Event activity dependence of excited-to-ground state charmonium production ratio with the LHCb

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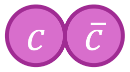
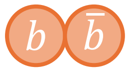
June 17th, 2024

Motivation

- Heavy quarkonia = a bound state of ***b*** or ***c*** quark and antiquark



charmonia



bottomonia

- Heavy quarkonia is subject to suppression in a hadronic environment

quark-gluon plasma (QGP)

shadowing
comover interactions
nuclear absorption
scattering
…

cold nuclear effects

Motivation

- Heavy quarkonia = a bound state of ***b*** or ***c*** quark and antiquark

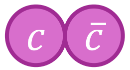
$c\bar{c}$ charmonia

$b\bar{b}$ bottomonia

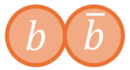
- Heavy quarkonia is subject to suppression in a hadronic environment
  - → quark-gluon plasma (QGP): almost uniquely in heavy-ion collisions
  - → cold nuclear effects: shadowing, **comover interactions**, nuclear absorption, scattering, …: noticed in pA, pp collisions

Motivation

- Heavy quarkonia = a bound state of ***b*** or ***c*** quark and antiquark



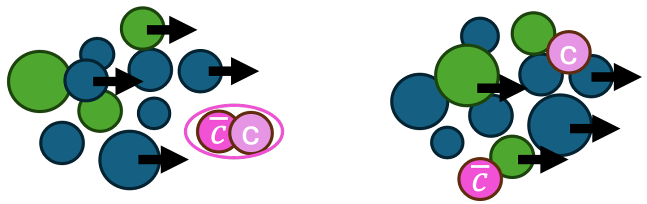
charmonia



bottomonia

- Heavy quarkonia is subject to suppression in a hadronic environment
  - quark-gluon plasma (QGP) — almost uniquely in heavy-ion collisions
  - cold nuclear effects: shadowing, **comover interactions**, nuclear absorption, scattering, … — noticed in pA, pp collisions

- **Comovers** = hadrons created in the collision moving along with quarkonium state



charmonium dissociation due to the comoving medium

- **Comover Interaction Model -** <u>working theory</u> describing suppression due to interactions with the comovers
  - ✚ Shows considerable agreement with experimental data
  - ★ Can it be improved? Sure!

<u>Idea</u>: Current model takes into account the whole space. Only comovers close to the quarkonium state can break it => localized approach for improving precision.

Overview of the project

Idea: Current model takes into account the whole space. Only comovers close to the quarkonium state can break it => localized approach for improving precision.

Part 1: Constraining space to a cone around quarkonium state and introducing this constraint to the Comover Interaction Model => new theoretical prediction } Done as a student project since last September

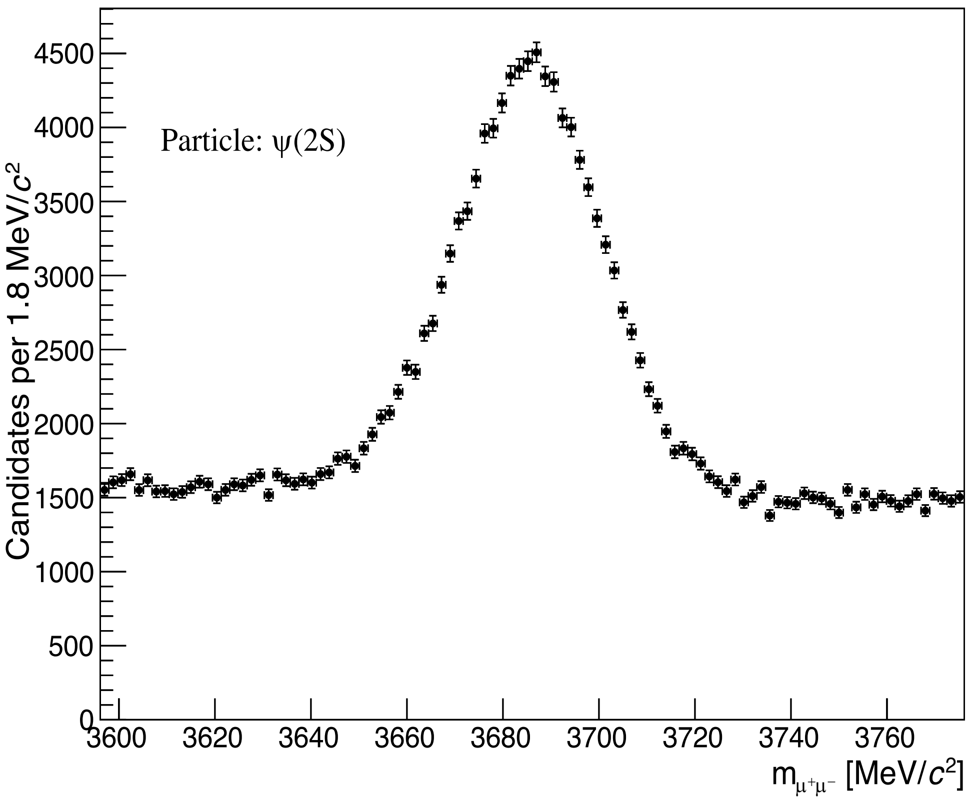
Part 2: Analysis and comparison with the new model

- LHCb 13 TeV pp data from 2016
- Focus on J/ψ and $\psi(2S)$
- Extracting signal in different momentum and multiplicity bins
- Separating prompt and nonprompt (from b decays) signal
- Preliminary comparisons of relevant quantities (ratio of number of tracks in a cone around $\psi(2S)$ over J/ψ, survival probabilities of charmonia, …) obtained in analysis and from theory
- Computing efficiencies, systematic uncertainties and applying corrections

● Done ● In progress ● Future work/won't be finished before the end of the internship

