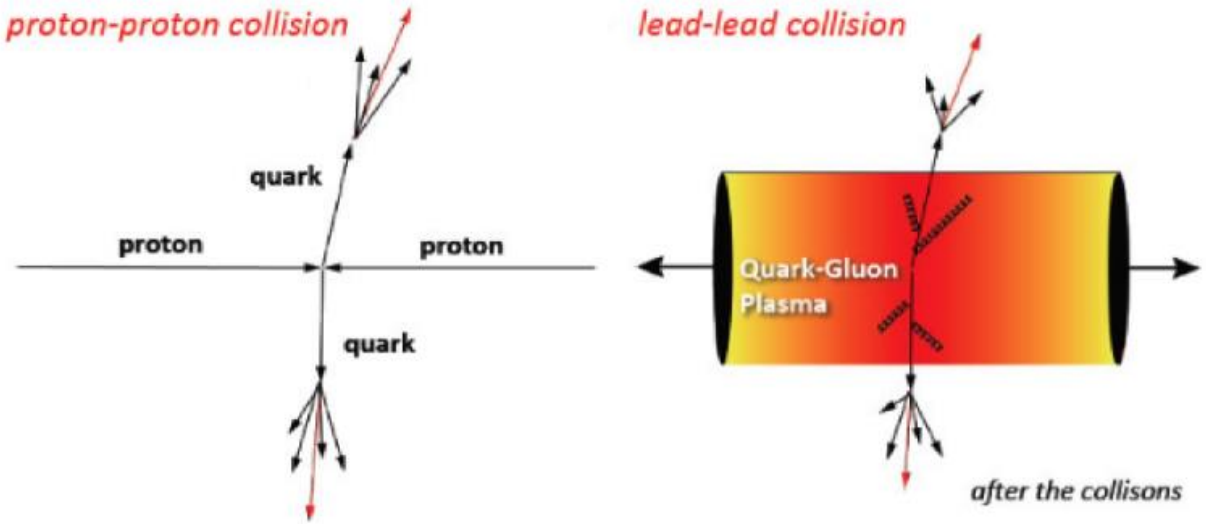
Study of charmonia production in proton-proton and heavy-ion collisions at the LHC

Heavy ion collisions

- Motivation:
  - Phase transition between quarks and gluons and hadrons
  - Study non-perturbative aspects of QCD and collective phenomena connected with the strong interaction
  - Study matter which is similar to the matter present in the early stages of the universe.
- First collisions: LBNL USA and JINR USSR with energies about 1-2GeV per nucleon
- Present experiments: RHIC (2000-), LHC (2010-)

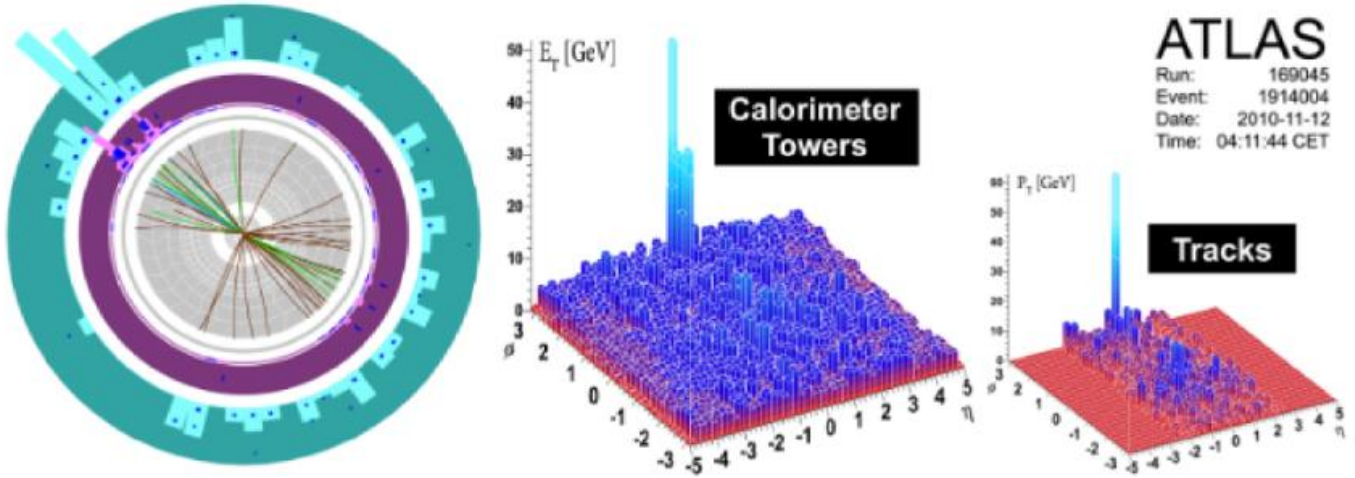
Quark-gluon plasma

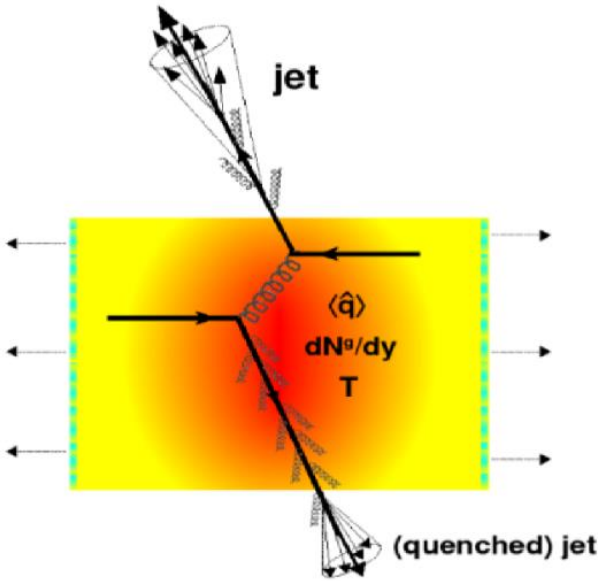
- High temperatures and high pressure-> quarks and gluons not confined in hadrons
- Is most likely not produced in *pp* collisions



Jet quenching

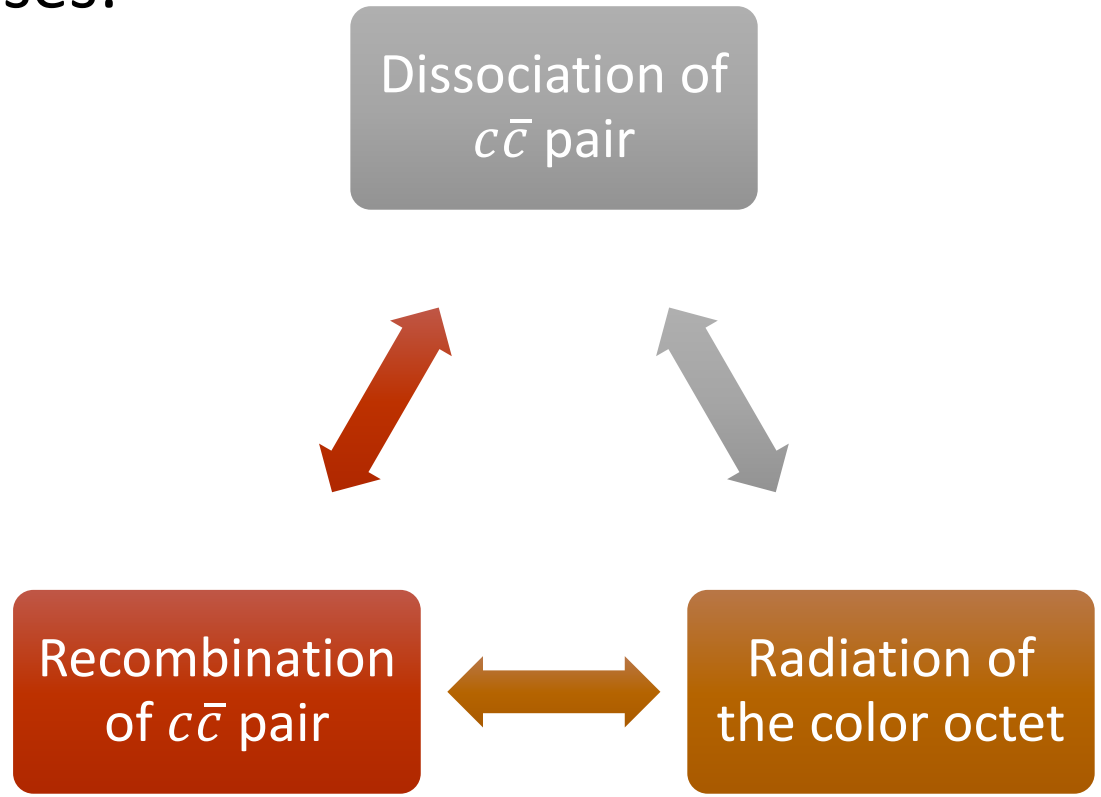
- Collective name for all processes present in jet traversing the QGP
- Energy losses in QGP:
  - Elastic scattering
  - Gluonstrahlung (dominates)





