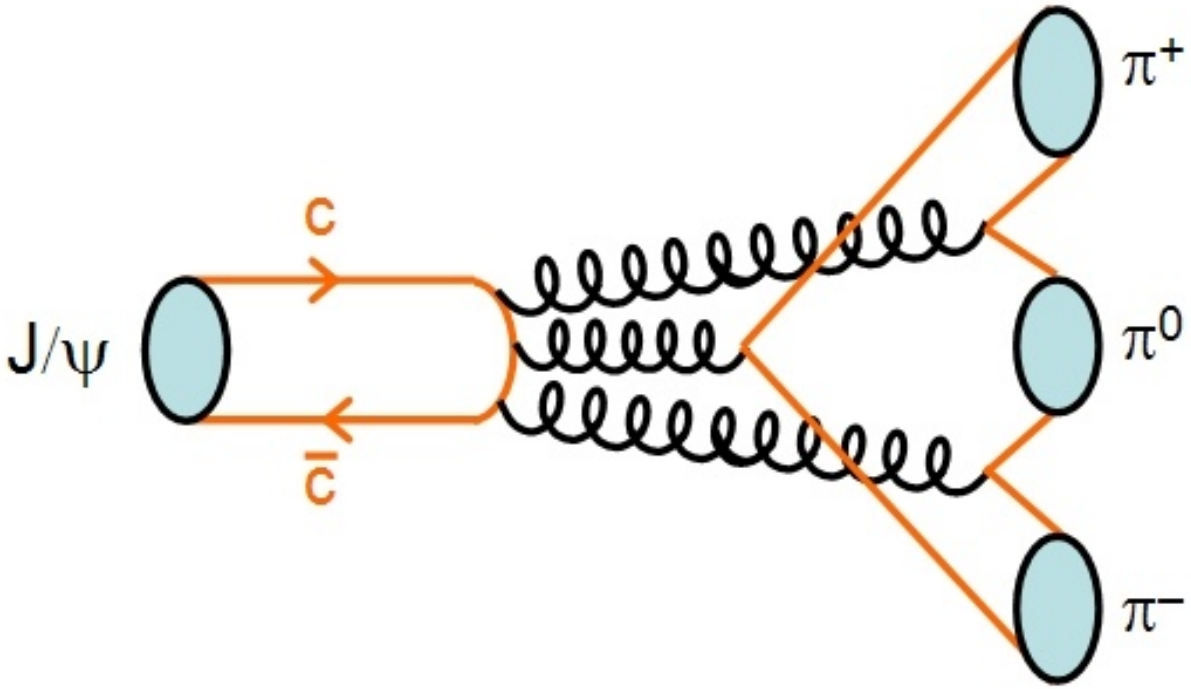

b
$\overline{b}$

Quarkonia

- Bound state of a heavy quark (c, b) and its corresponding antiquark
- Produced in early stages of the collision
- Focus on Υ mesons - S states (L = 0) of bottomonia ($b\bar{b}$)
- 3 Υ states below the open beauty threshold

$$m_{b\bar{b}} < 2m_{B^+} \doteq 2 \cdot 5,28 \mathrm{GeV/c}^2$$

Quarkonium decay



- $m_{\Upsilon(1S)} \simeq 9.46\ \mathrm{GeV/c^2}$, $\mathrm{BR_{ee}(1S)} = 2.38 \pm 0.11\%$
- $m_{\Upsilon(2S)} \simeq 10.02\ \mathrm{GeV/c^2}$, $\mathrm{BR_{ee}(2S)} = 1.91 \pm 0.16\%$
- $m_{\Upsilon(3S)} \simeq 10.35\ \mathrm{GeV/c^2}$, $\mathrm{BR_{ee}(3S)} = 2.18 \pm 0.20\%$

[Phys. Rev. D 98, 030001 (2018)]

Quarkonium production

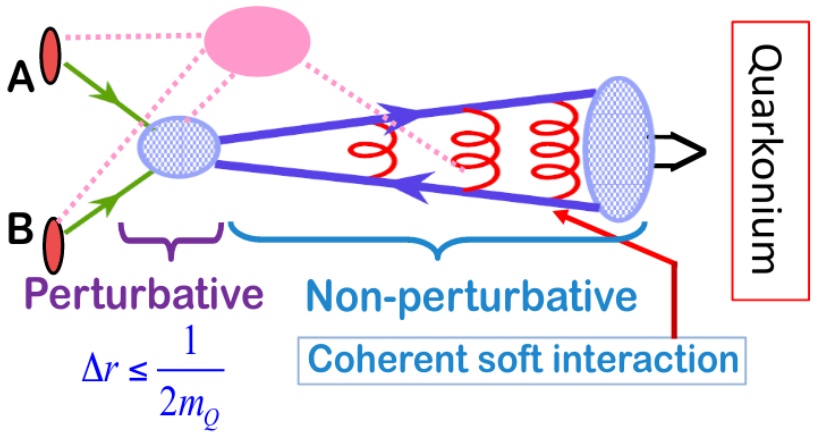
- Quarkonium production mechanism - hard scattering and non-perturbative hadronisation

- Several production models:
  - Colour singlet

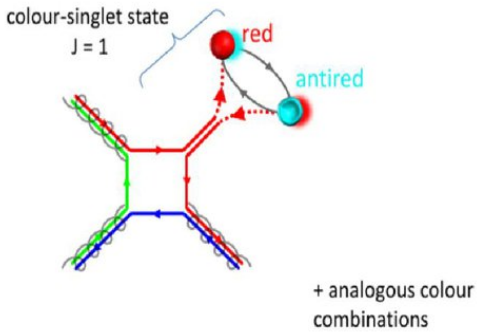
    [Nuc. Phys. B 172, 425-434]
  - Colour octet

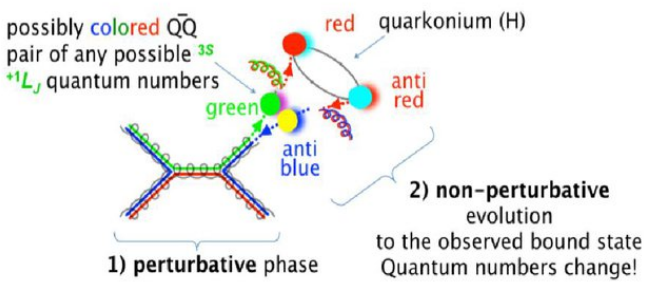
    [Phys. Rev. D 46, R3703(R)]
  - Colour evaporation

    [Phys. Lett. B 47 2, 217-221]



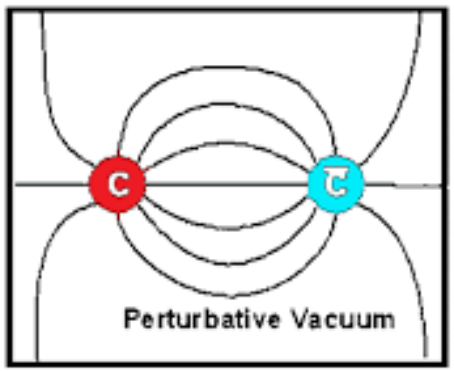
- Possible production in multiple parton interactions (MPIs)

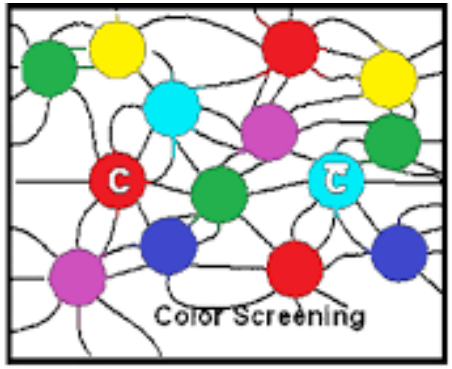




Effects on quarkonia

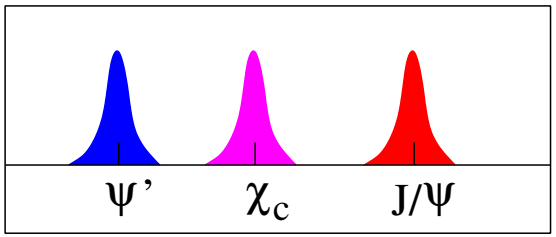
- Dissociation in QGP at high T via Debeye-like screening
  [Phys. Lett. B 178 4]
  - Heavier states dissociate at lower T
  - Sequential suppression of states
    *[Phys. Rev. Lett. **109**, 222031]*
- Feed-down from excited states