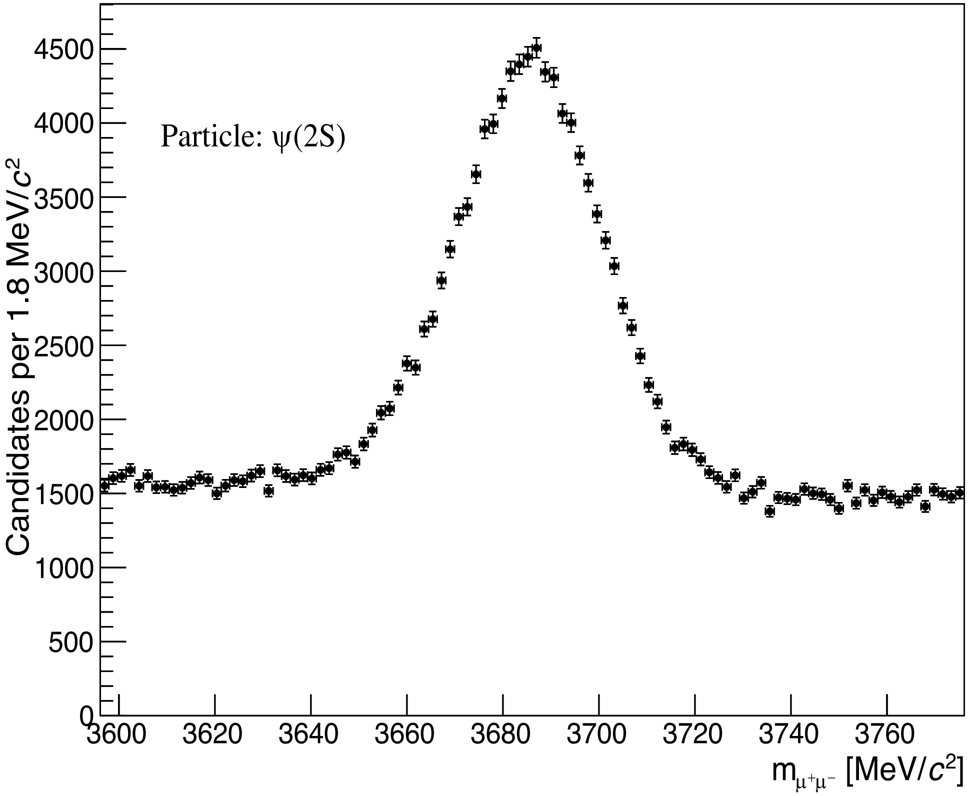
Signal extraction

Step 1: Total signal yield determination – invariant mass fit



Signal extraction: Invariant mass fit

Step 1: Total signal yield determination – invariant mass fit



- Signal = sum of two Crystal Ball functions

$$f_{CB}(m;\mu,\sigma,\alpha,n) = \begin{cases} \left(\frac{n}{|\alpha|}\right)^n e^{-\frac{1}{2}\alpha^2}\left(\frac{n}{|\alpha|} - |\alpha| - \frac{m-\mu}{\sigma}\right)^{-n} & \frac{m-\mu}{\sigma} < -|\alpha| \\ \exp\left(-\frac{1}{2}\left(\frac{m-\mu}{\sigma}\right)^2\right) & \frac{m-\mu}{\sigma} > -|\alpha| \end{cases}$$

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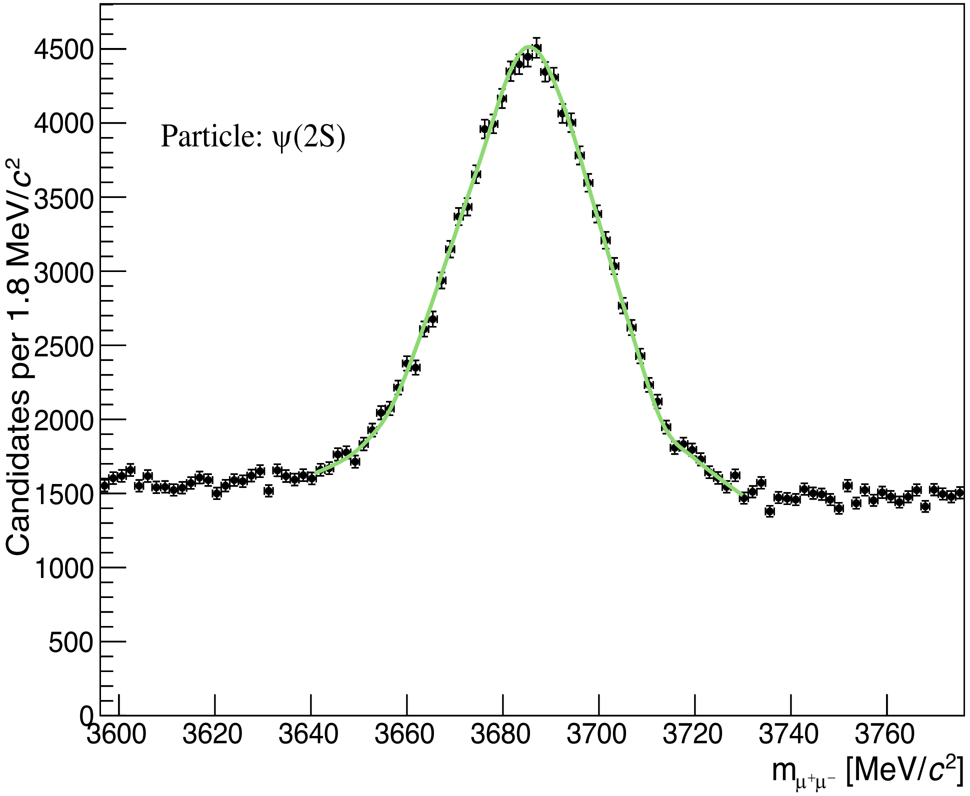

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Gaussian core

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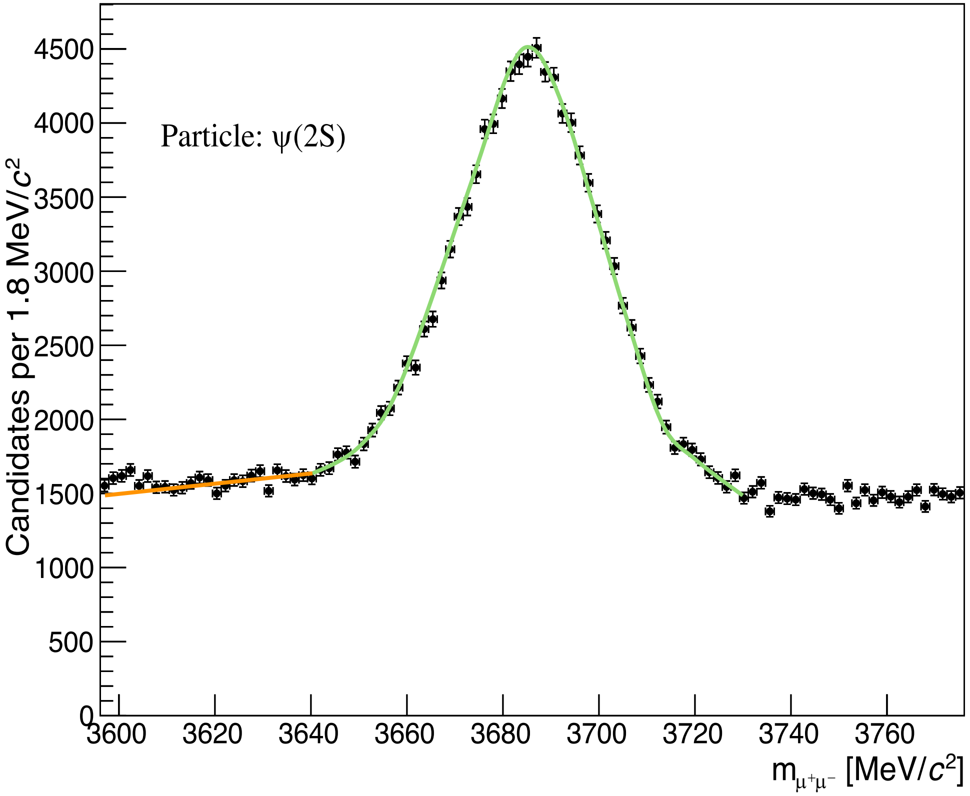

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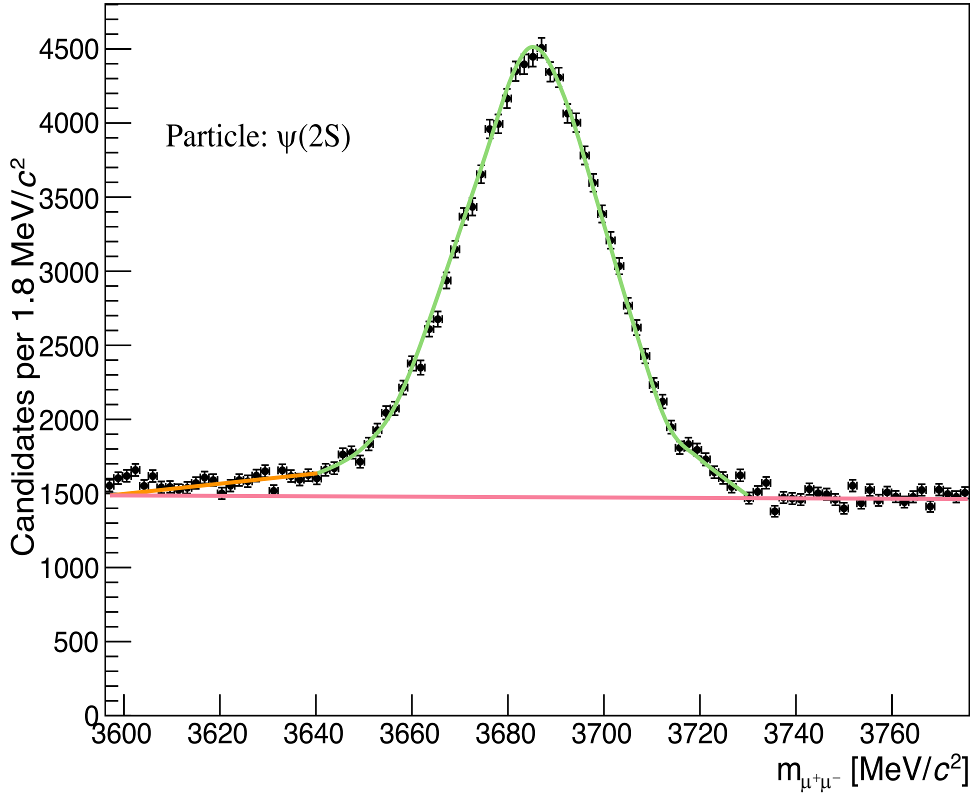