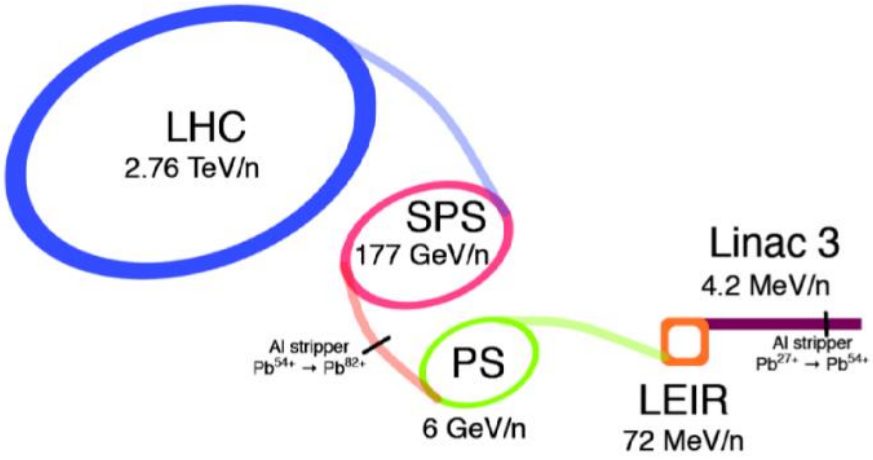
Suppression of charmonia production

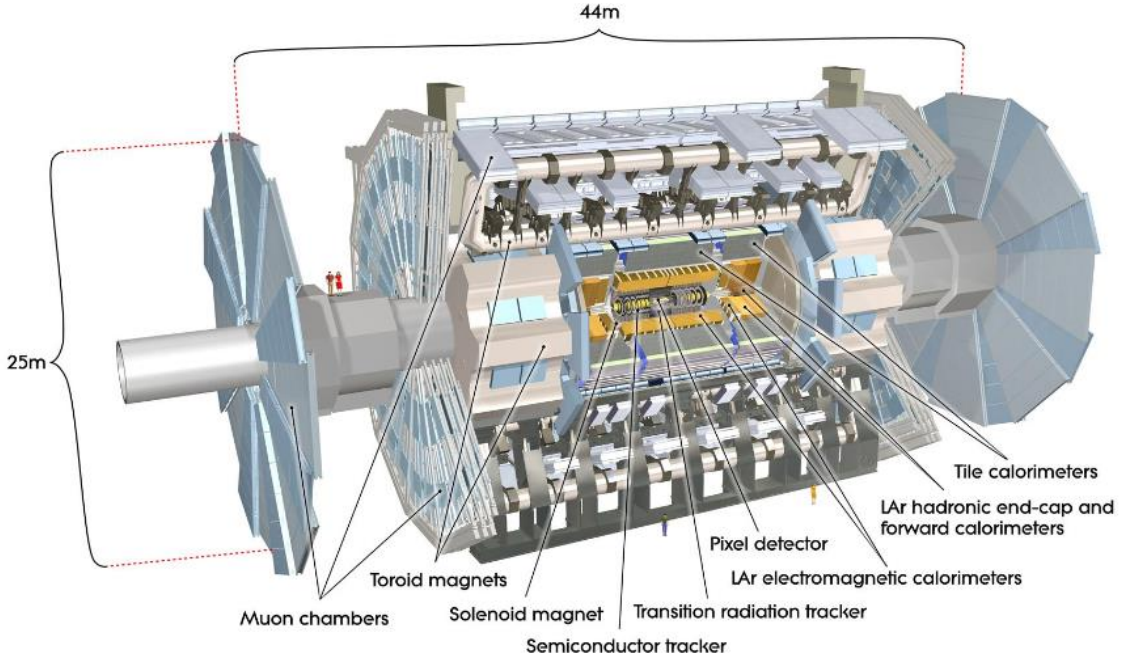
- Charmonia might be used as a tool to study QGP
- Modeled in non-relativistic QCD
- 3 main processes:



Experimental setup

- Pb ion collisions in ATLAS experiment at LHC in CERN





- Injector circuit for heavy ions at LHC
- First collisions of Pb in November 2011

Detector ATLAS

Motivation

- Study of quark gluon plasma
- New information about hadronization
- Better understanding of charmonia suppression in heavy-ion collisions
- Determine correlation of charmonia production and jet production

PYTHIA MC generator

- PYTHIA
  - MC generator of high-energy particle physics
  - Version 8.235 (C++)

- Data:
  - Proton-proton collisions at $\sqrt{s} = 7\ \mathrm{TeV}$ or $\sqrt{s} = 5{,}02\ \mathrm{TeV}$
  - 10^6events
  - Only $J/\psi \rightarrow \mu^+ + \mu^-$ decay channel allowed

Jet kinematics

- Jet reconstruction was done using FastJet library
- Jet anti-k_T algorithm
- Jet size in $\eta \times \phi$ space: $\Delta R < 0{,}4$

$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$

- As protojets, we have used all stable particles except muons and neutrinos
- Jet selection rules: $p_T \geq 5$ GeV