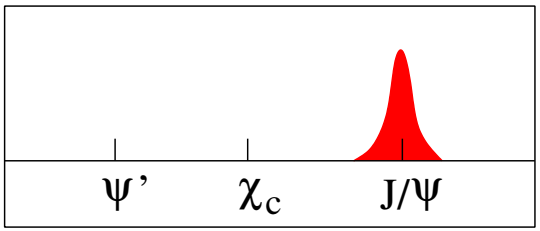


- Regeneration
  [Phys. Rev. C 96, 054901]
  - Small for Υ at RHIC energies (small production cross section - $\sim$100 pb)
- Cold nuclear matter (CNM) effects *[Eur. Phys. J. C **76**, 107]*
  - Nuclear absorption
  - Comover interactions
  - Nuclear PDF effects

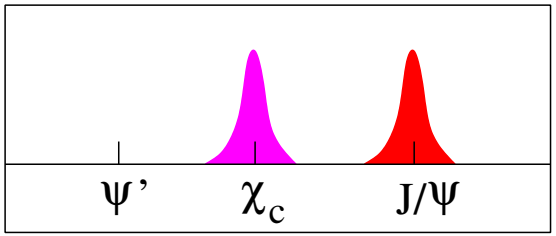
Sequential suppression



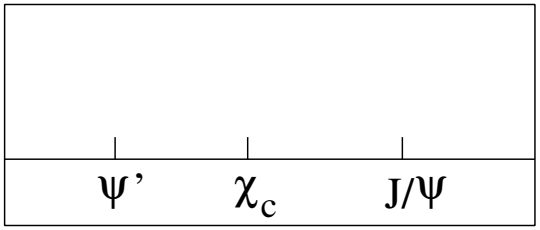
$T < T_c$



$T_\chi < T < T_\psi$

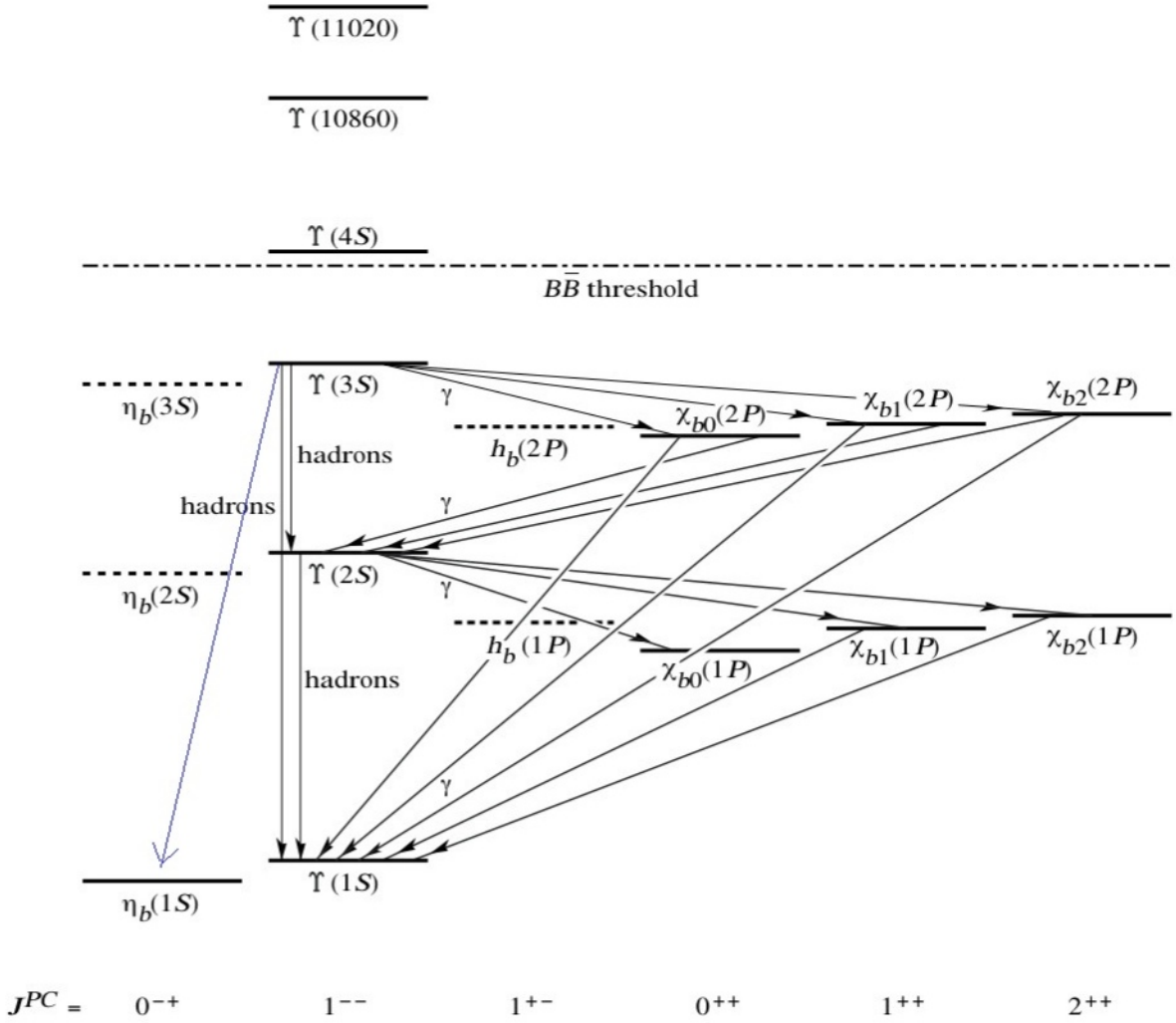


$T_{\psi'} < T < T_\chi$



$T > T_\psi$

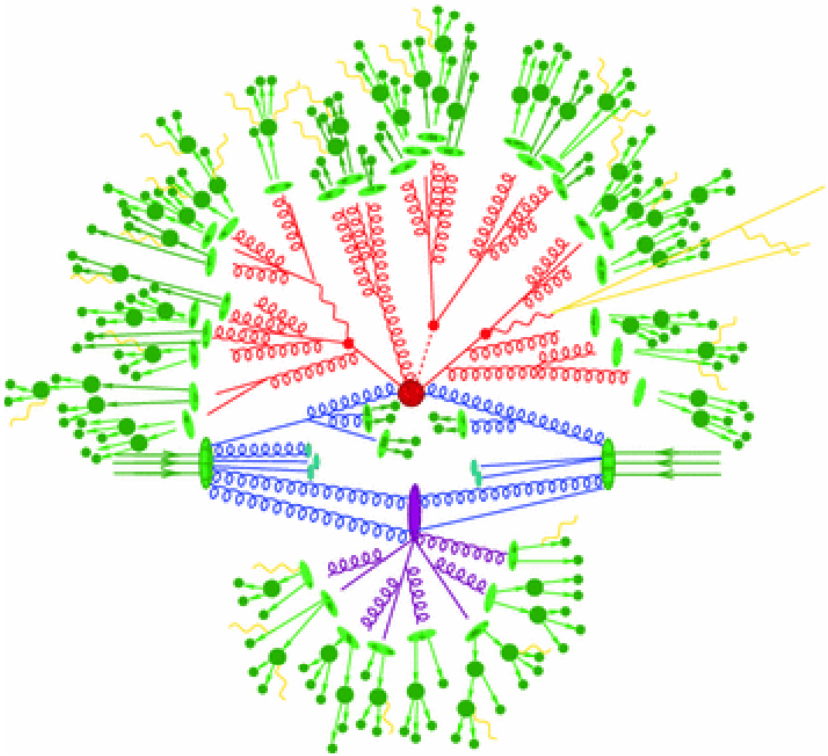
Feed-down effect

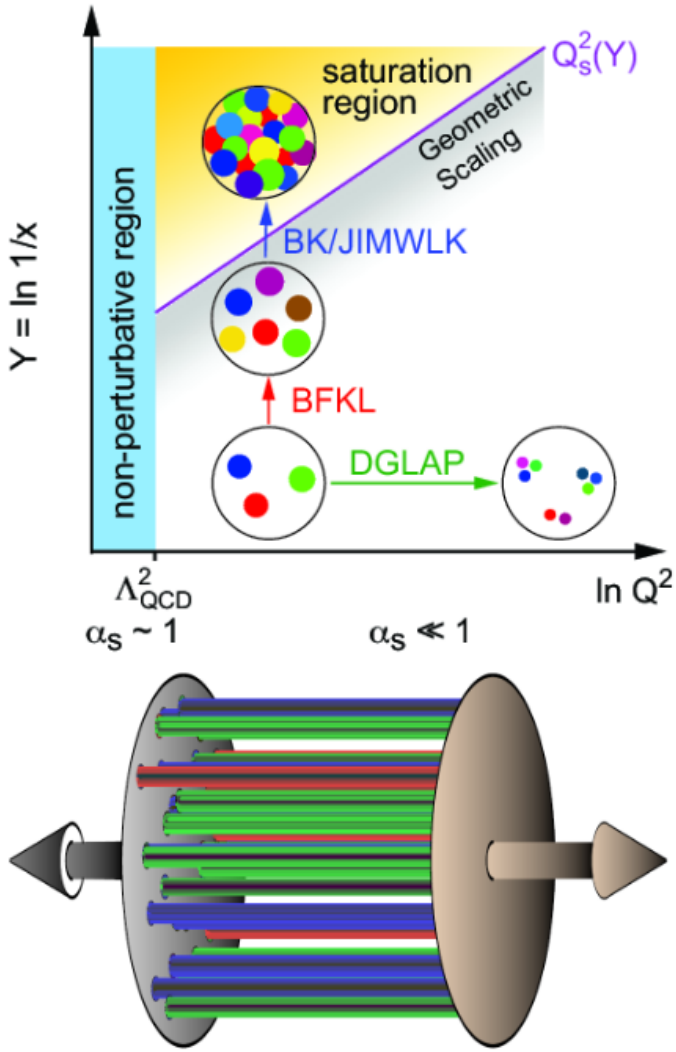


Motivation

- Υ p and p_{T} spectra - production mechanism (comparison of spectra to model calculations)
- Υ states ratios - production mechanisms and comover interactions
- **Normalised charged particle multiplicity dependence** - main aim of study ($N_{\Upsilon} \sim N_{\mathrm{MPI}}$, $N_{\mathrm{ch}} \sim$ energy density)
  - MPI influence on Υ production
- Small interacting systems study - possible CGC influence?

Motivation




saturation
region
$Q_s^2(Y)$