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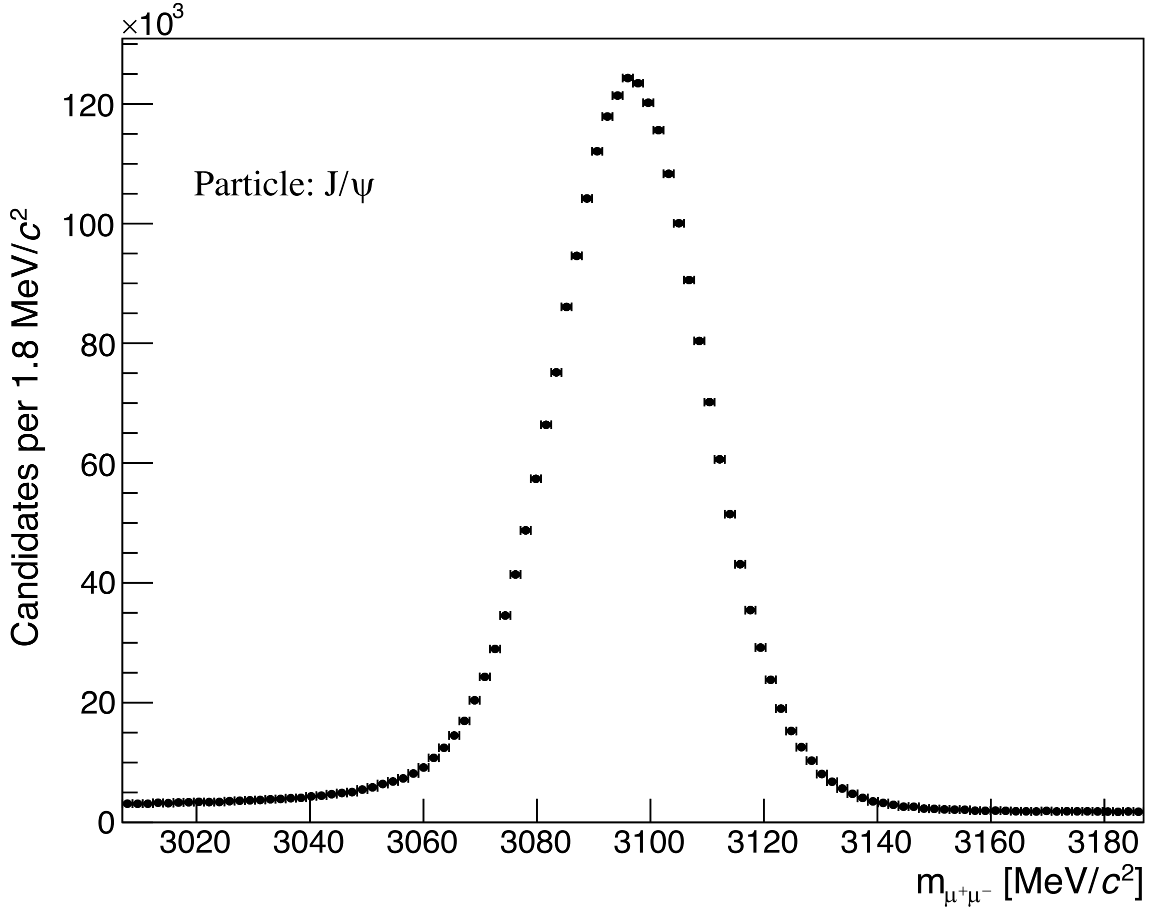
Gaussian core