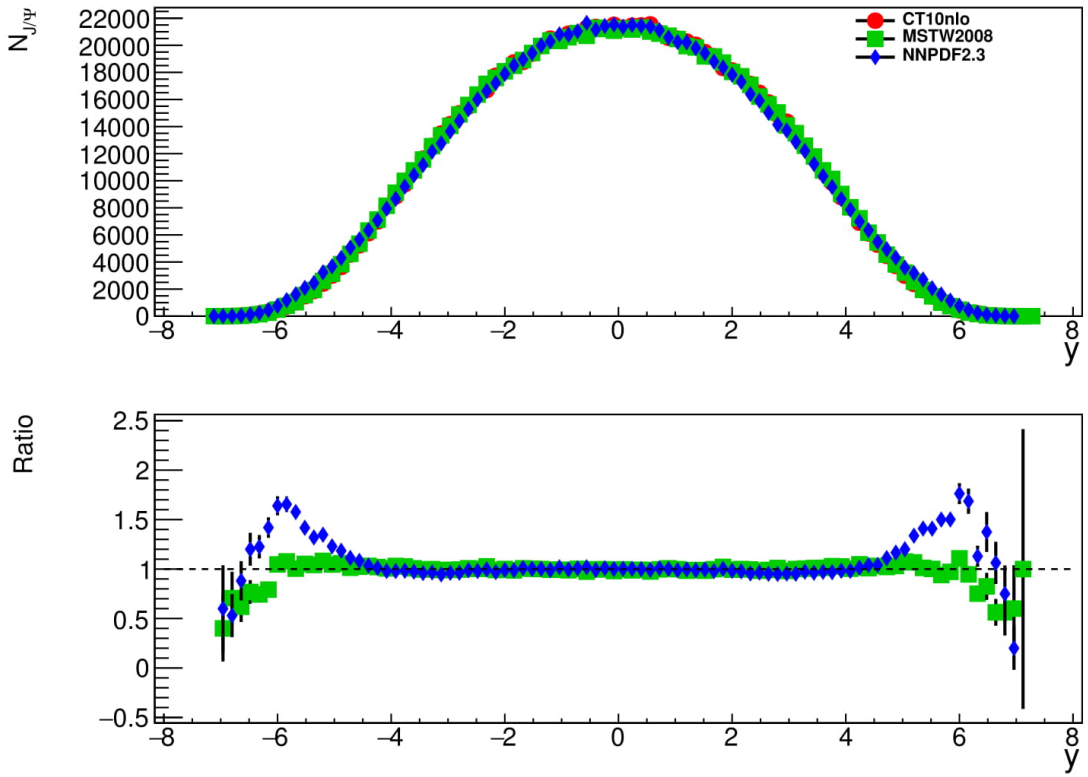
ATLAS data

- Collected between 19.-24.11. 2015 (ATLAS detector)
- Integrated luminosity: $25\ pb^{-1}$
- CMS energy of the pp collision $\sqrt{s} = 5.02$GeV
- Number of events: 37 634 508
- Dimium trigger selecte only muon pairs with the opposite charge sign with $p_T > 4$ GeV
- Muon selection criteria:
  - "Tight working point"
  - $p_T > 4$ GeV, $|\eta| < 2{,}4$
  - pixel hits + pixel dead sensors > 0
  - SCT hits + SCT dead sensors > 4
  - pixel holes + SCT holes < 3

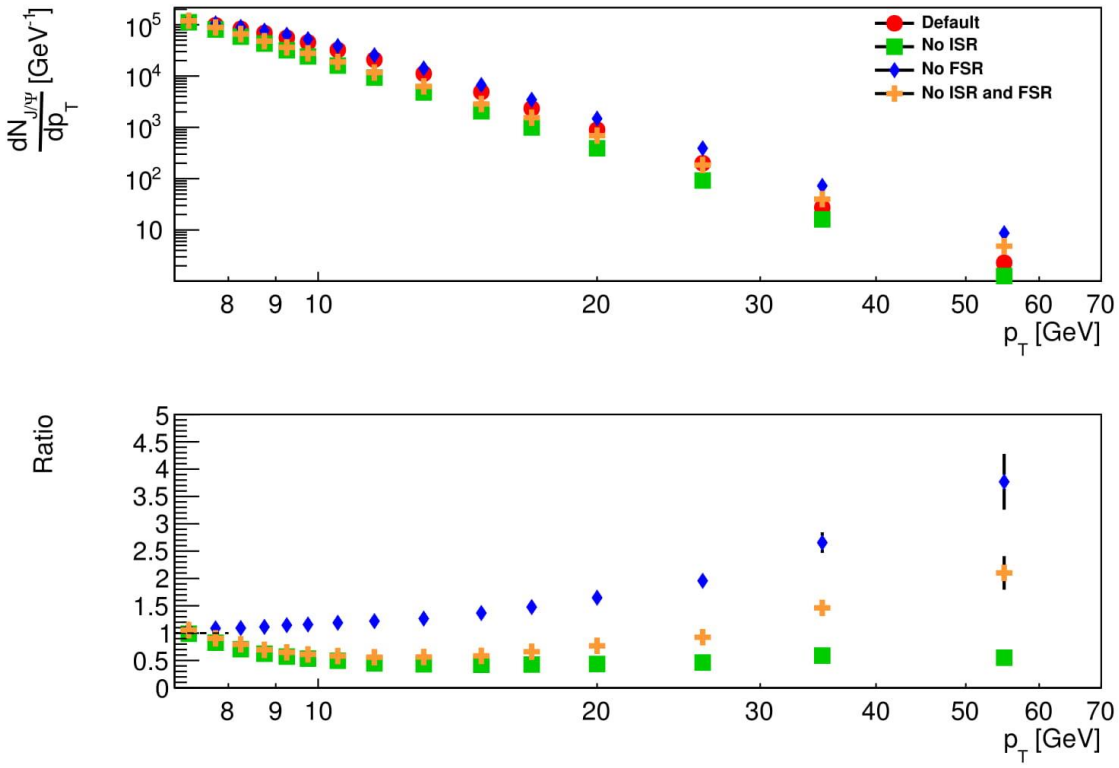
Structure of the thesis

- Tests of program PYTHIA
  - Default settings PYTHIA
  - Impact of *initial state radiation (ISR)* and *final state radiation (FSR)*
  - Impact of parton distribution function sets (PDF)
- Comparison of PYTHIA and ATLAS data
  - Comparison of the cross section
  - Analysis of MC data – comparison of correlation of charmonia and jet production
  - Analysis of ATLAS data - comparison of correlation of charmonia and jet production