Geometric
Scaling
BK/JIMWLK
BFKL
DGLAP
non-perturbative region
Y = ln 1/x
Λ^2_{QCD}
ln Q^2
$\alpha_s \sim 1$
$\alpha_s \ll 1$

Normalised multiplicity dependence

Experimental observable $N_\Upsilon / \langle N_\Upsilon \rangle$ defined as:

$$N_\Upsilon / \langle N_\Upsilon \rangle = (N_{\mathrm{MB}} / N_{\mathrm{MB}}^{\mathrm{bin}})(N_\Upsilon^{\mathrm{bin}} / N_\Upsilon) \tag{1}$$

$N_{\mathrm{ch}} / \langle N_{\mathrm{ch}} \rangle$ ... self-normalised particle multiplicity

N_Υ ... total number of events containing Upsilon meson

$N_\Upsilon^{\mathrm{bin}}$ ... number of Upsilon events in corresponding multiplicity bin

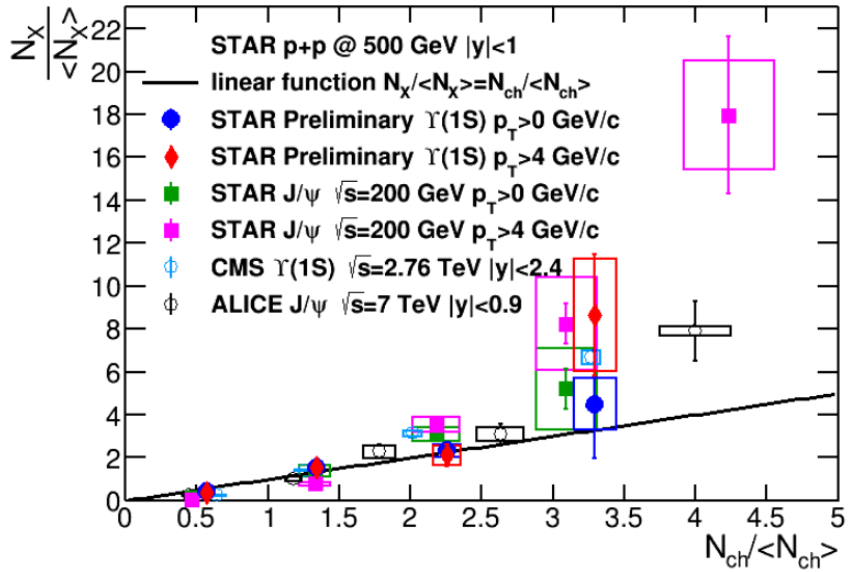
N_{MB} ... total number of minimum bias (MB) events

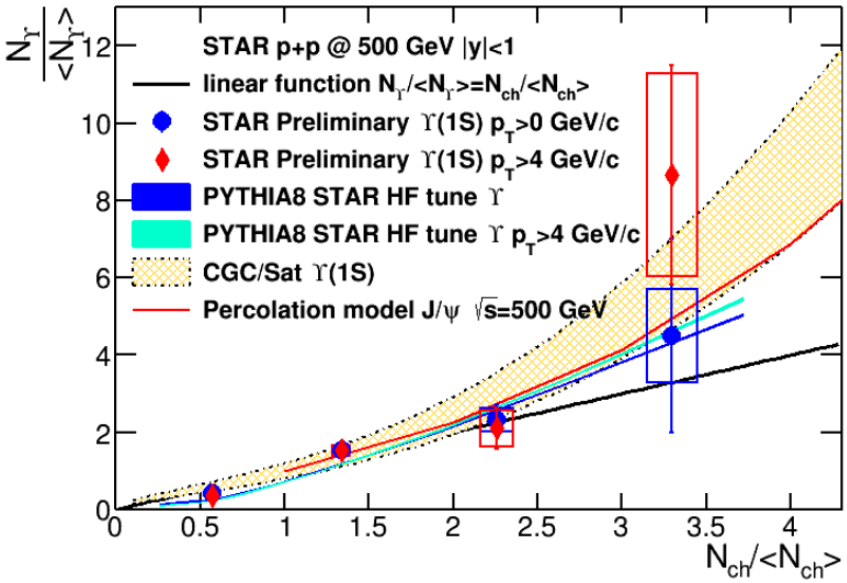
$N_{\mathrm{MB}}^{\mathrm{bin}}$ ... number of MB events in corresponding $N_{\mathrm{ch}} / \langle N_{\mathrm{ch}} \rangle$ bin

Previous results

- Preliminary results from STAR experiment available (Run11) - now 10x more data
- Previous results show stronger than linear increase in normalised charged particle multiplicity dependence