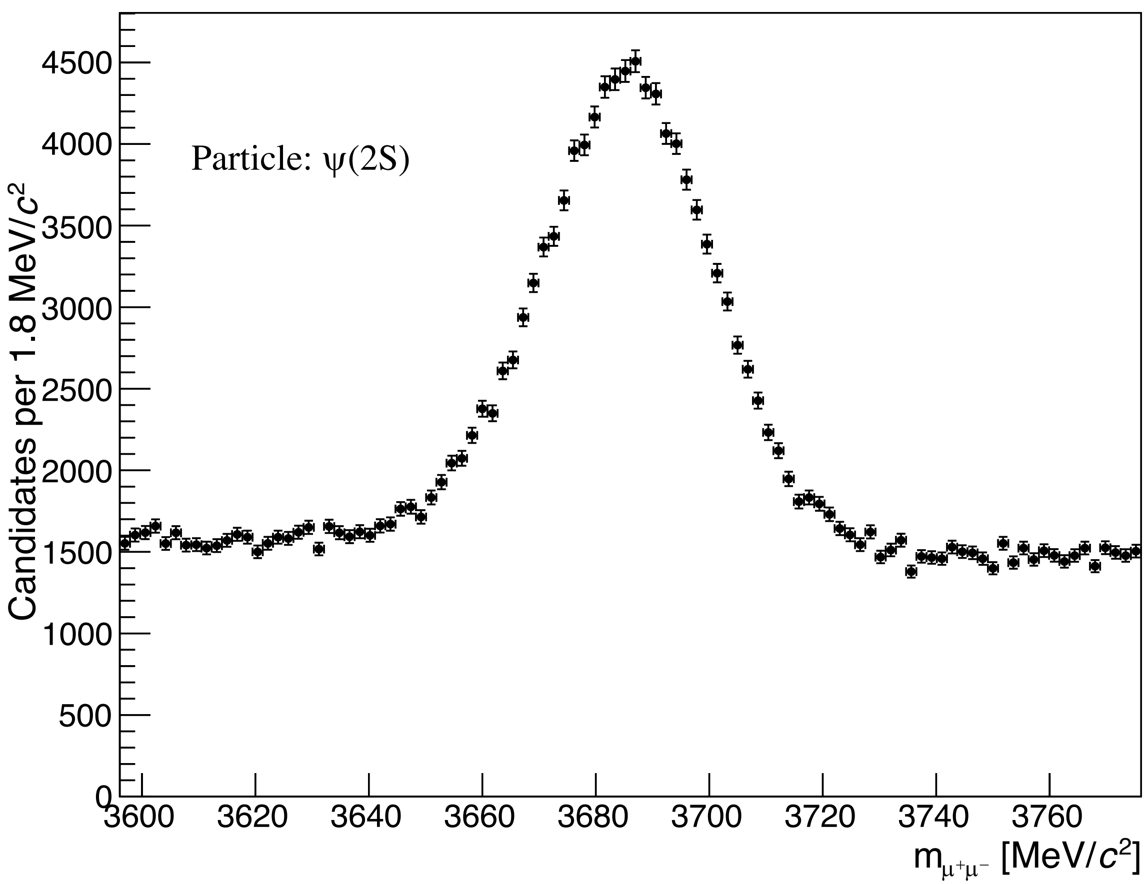
- Exponential background

$$f_{bkg}(m) = a_0 e^{-p_0 m}$$

Invariant mass fit example

$4 < p_T < 6$ [GeV] | $12 < nBackTracks < 22$ | $3 < \eta < 4$





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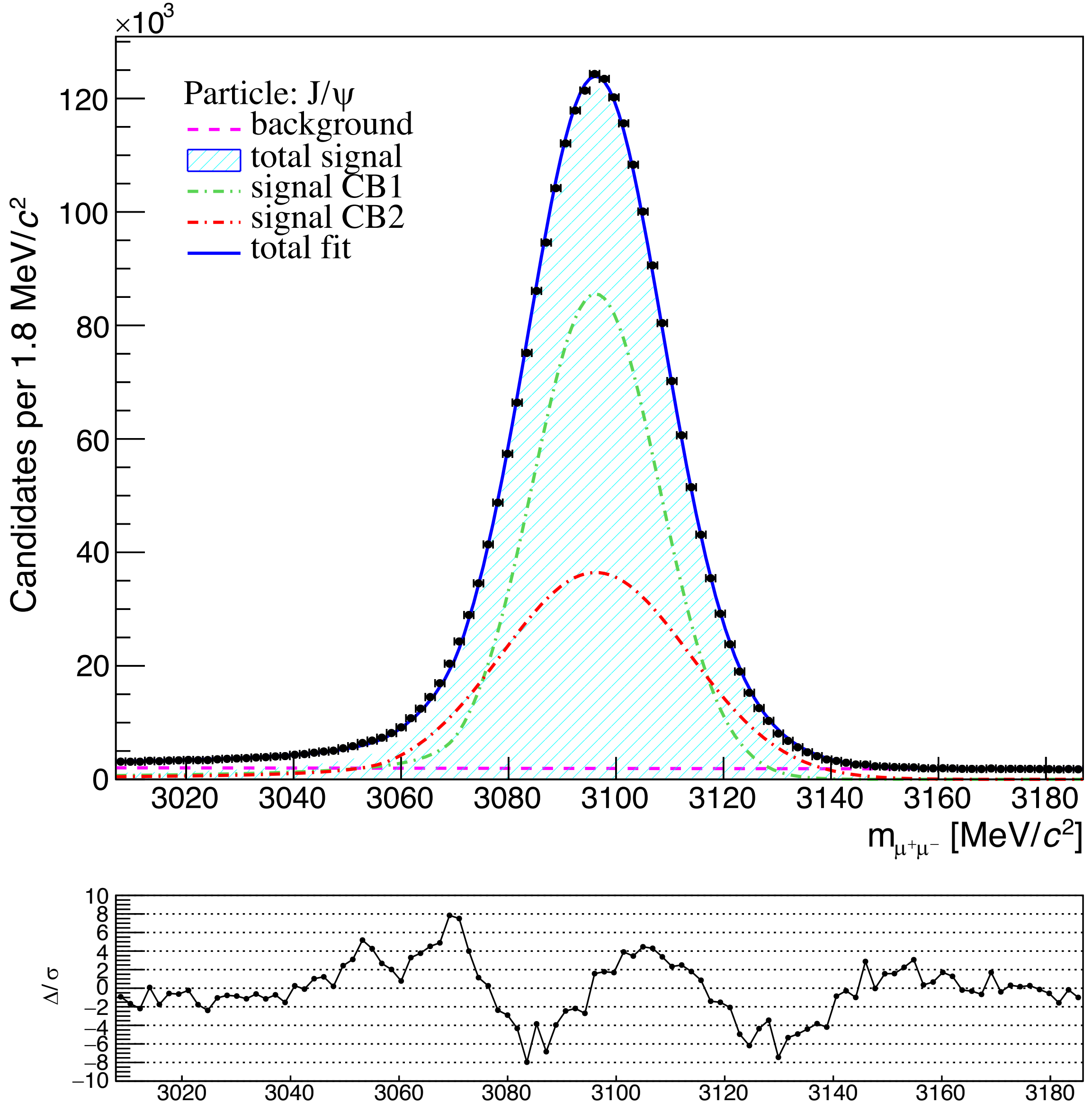
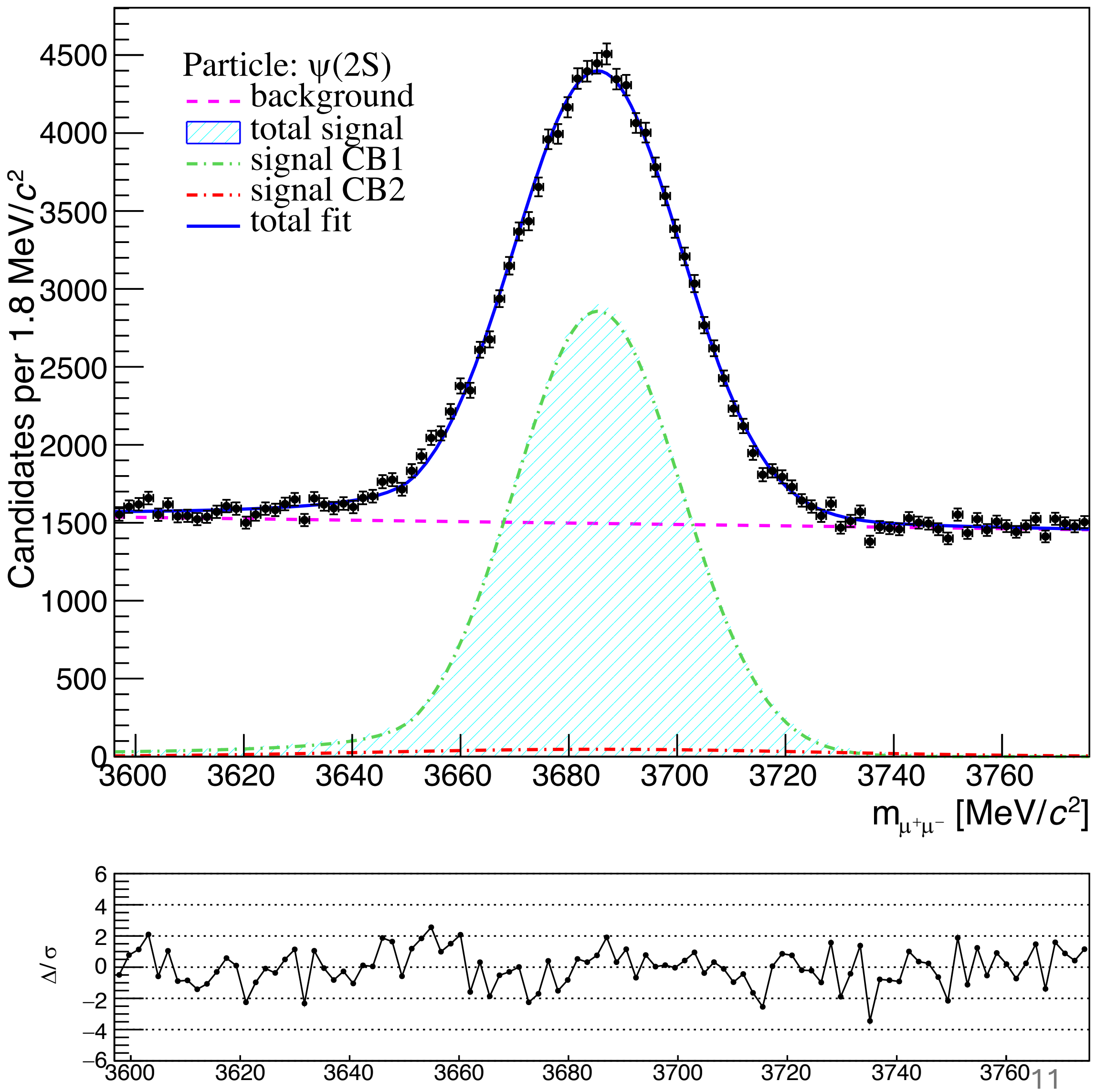