Tests of PYTHIA

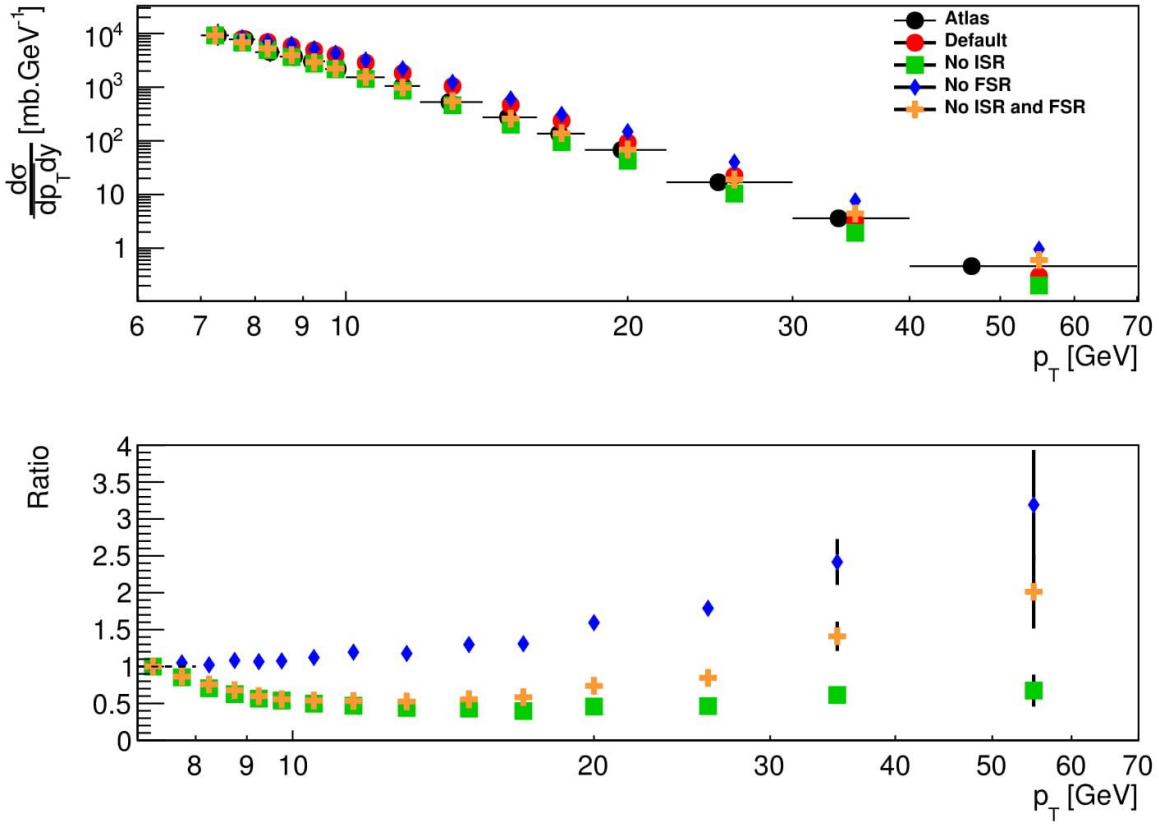


Effect of PDF on rapidity distribution

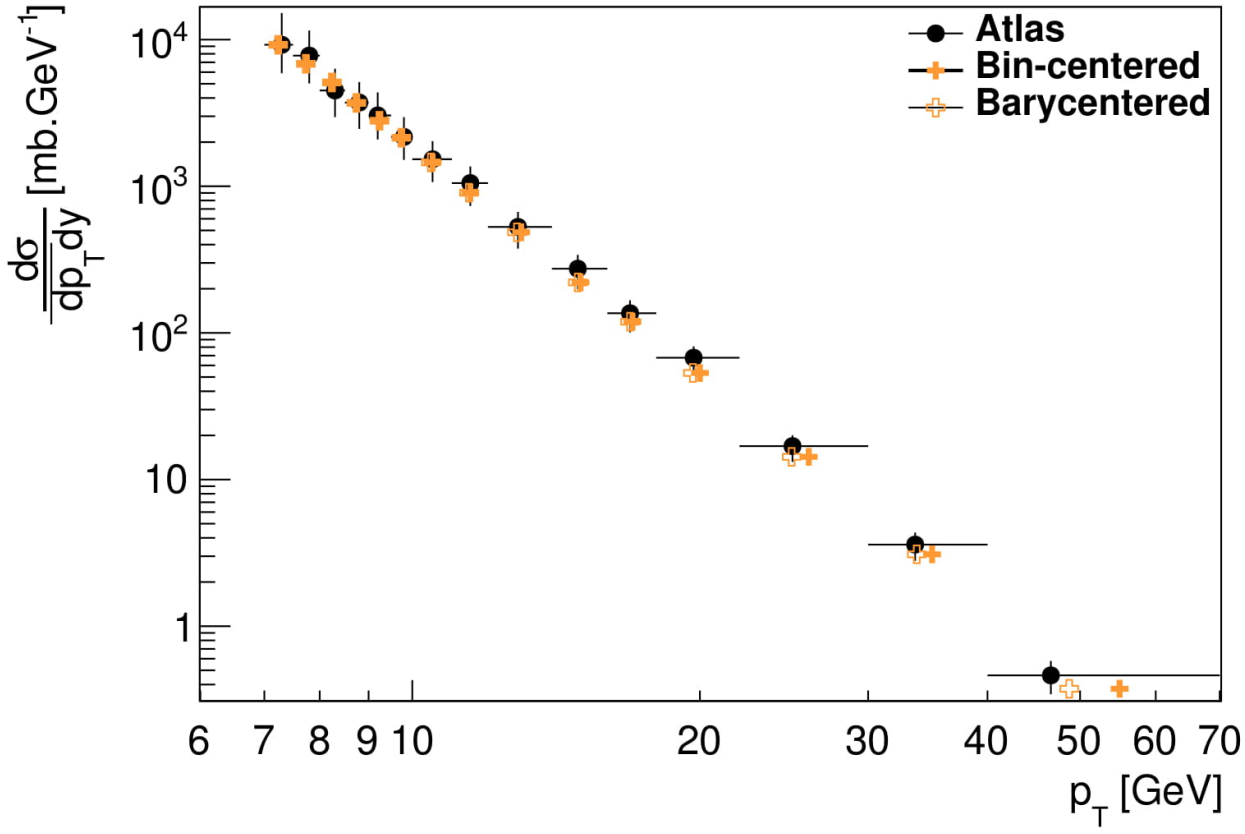


Effect of ISR and FSR on p_T spectrum

Comparison of the cross section with the ATLAS experiment



Different radiation comparison (normalized in 1st bin)



Barycentrum vs bin-centrum

Charmonia in jets

- Defined observables:

$$\rho_{jet} = \frac{N_{jet}^{J/\psi}}{N_{jet}^{all}}$$

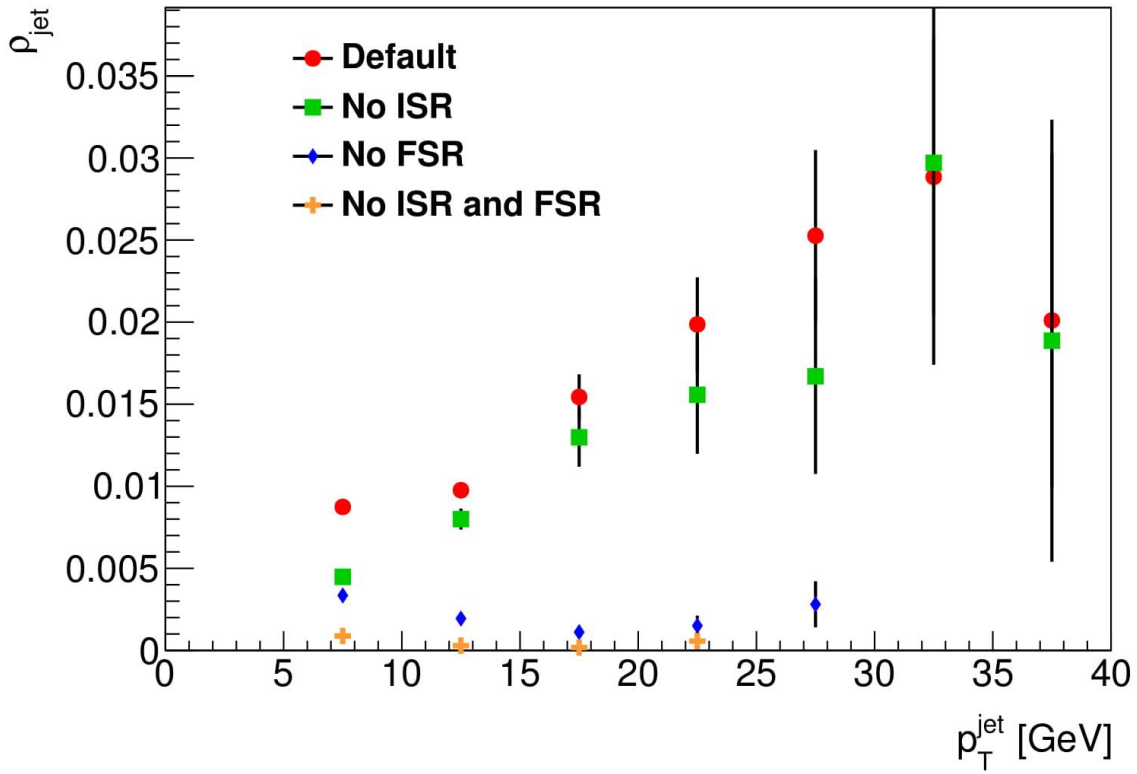
$$\rho_{J/\psi} = \frac{N_{J/\psi}^{jet}}{N_{J/\psi}^{all}}$$

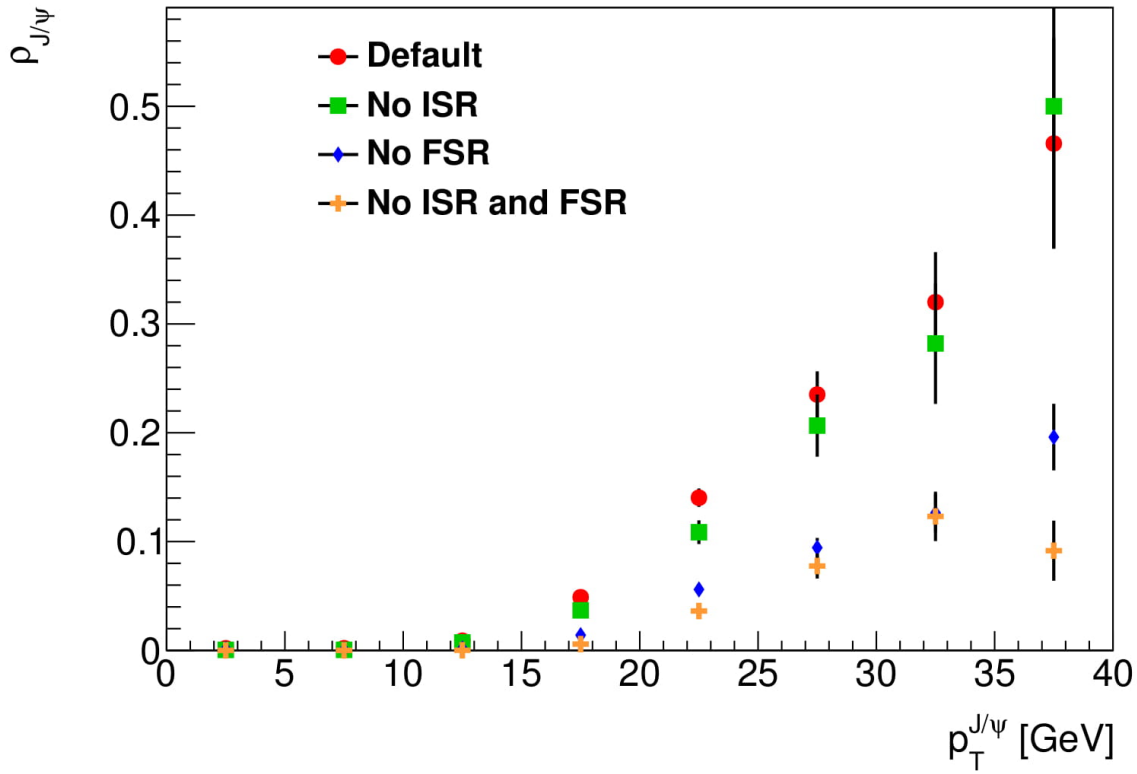
- Note.: Charmonium is associated with jet, when their distance in v $\eta \times \phi$ space is $\Delta R < 0{,}4$ ($\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$).