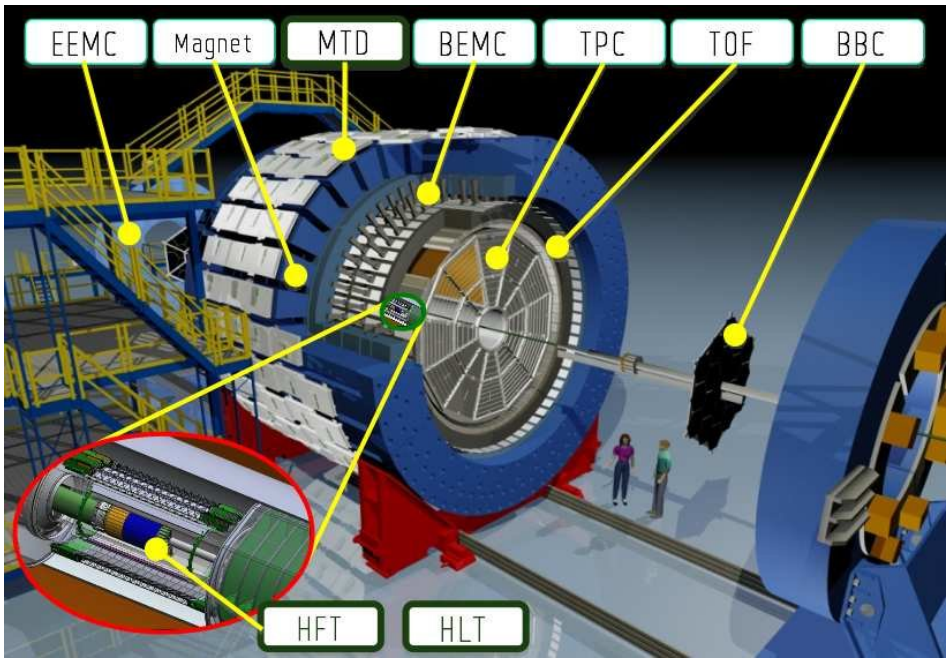
[L. Kosarzewski, PoS ICHEP2020 (2021) 545]





STAR detector

- Experiment at the RHIC in BNL
- Intended primarily for QGP study
- Composed of many sub-detectors:
  - Time Projection Chamber (TPC)
    - ★ Track momentum & PID
  - Time of Flight (TOF)
    - ★ PID
  - Barrel Electromagnetic Calorimeter (BEMC)
    - ★ high-p_{T} e/γ energy
    - ★ BHT trigger for high-p_{T} electrons



- STAR acceptance at the time of the run $|\eta| < 1, 0 < \varphi < 2\pi$

Data

- p+p collisions at $\sqrt{s} = 510$ GeV, Run17, recorded by the STAR detector
- Approximately 450 million BHT2 triggered events (2.9 billion total recorded)
- Previously available version of the reconstructed data missing BEMC information
  - Newly reconstructed data includes BEMC information
  - Reconstruction not finished in time to analyse the new version and implement BEMC cuts
- Improved precision over previously analysed data (Run11)
- Integrated luminosity of Run17 BHT2*BBCMB triggered data $\mathcal{L} \sim 340$ pb^{-1} (Run11 triggered data $\mathcal{L} \sim 21.5$ pb^{-1})

Methodology

- Event selection
- Track selection
- Event multiplicity (TofMult) measurement
- Electron/positron ID via TPC and BEMC - BEMC not included in the current version of the analysis
- Υ candidate reconstruction (dielectron channel)
- Signal extraction, analysis, ... - work in progress
- Algorithm successfully tested on J/ψ ($m_{J/\psi} \doteq 3.1$ GeV/c^2) signal

[Phys. Rev. D 98, 030001 (2018)]

Cuts

Event selection

- $|v_z| < 40$ cm
- BHT2*BBCMB trigger

Track selection

- nHitsFit ≥ 20
- nHitsRatio $> .52$
- $p_{\mathrm{T}} > 200$ MeV/c
- DCA to primary vertex < 3 cm

Electron selection

- $-3 < n\sigma_e < 3$
- $E_{\mathrm{TOW}}/E_{\mathrm{CLU}} > 0.5$
- $0.5 < E_{\mathrm{CLU}}/p < 1.5$

TofMult

- nHitsFit ≥ 15
- $|\eta| < 1$
- $p_{\mathrm{T}} > 200$ MeV/c
- DCA to primary vertex $< .5$ cm
- track matched to TOF

Event selection

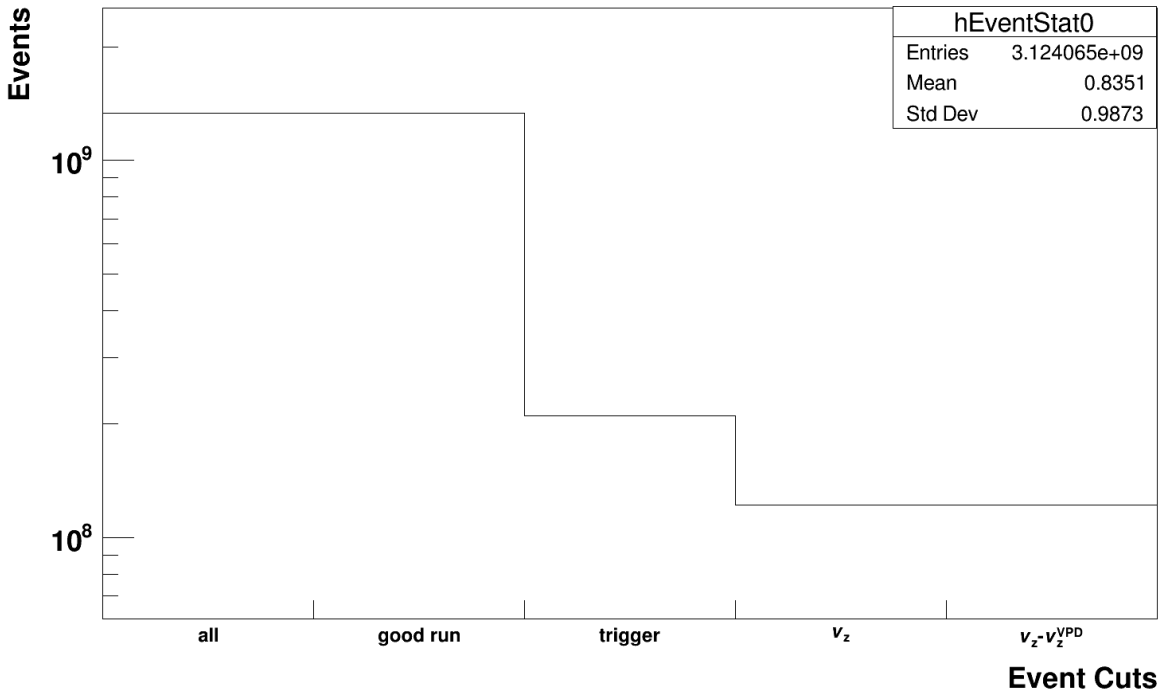


Figure 1: Number of accepted events in the stages of event selection (from left to right: before any cuts, after bad run removal, after trigger condition application, after v_z cut and after $v_z - v_z^{\mathrm{VPD}}$ cut).