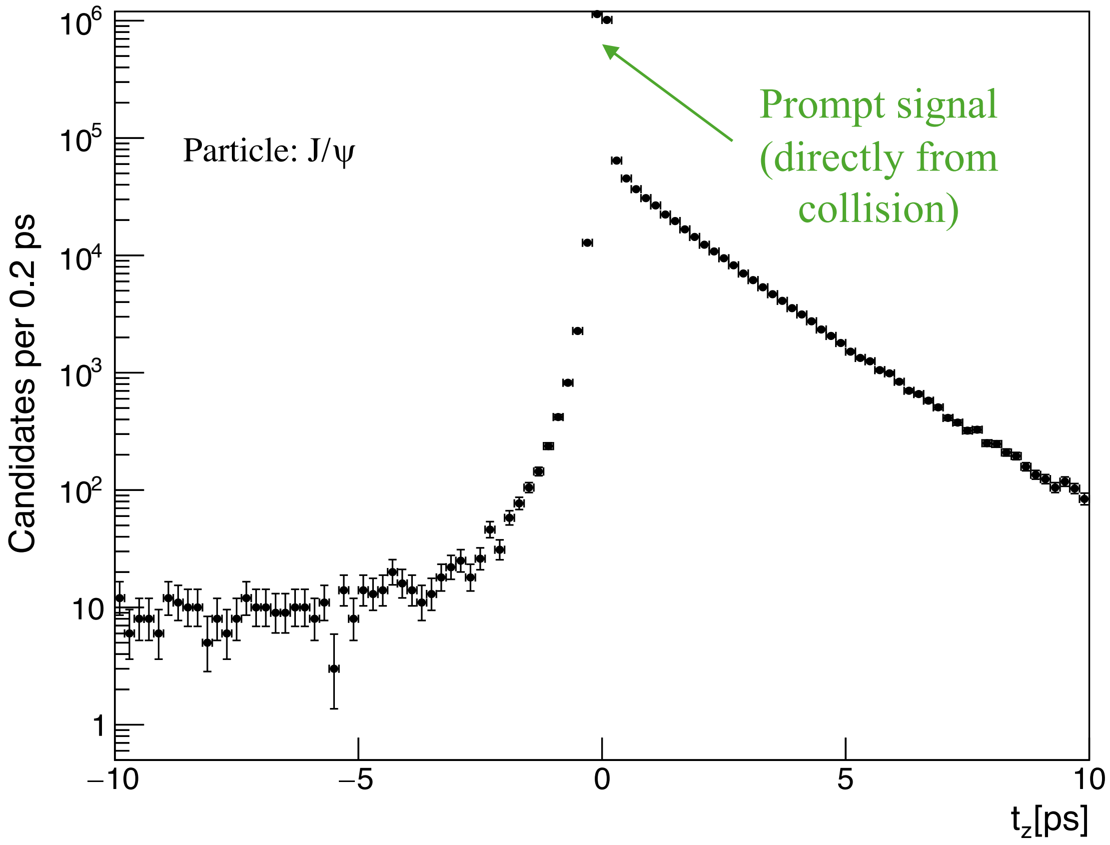
Signal extraction

Step 2: Determination of prompt and nonprompt signal yields

- Pseudo-proper decay time

$$t_z = \frac{(z_\Psi - z_{PV})m_\Psi}{p_z}$$

z_Ψ – position of the decay vertex
z_{PV} – position of the primary vertex
m_Ψ – known mass of the quarkonia Ψ
p_z – momentum along z axis
$\Psi \in \{J/\psi, \psi(2S)\}$



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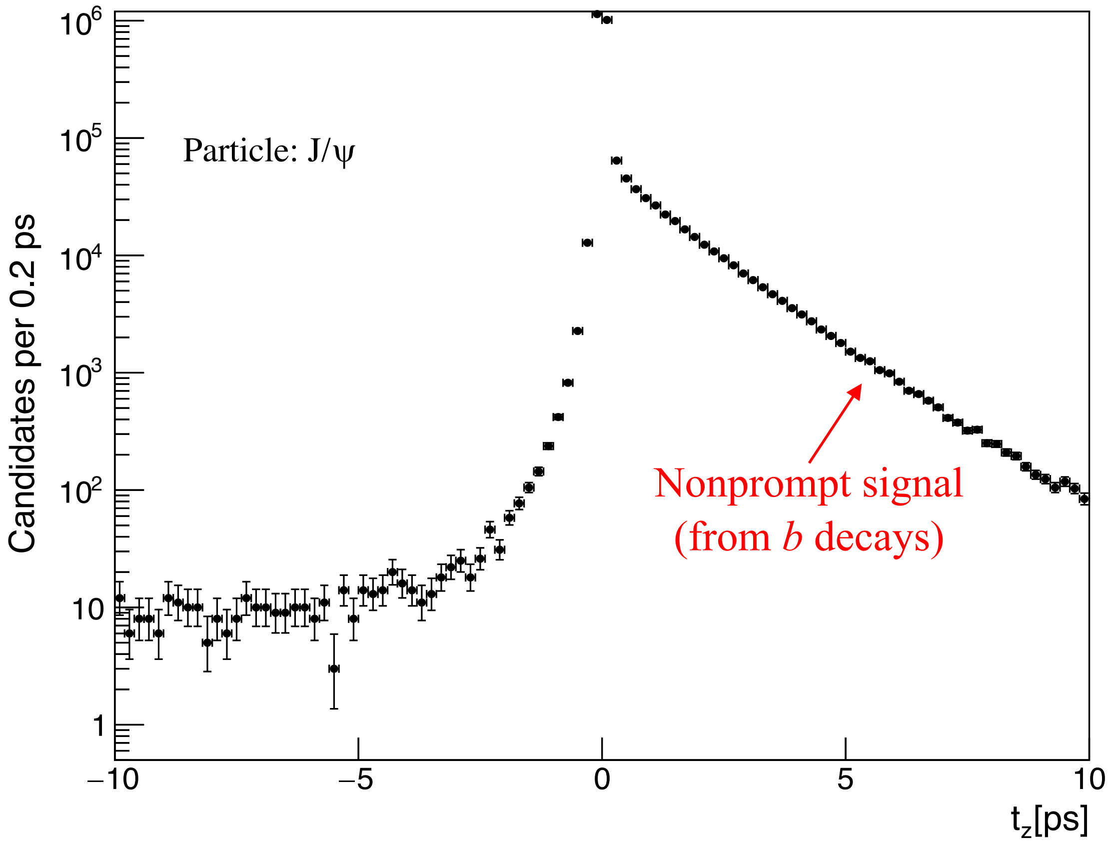
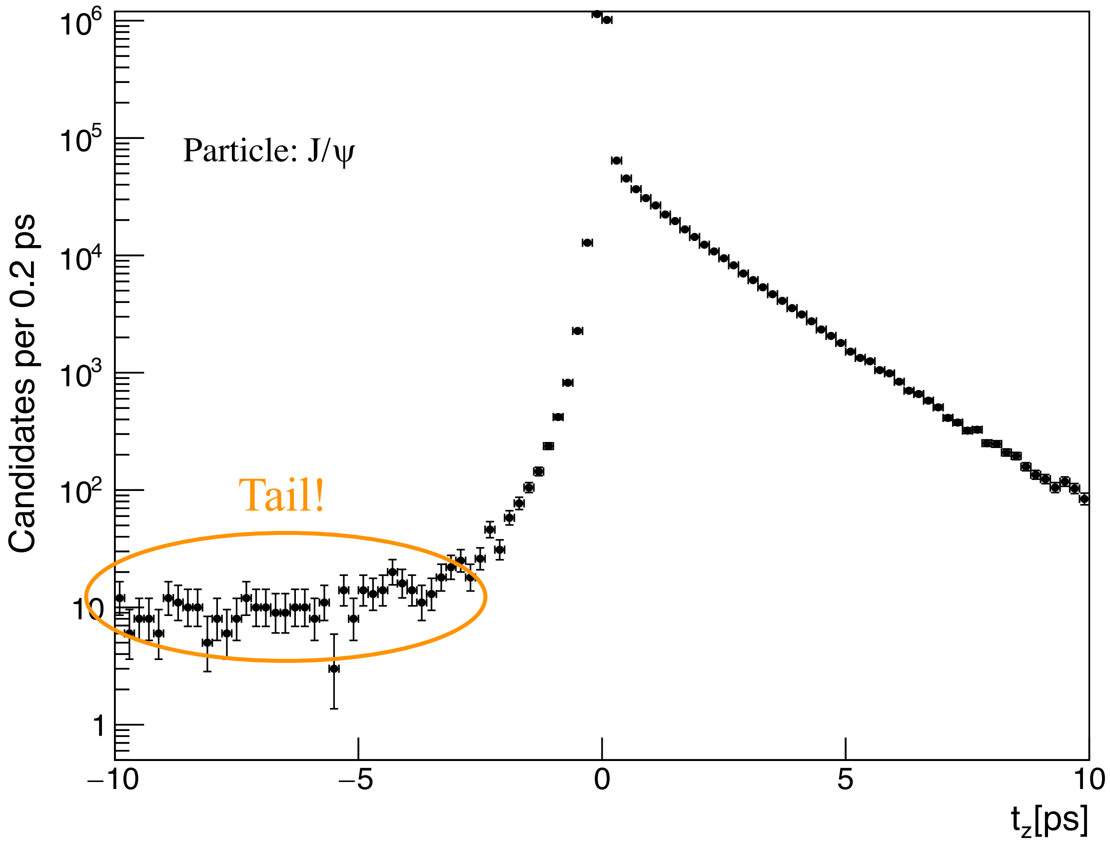