Correlation of J/ψ and jets

$$\rho_{jet} = \frac{N_{jet}^{J/\psi}}{N_{jet}^{all}}$$

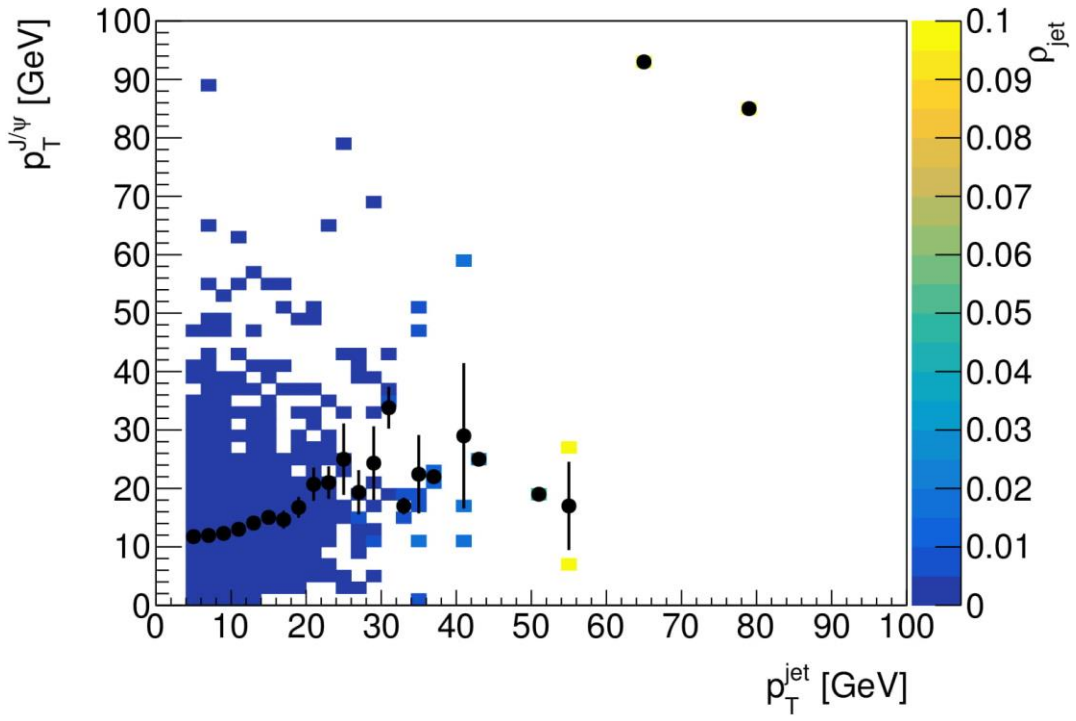
$$\rho_{J/\psi} = \frac{N_{J/\psi}^{jet}}{N_{J/\psi}^{all}}$$



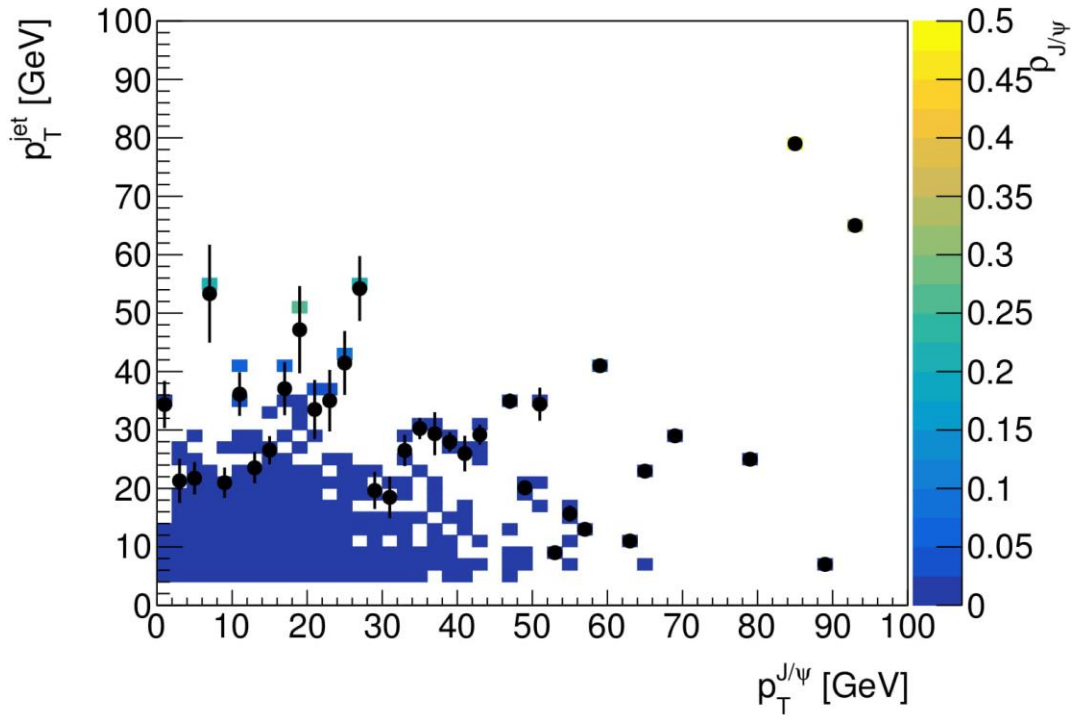


Is there a region with higher correlations?