TofMult

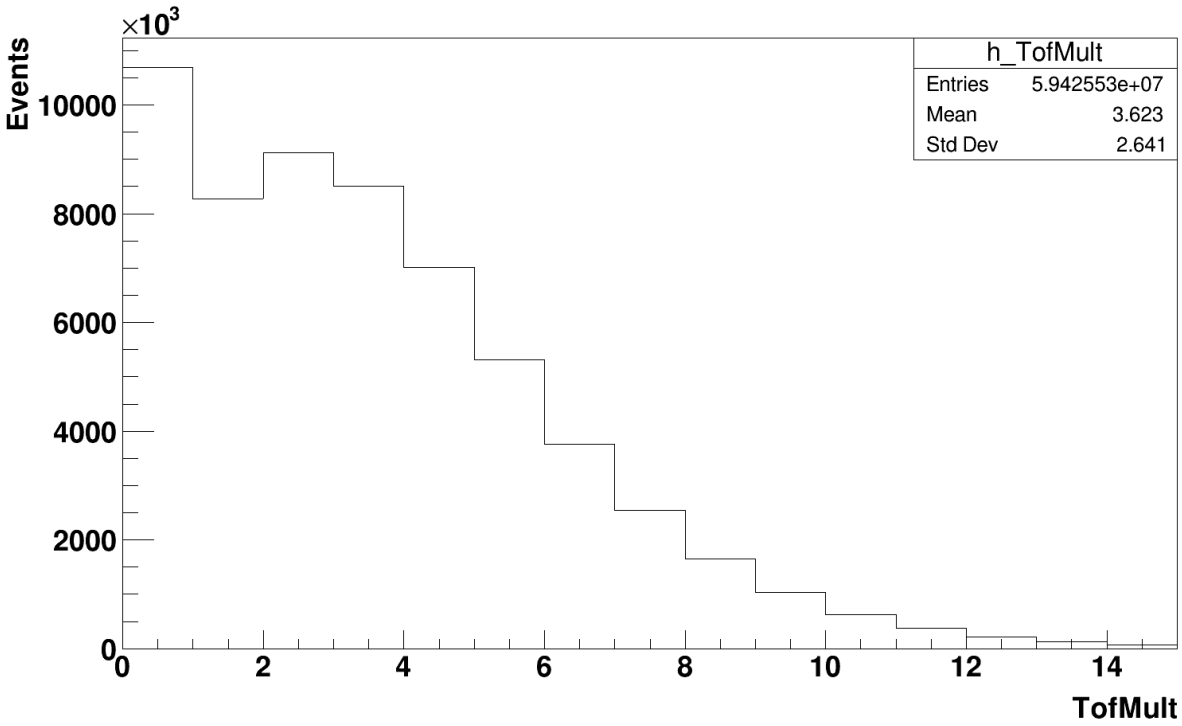


Figure 2: *TofMult* - TOF matched charged particle multiplicity spectrum.

$n\sigma_e$ and $n\sigma_\pi$

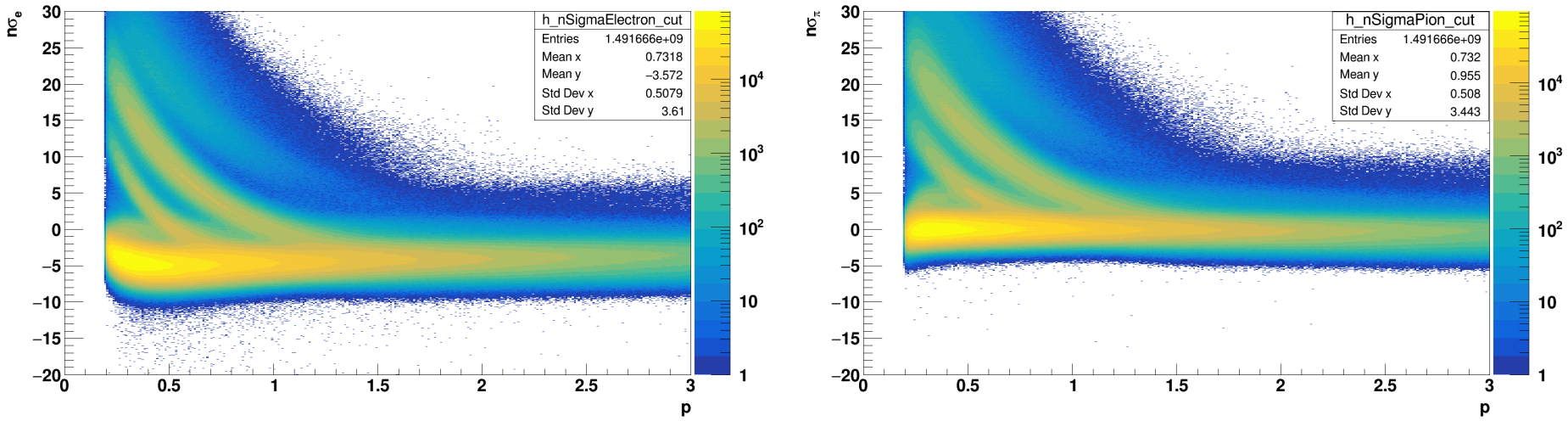


Figure 3: $n\sigma$ of electrons (left) and pions (right) with regards to track momentum.

$$n\sigma_{\text{particle}} = \ln\left(\frac{\mathrm{d}E/\mathrm{d}x}{\mathrm{d}E/\mathrm{d}x|_{\text{expected}}}\right)/\sigma_{\text{TPC}}$$

- $\mathrm{d}E/\mathrm{d}x$ measured energy loss
- $\mathrm{d}E/\mathrm{d}x|_{\text{expected}}$ expected value (Bichsel)
- σ_{TPC} TPC energy loss resolution

Upsilon candidate reconstruction

$$m_{ee} = \sqrt{(E_1 + E_2)^2 - (\vec{p_1} + \vec{p_2})^2}, \tag{2}$$

- Electrons/positrons passing cuts selected and combined into pairs
- Candidates reconstructed using Lorentz momentum 4-vector addition
- Two invariant mass spectra of reconstructed candidates produced:
  - Unlike-sign (e^+e^-): should include signal + background
  - Like-sign (e^-e^- & e^+e^+): reasonable approximation of combinatorial background

J/ψ test

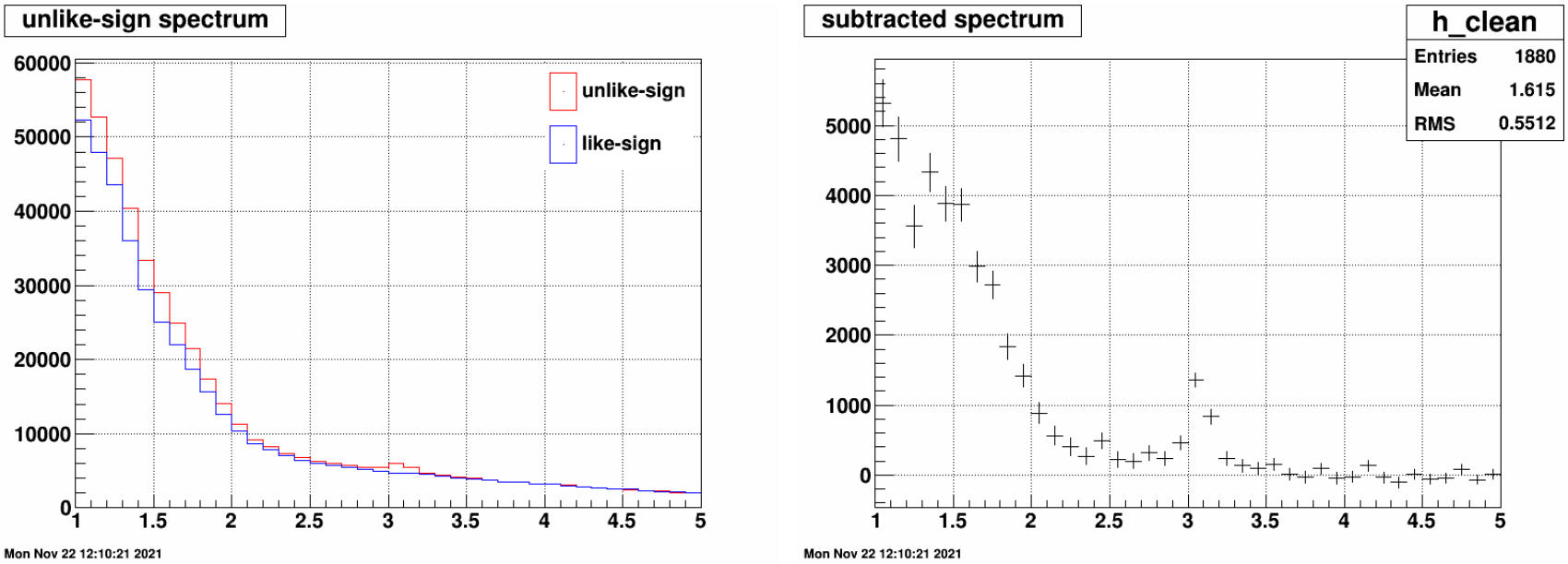


Figure 4: Invariant mass spectrum of: left: unlike-sign (red) and like-sign (blue) reconstructed J/ψ candidate; right: unlike-sign reconstructed J/ψ candidates with like-sign candidates subtracted.