Signal extraction

Step 2: Determination of prompt and nonprompt signal yields

$$t_z^{next} = \frac{(z_{\mu\mu} - z_{PV}^{next})m_{\mu\mu}}{p_z}$$



Signal extraction

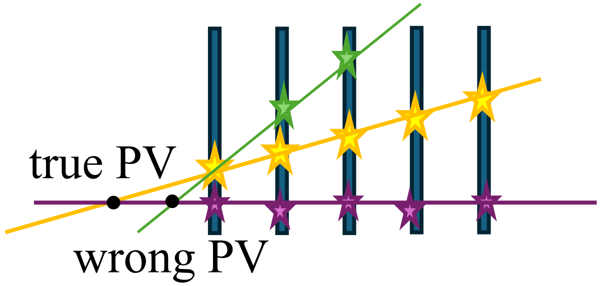
Step 2: Determination of prompt and nonprompt signal yields

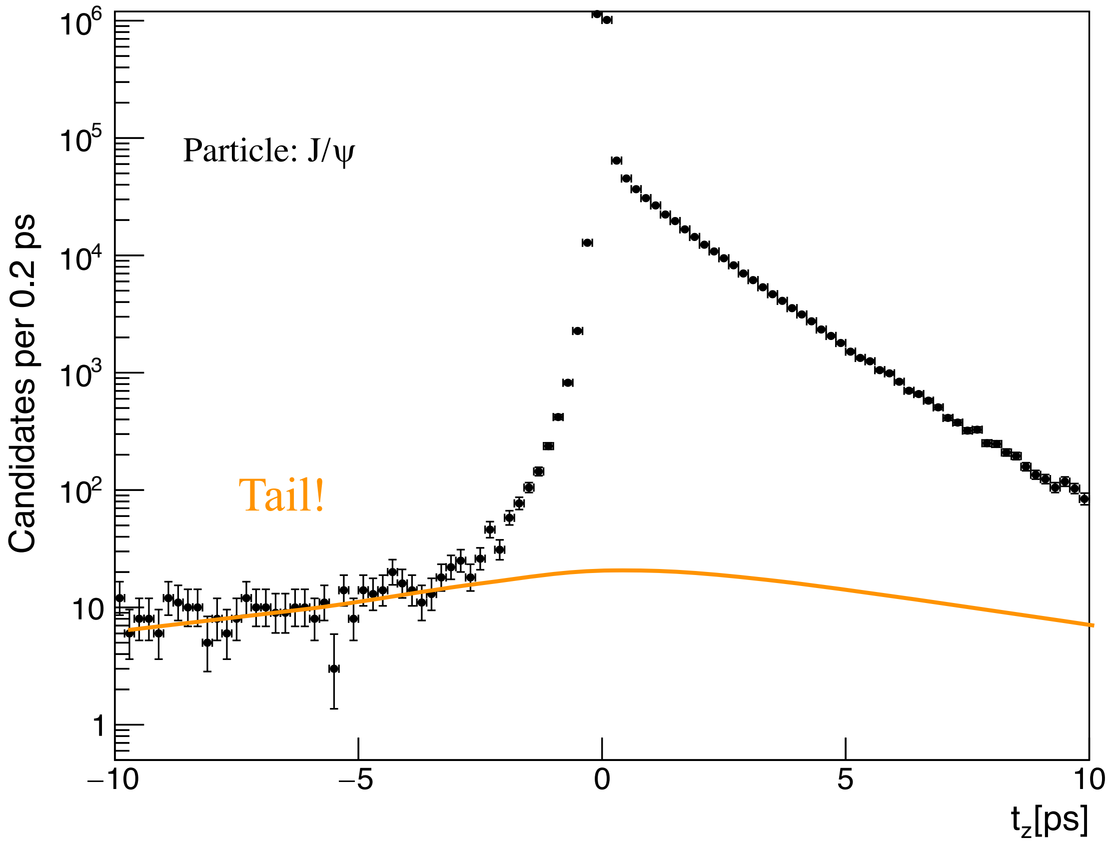
$$t_z^{next} = \frac{(z_{\mu\mu} - z_{PV}^{next})m_{\mu\mu}}{p_z}$$

PV = primary vertex

Candidates associated to a wrong PV because:

- True PV not reconstructed
- There is a wrong PV close to true one

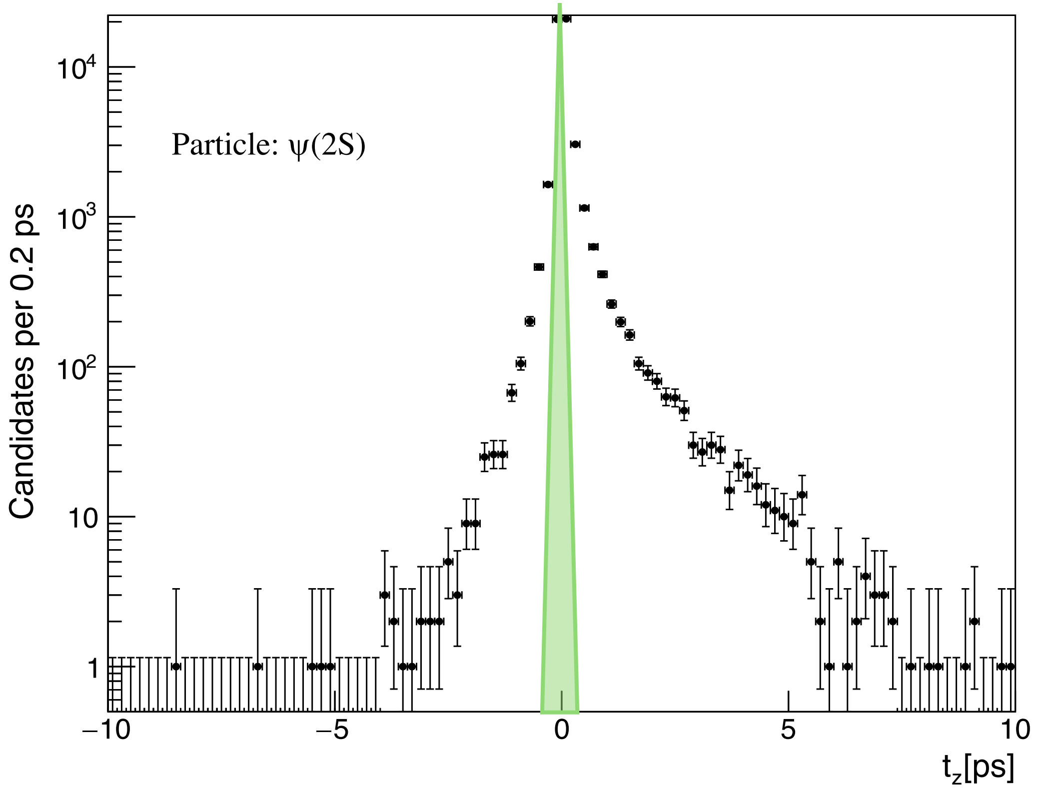




! not convolved with resolution because already quite wide

Signal extraction

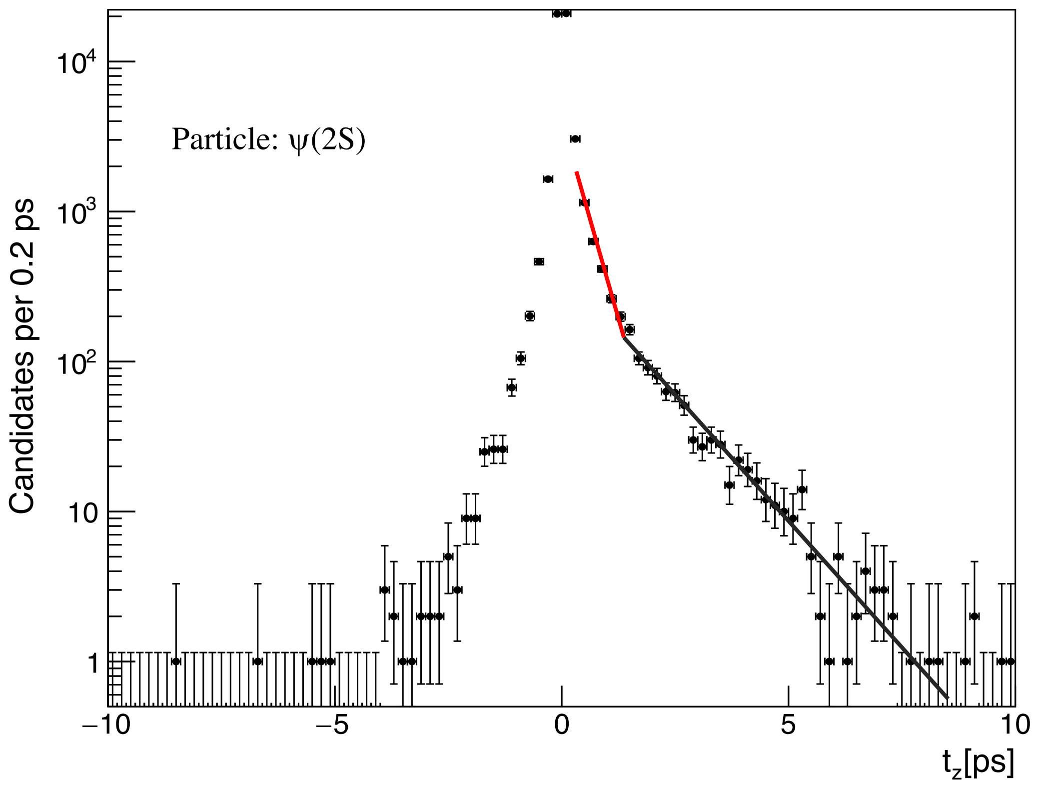
Background t_z distribution ($\pm$60 MeV/c^2 from m)



$$f_{bkg}(t_z) = f_\delta \delta(t_z) + \cdots$$

Prompt background particles

Background t_z distribution

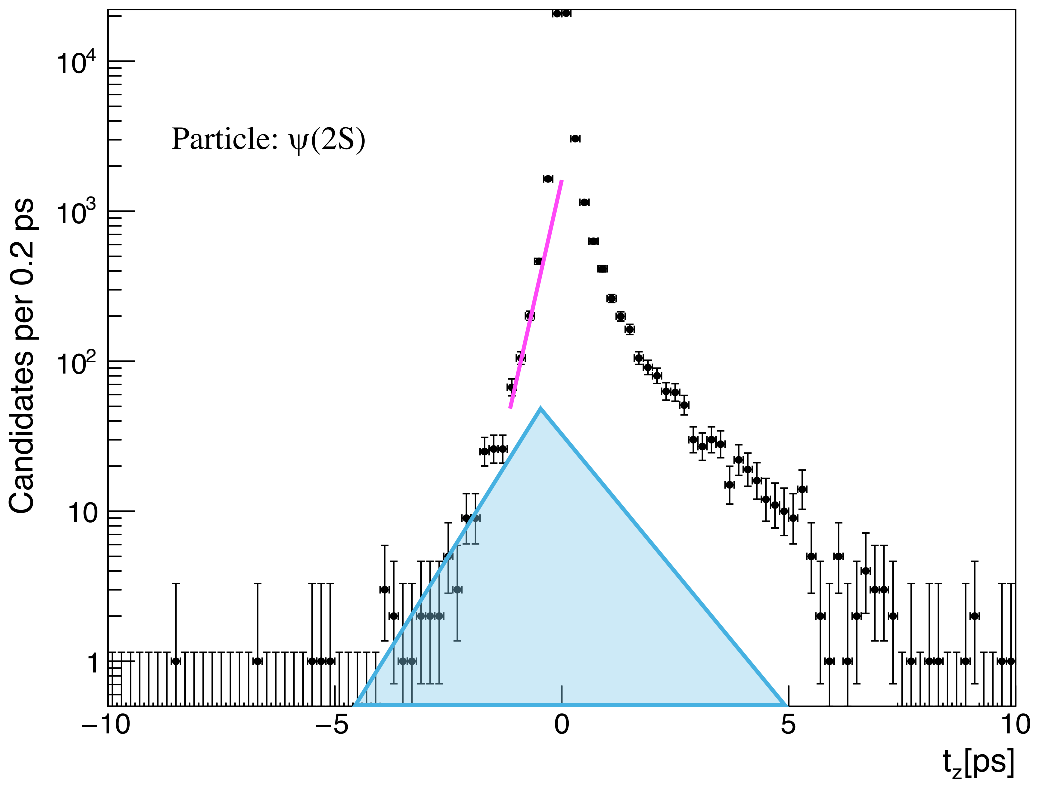


$$f_{bkg}(t_z) = f_\delta \delta(t_z) + \theta(t_z)\left(\frac{f_1}{\tau_1} e^{-\frac{t_z}{\tau_1}} + \frac{f_2}{\tau_2} e^{-\frac{t_z}{\tau_2}}\right) + \cdots$$