Default PYTHIA settings



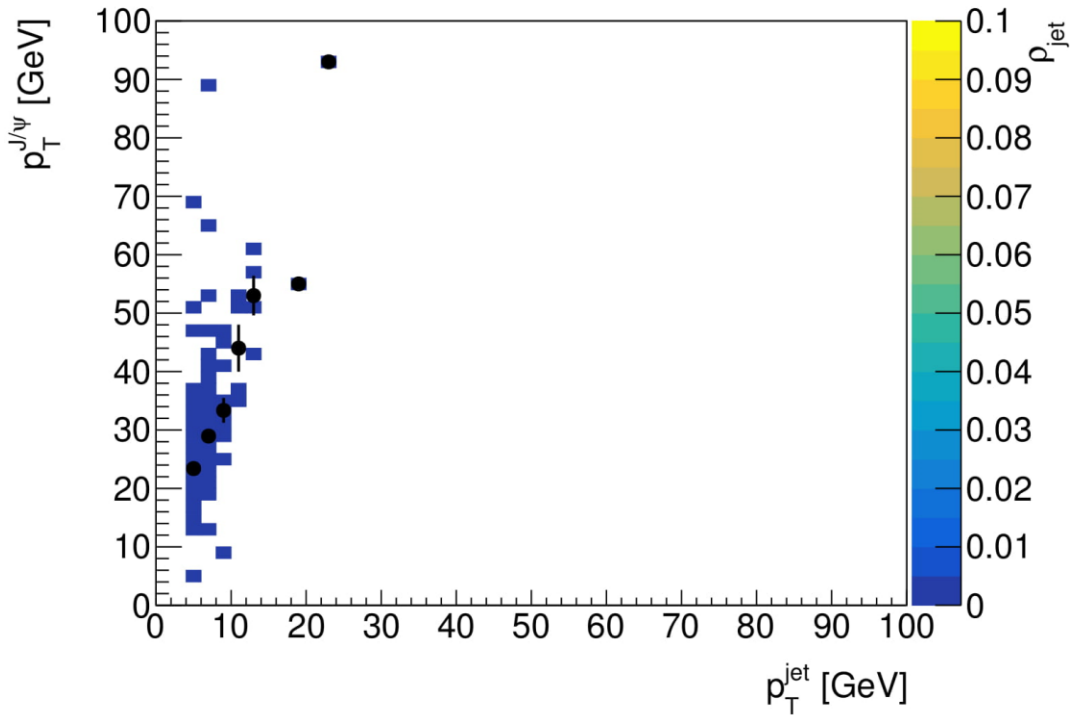
Fraction of jets with charmonia



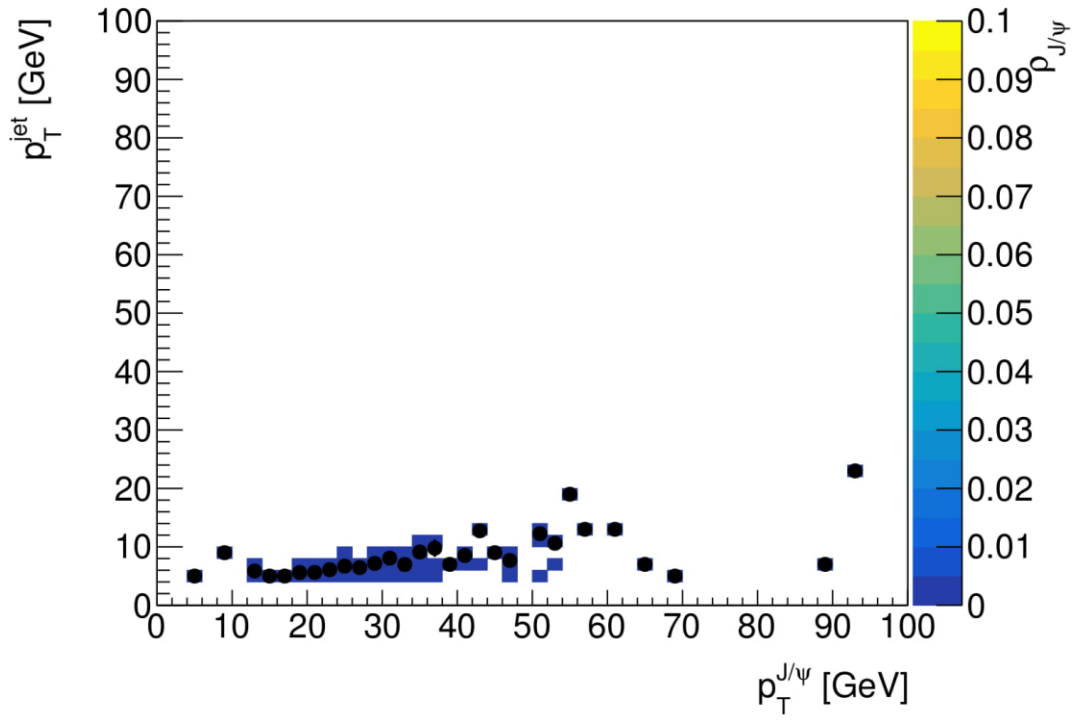
Fraction of charmonia with jets

Is there a region with higher corellations?

PYTHIA without ISR and FSR



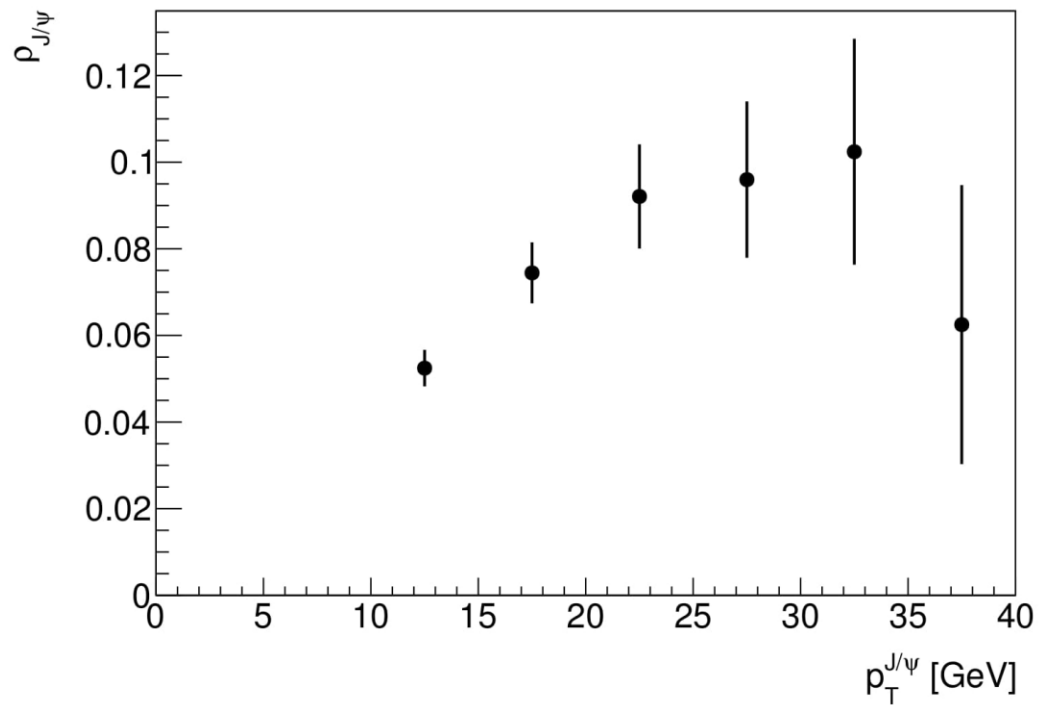
Fraction of jets with charmonia

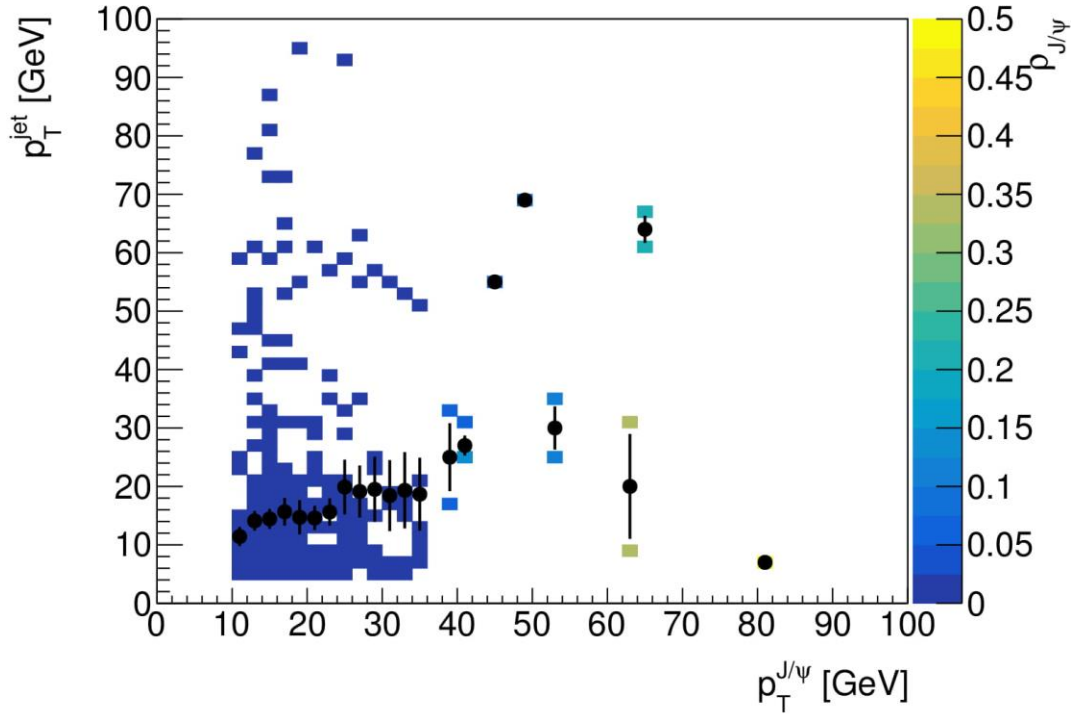


Fraction of charmonia with jets

Experimental data

- As J/ψ we have used muon-muon pair candidates with invariant mass between 2,9 – 3,1 GeV