Results

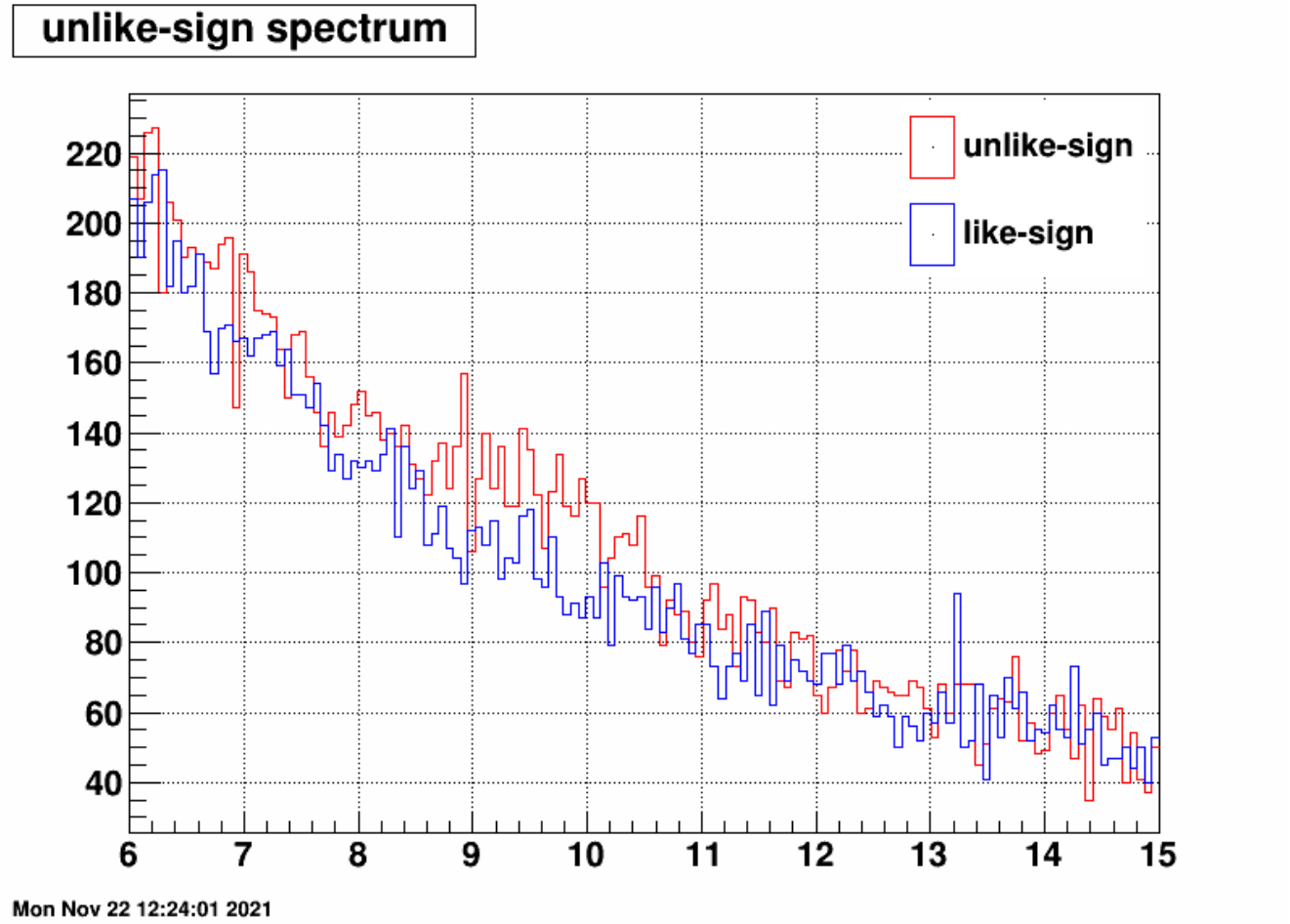


Figure 5: Invariant mass spectrum of unlike-sign (red) and like-sign (blue) reconstructed candidates.

Dataset reproduction

- Missing BEMC information reported to the STAR collaboration - dataset scheduled for reproduction
- Author involved in the validation of the quality of the reproduced data
- Testing performed on a small subset of the data, which was made available for this purpose
- With the help of the QA work done, the entire dataset has been fully reproduced and contains BEMC information

Dataset reproduction

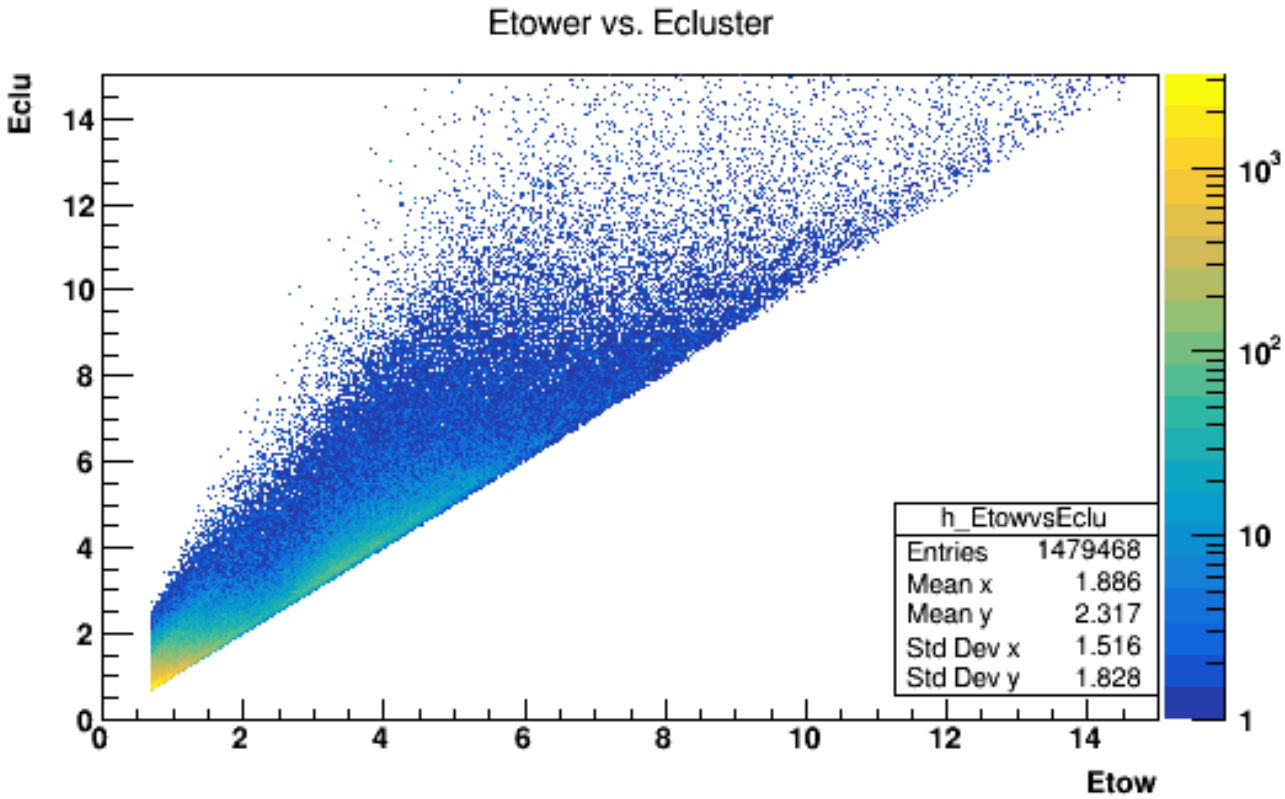


Figure 6: Distribution of BEMC tower energy E_{TOW} and cluster energy E_{CLU} obtained during reconstruction QA.