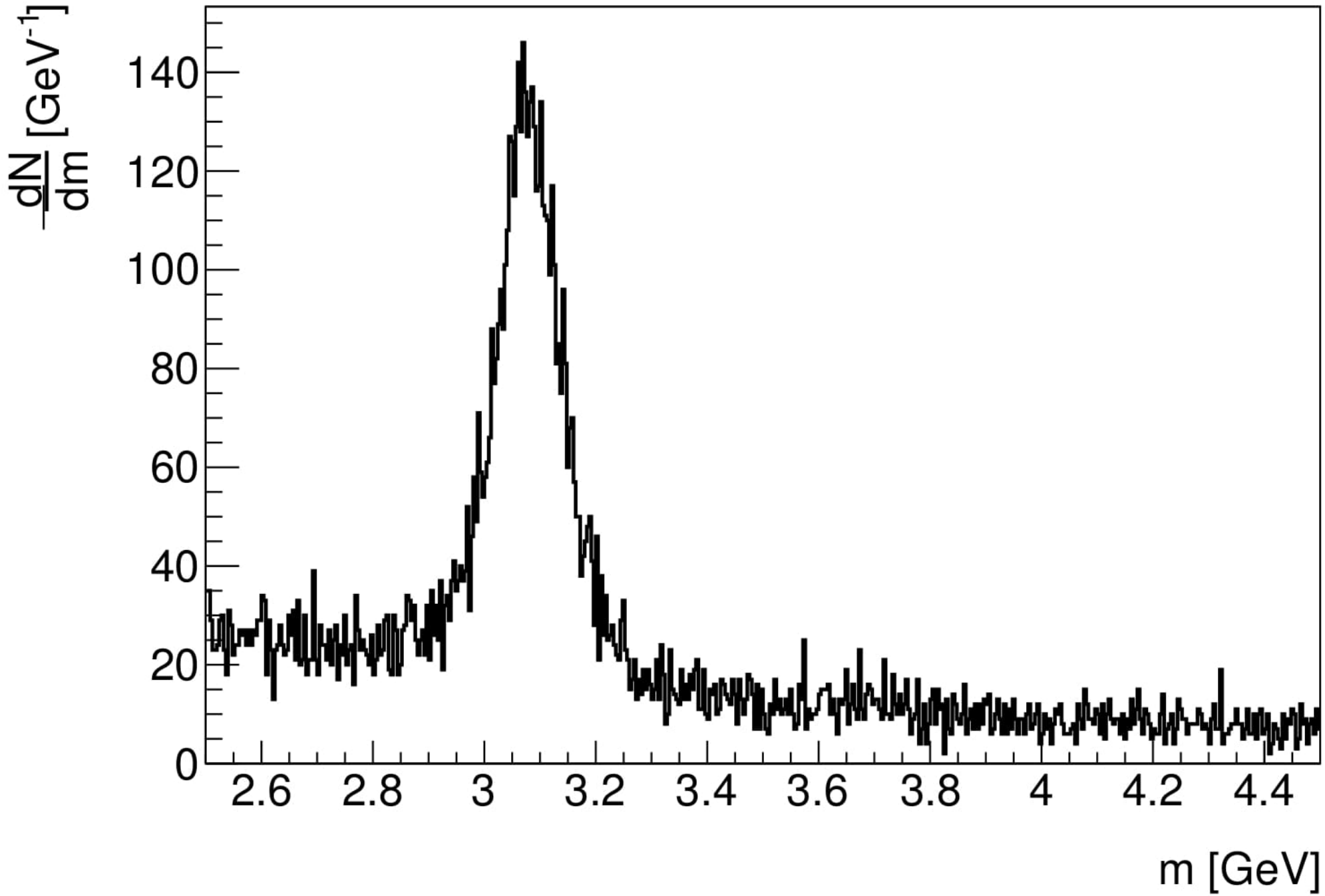


Conclusions

- We have studied the correlation of jets and J/ψ in PYTHIA and in experimental data from ATLAS
- While PDF has no effect, ISR and FSR effects are visible
  - Option with neither ISR and FSR has best fit to the ATLAS data
- PYTHIA:
  - Low percentage of jets contained J/ψ
  - For high-energy J/ψ, up to one half was produced in jets
- Data:
  - Less than 10% of J/ψ was associated with jets

Thank you for your attention

Backup slides


$\frac{dN}{dm}$ [GeV^{-1}]
140
120
100
80
60
40
20
0
2.6
2.8
3
3.2
3.4
3.6
3.8
4
4.2
4.4
m [GeV]

Muon selection criteria

4.3 Data samples and event selection

The pp data used in this thesis were taken during LHC proton-proton collisions at $\sqrt{s} = 5.02$ TeV. The integrated luminosity of 25 pb^{-1} was collected between 19th of November 2015 and 24th of November 2015. The collision data were required to satisfy the good run list which ensures stable beams and fully operational ATLAS detector. Events were collected using the dimuon trigger which requires two oppositely charged muons with $p_T > 4$ GeV [34]. In total 37634508 events were used for the study in this thesis.

Muon candidates are required to pass the "Tight working point"[1] as well as the following criteria [34]:

- $p_T > 4$ GeV and $|\eta| < 2.4$;
- pixel hits + pixel dead sensors > 0;
- SCT hits + SCT dead sensors > 4;
- pixel holes + SCT holes < 3;
- for $0.1 < |\eta| < 1.9$, $n_{\mathrm{TRT}}^{\mathrm{hits}} + n_{\mathrm{TRT}}^{\mathrm{outliers}} > 5$ and $n_{\mathrm{TRT}}^{\mathrm{outliers}} < 0.9(n_{\mathrm{TRT}}^{\mathrm{hits}} + n_{\mathrm{TRT}}^{\mathrm{outliers}})$
- the selected muon must be matched with trigger elements within a cone of $\Delta R < 0.01$ from the trigger candidate.

Here hit represents a signal in one channel of a given tracking subdetector and outlier represents a signal which is distant with respect to an expectation from the fit procedure. The two muons in the pair which constitute a charmonium candidate are required to originate from a common vertex. The charmonium candidate is required to have invariant mass in the interval of $2.9 - 3.1$ GeV. No correction on tracking efficiency and acceptance are applied, but for a given kinematic selection, those were shown to vary only weakly with changing p_T and η [34].

Jets used in the data were reconstructed using the anti-k t algorithm with R = 0.4 with a dedicated underlying event subtracion [37] which prevents jets for being distorted by the presence of large underlying event of a heavy-ion collision.