Dataset reproduction

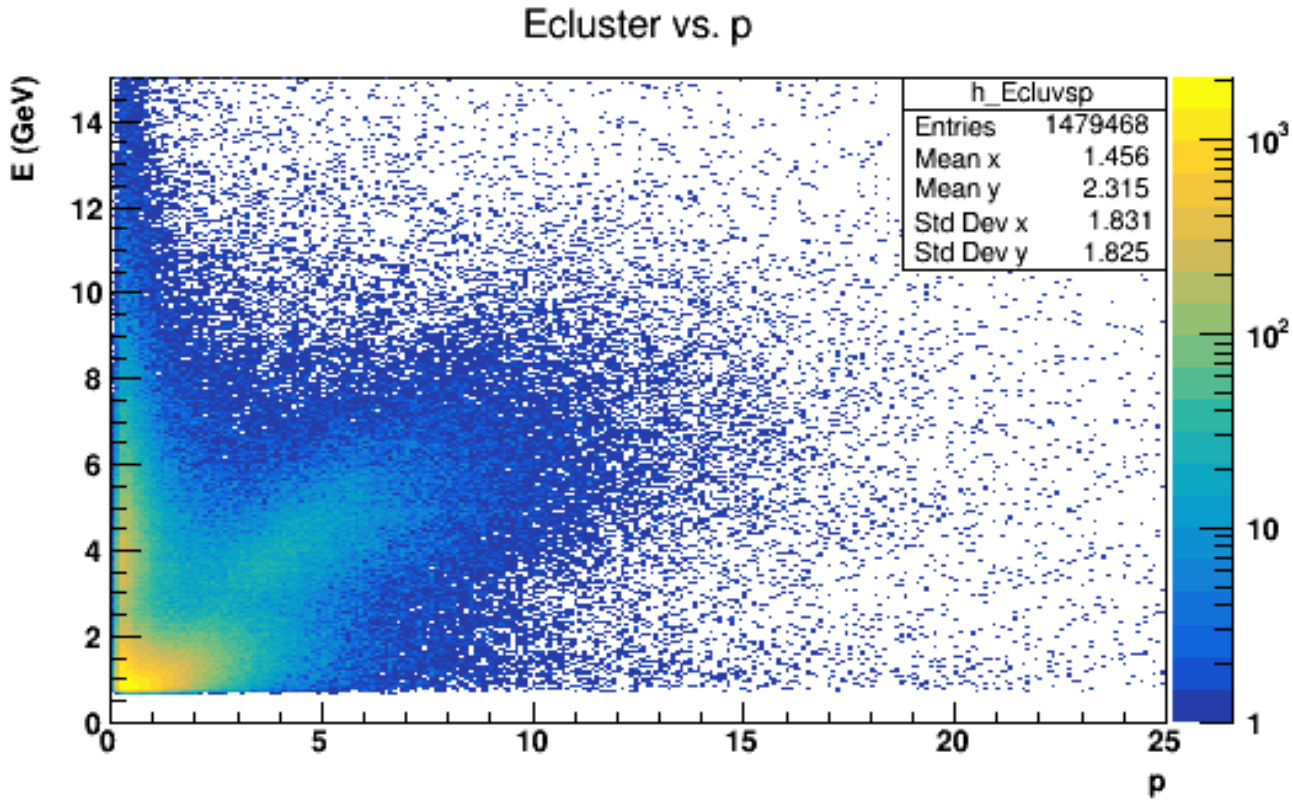


Figure 7: Distribution of BEMC cluster energy E_{CLU} and track momentum p obtained during reconstruction QA.

PYTHIA study

- Detailed Monte Carlo study performed by PYTHIA 8.240 (based on the study done for my Bc. thesis)
- Normalised quarkonium yield in dependence on charged particle multiplicity
- Separate data for inclusive, direct and feed-down originated $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ states
- Auto-correlation effects (electrons contribute to measured N_{ch}, gluons produced in NRQCD process (1 for CS, 2 for CO)
  *[Eur. Phys. J. C **79**, 36 (2019)]*

PYTHIA study

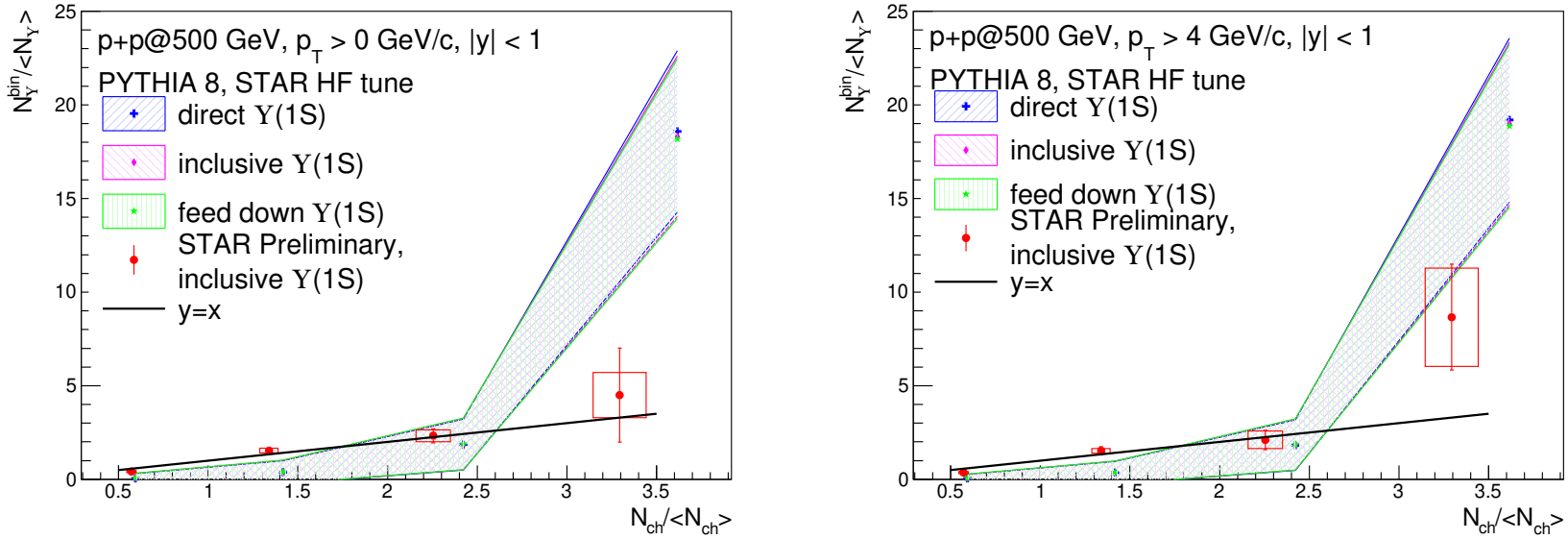


Figure 8: Normalised Υ meson yield dependence on charged particle multiplicity for direct, inclusive and non-direct $\Upsilon(1S)$ state for PYTHIA compared to STAR preliminary data. Left: integrated p_{T}, right: $p_{\mathrm{T}} > 4$ GeV/c.

PYTHIA study

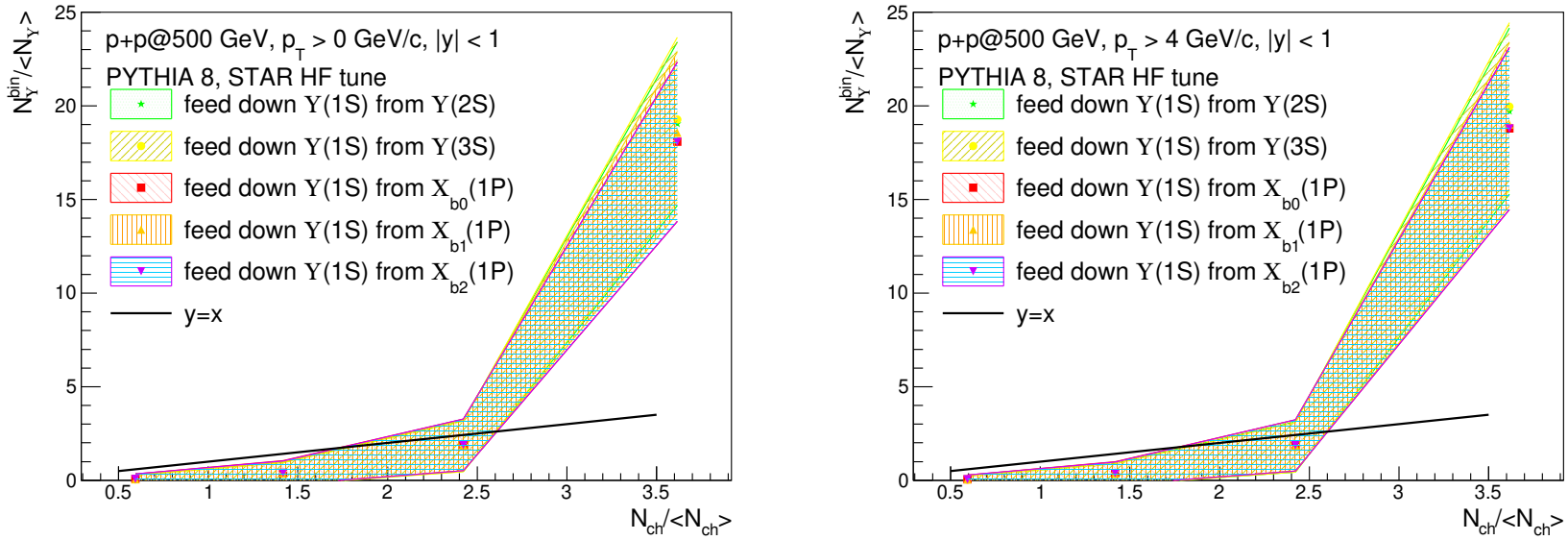


Figure 9: Normalised Υ meson yield dependence on charged particle multiplicity for non-direct $\Upsilon(1S)$ state for PYTHIA. The data is separated by the state, from which the measured Υ originated. Left: integrated p_{T}, right: $p_{\mathrm{T}} > 4$ GeV/c.

PYTHIA study

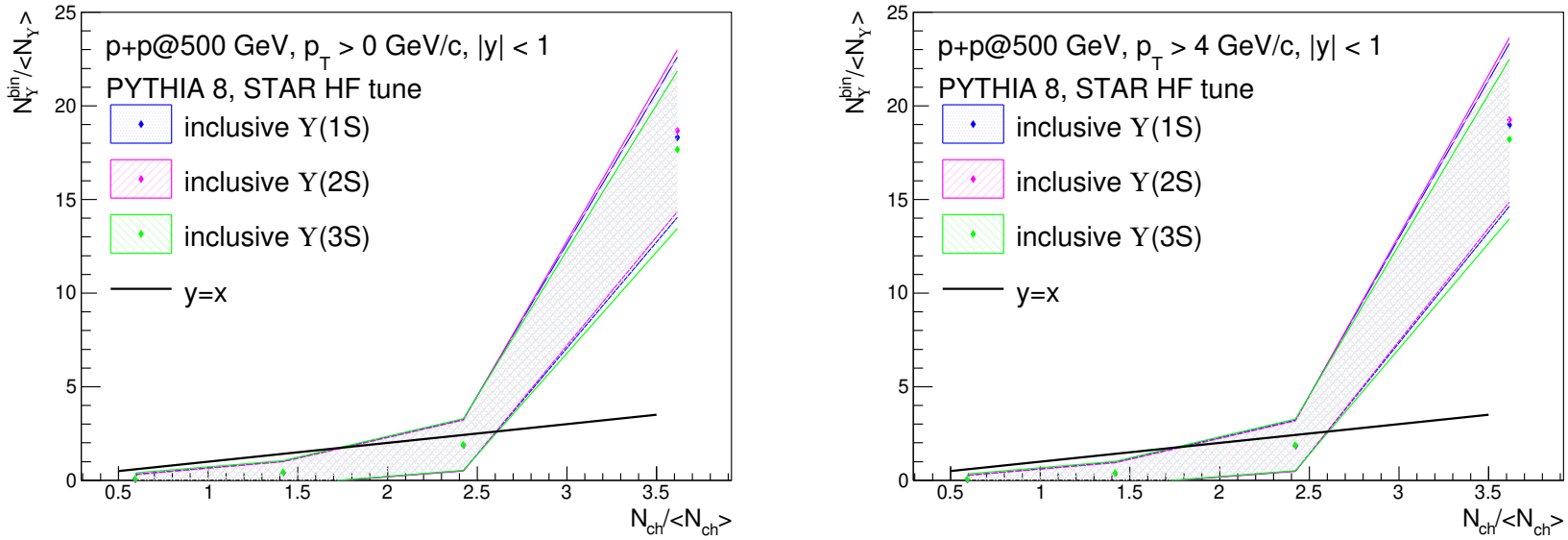


Figure 10: Normalised Υ meson yield dependence on charged particle multiplicity for inclusive Υ(1S), Υ(2S) and Υ(3S) states for PYTHIA compared to STAR preliminary data. Left: integrated p_{T}, right: $p_{\mathrm{T}} > 4$ GeV/c.

Outlook

- Steps up until pair signal extraction implemented
- Signal reconstruction algorithm successfully tested on J/ψ signal - analysis algorithm working properly
- Author involved in data reproduction QA - reproduction successful
- Detailed PYTHIA Monte Carlo study of Υ meson yield performed
  - No difference for Υ states observed
- The work on the analysis can now continue with the newly acquired BEMC information

Thank you for your attention and enjoy the rest of the workshop!

Appendix

dE/dx

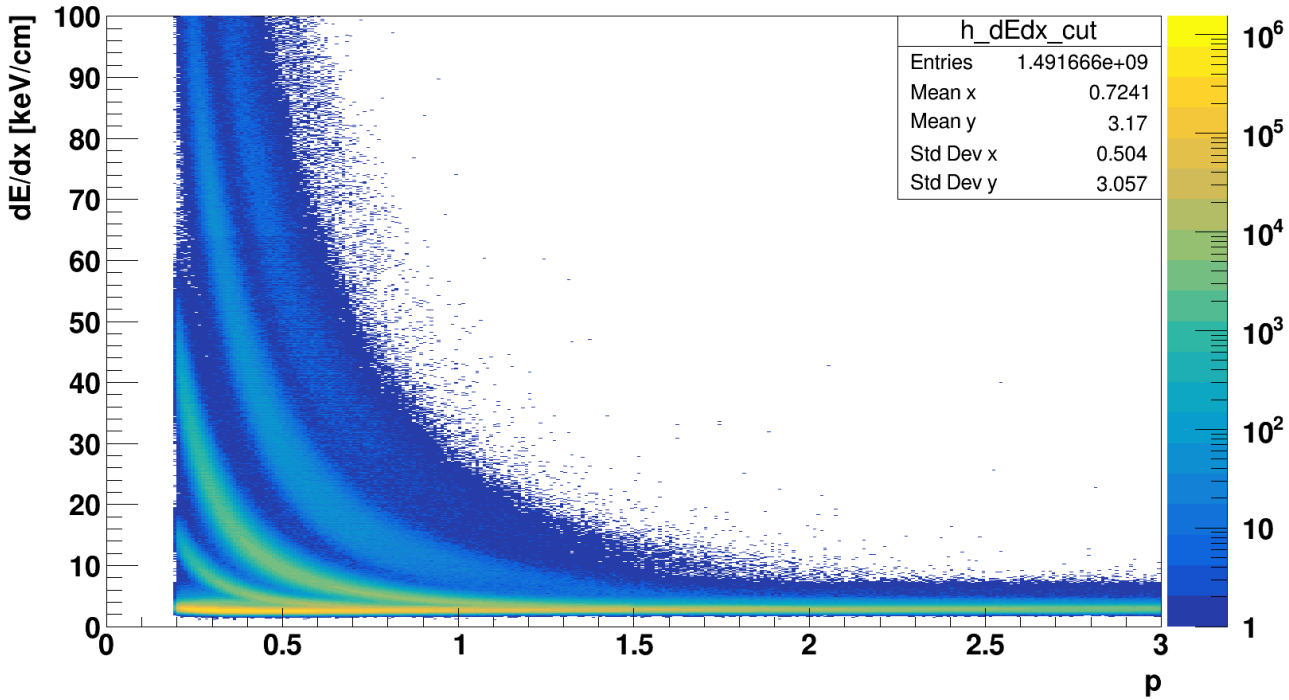


Figure 11: dE/dx distribution with regards to momentum p with track quality cuts applied.