[1] Working point is a set of requirements imposed on signal in ID and muon system which ensure high probability for a muon candidate to be the actual muon while ensuring minimal loss of candidates due to requiring restrictive cuts (that is while keeping a high efficiency for the muon reconstruction [35, 36])

PYTHIA Settings

```
Beams:eCM = 7000.
Main:numberOfEvents = 1000000
Main:timesAllowErrors = 10
Random:setSeed = on
Init:showAllSettings = off
Init:showChangedParticleData = on
Init:showAllParticleData = off

! common ATLAS Pythia8
Main:timesAllowErrors = 500
6:m0 = 172.5
23:m0 = 91.1876
23:mWidth = 2.4952
24:m0 = 80.399
24:mWidth = 2.085
StandardModel:sin2thetaW = 0.23113
StandardModel:sin2thetaWbar = 0.23146
ParticleDecays:limitTau0 = on
ParticleDecays:tau0Max = 10.0

Tune:pp = 5

PDF:pSet=LHAPDF6:CT10nlo
```

```
!Charmonia common
!Hard process
PhaseSpace:pTHatMin = 5.       ! //# Equivalent of CKIN3
ParticleDecays:mixB = off
```

```
! Quarkonia production mode
Charmonium:all = on
PhaseSpace:pTHatMinDiverge = 0.5
! standard resonances decaying to J/Psi
445:onMode = off     ! // chi_2c
445:onIfAny = 443    ! // chi_2c
10441:onMode = off   ! // eta_c(2S)
10441:onIfAny = 443 !// eta_c(2S)
10443:onMode = off !// h_1c
10443:onIfAny = 443 !
20443:onMode = off   ! // chi_1c
20443:onIfAny = 443 !
! color triplet resonances decaying to J/Psi
9940103:onMode = off
9940103:onIfAny = 100443
9941103:onMode = off
9941103:onIfAny = 100443
9942103:onMode = off
9942103:onIfAny = 100443
! color triplet resonances decaying to Psi(2) [note: no color
   singlet resonances going to Psi(2)]
9940003:onMode = off
9940003:onIfAny = 443
9941003:onMode = off
9941003:onIfAny = 443
9942003:onMode = off
9942003:onIfAny = 443
! signal
443:onMode = off      ! // J/Psi
443:onIfAny = 13
100443:onMode = off  ! // Psi(2S)
100443:onIfAny = 13
```

Inner detector

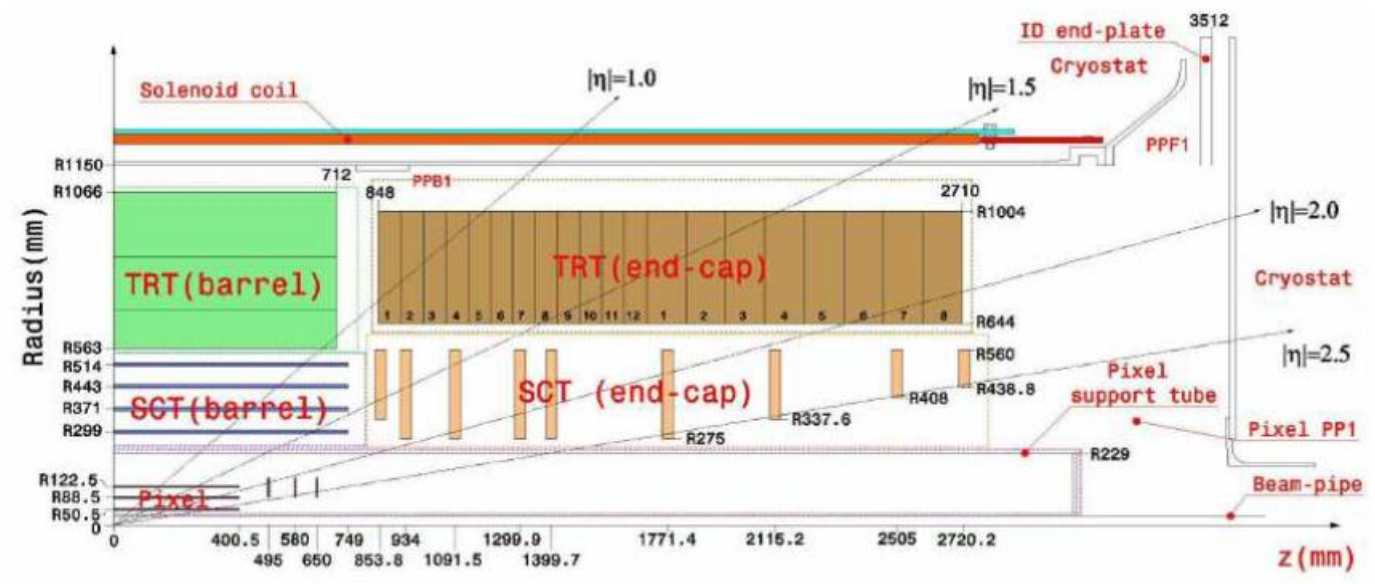
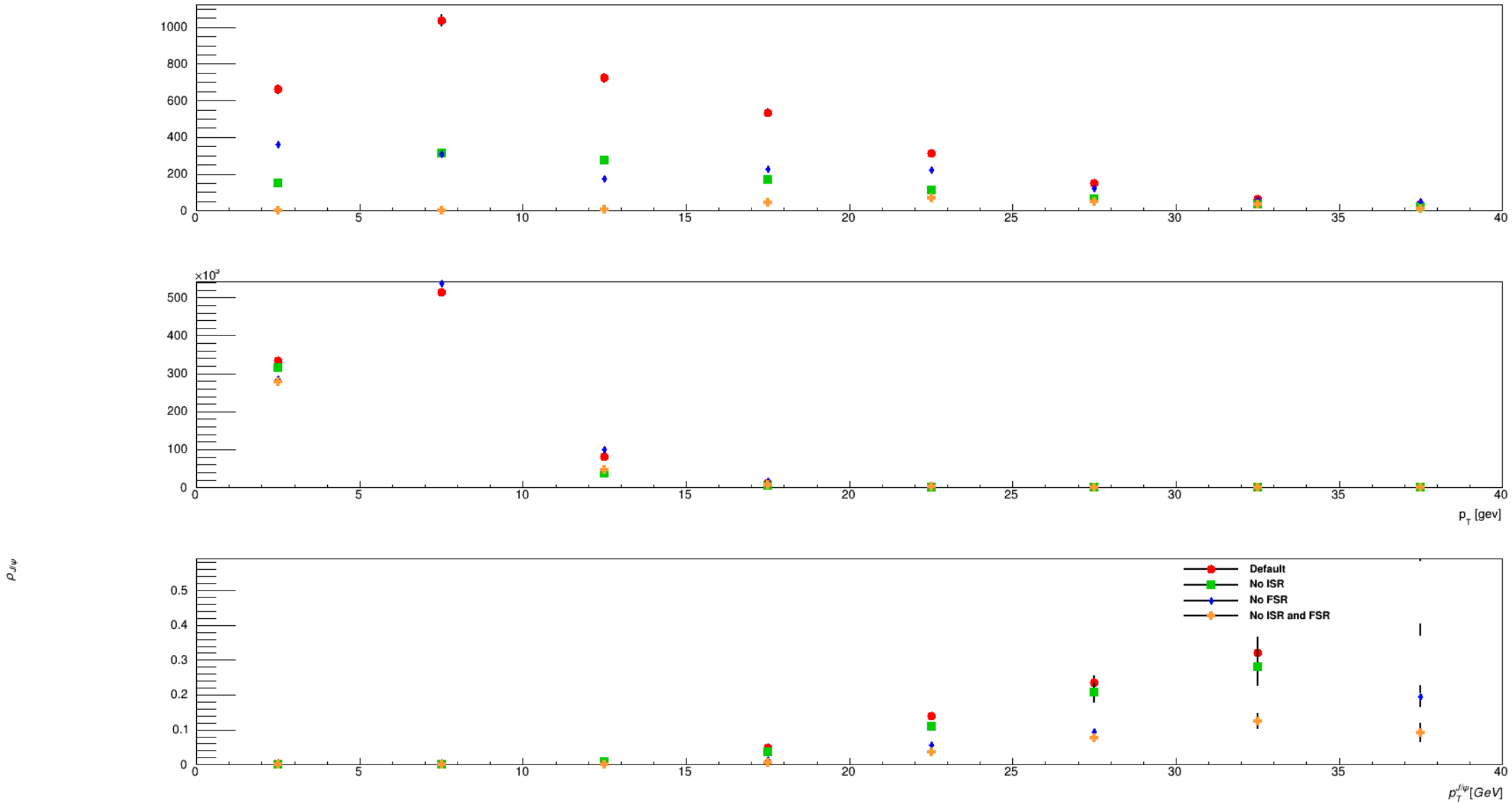


Figure 3.5: Schematics of the ATLAS Inner detector.

Charmónia s jetmi



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