Semi-leptonic b and c decays

Signal extraction

Background t_z distribution



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Decays of kaons and pions

Signal extraction

Background t_z distribution

Semi-leptonic *b* and *c* decays

$$f_{bkg}(t_z) = \left[(1 - f_1 - f_2 - f_3 - f_4)\delta(t_z) + \theta(t_z)\left(\frac{f_1}{\tau_1}e^{-\frac{t_z}{\tau_1}} + \frac{f_2}{\tau_2}e^{-\frac{t_z}{\tau_2}}\right) + \theta(-t_z)\frac{f_3}{\tau_3}e^{\frac{t_z}{\tau_3}} + \frac{f_4}{2\tau_4}e^{-\frac{|t_z|}{\tau_4}}\right] * f_{res}(t_z; \mu, \sigma_1^{res\prime}, \sigma_2^{res\prime}, \beta')$$

Prompt background particles

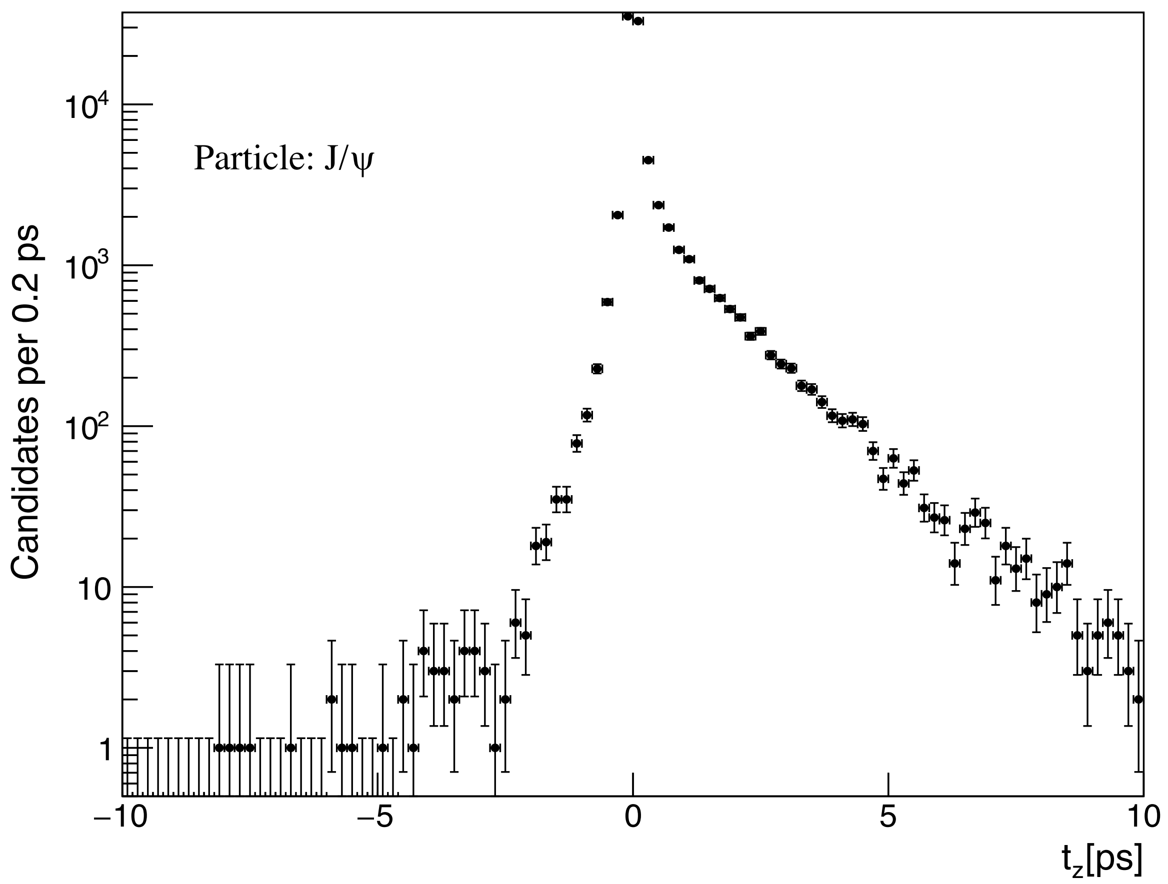
Decays of kaons and pions

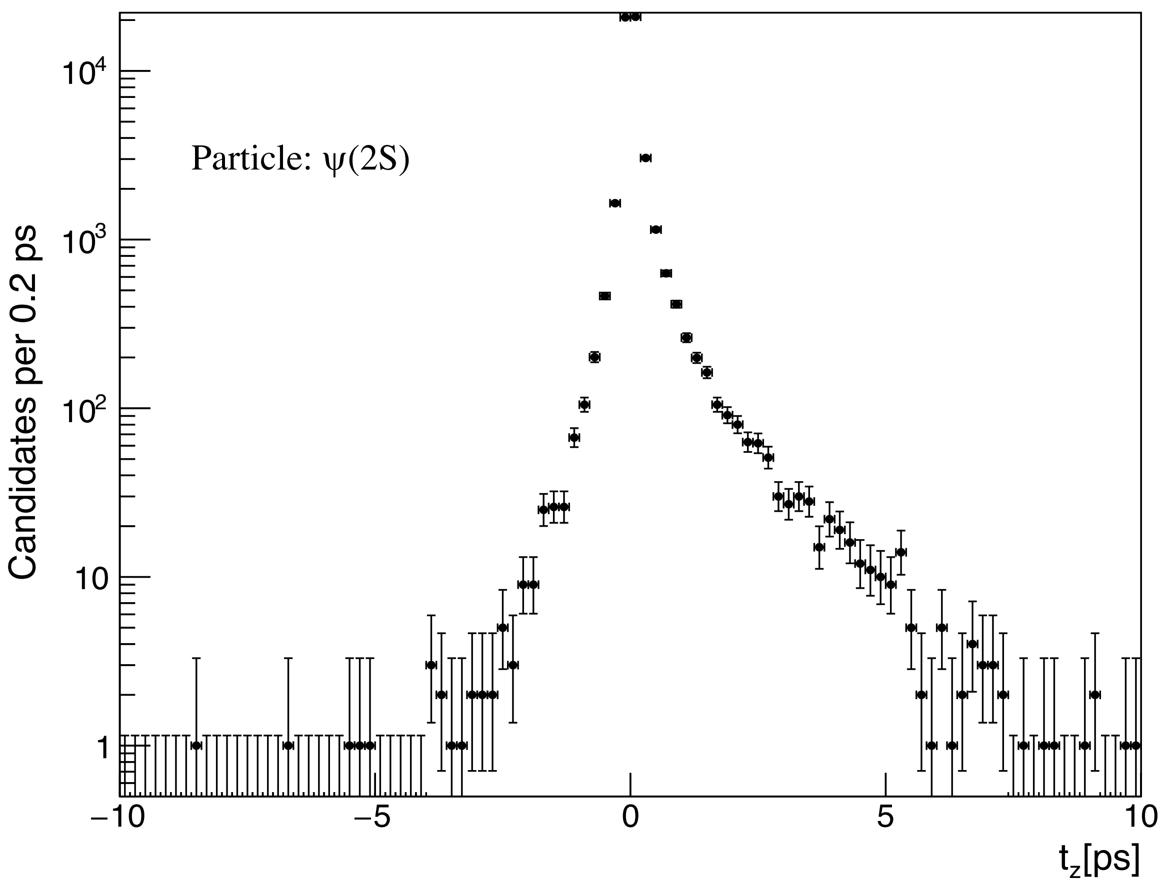
Detector resolution function

$$f_{res}(t_z; \mu, \sigma_1^{res}, \sigma_2^{res}, \beta) = \frac{\beta}{\sqrt{2\pi}\sigma_1^{res}} e^{-\frac{(t_z-\mu)^2}{2(\sigma_1^{res})^2}} + \frac{1-\beta}{\sqrt{2\pi}\sigma_2^{res}} e^{-\frac{(t_z-\mu)^2}{2(\sigma_2^{res})^2}}$$

Sideband fit example

$4 < p_T < 6$ [GeV] $12 < nBackTracks < 22$ $3 < \eta < 4$





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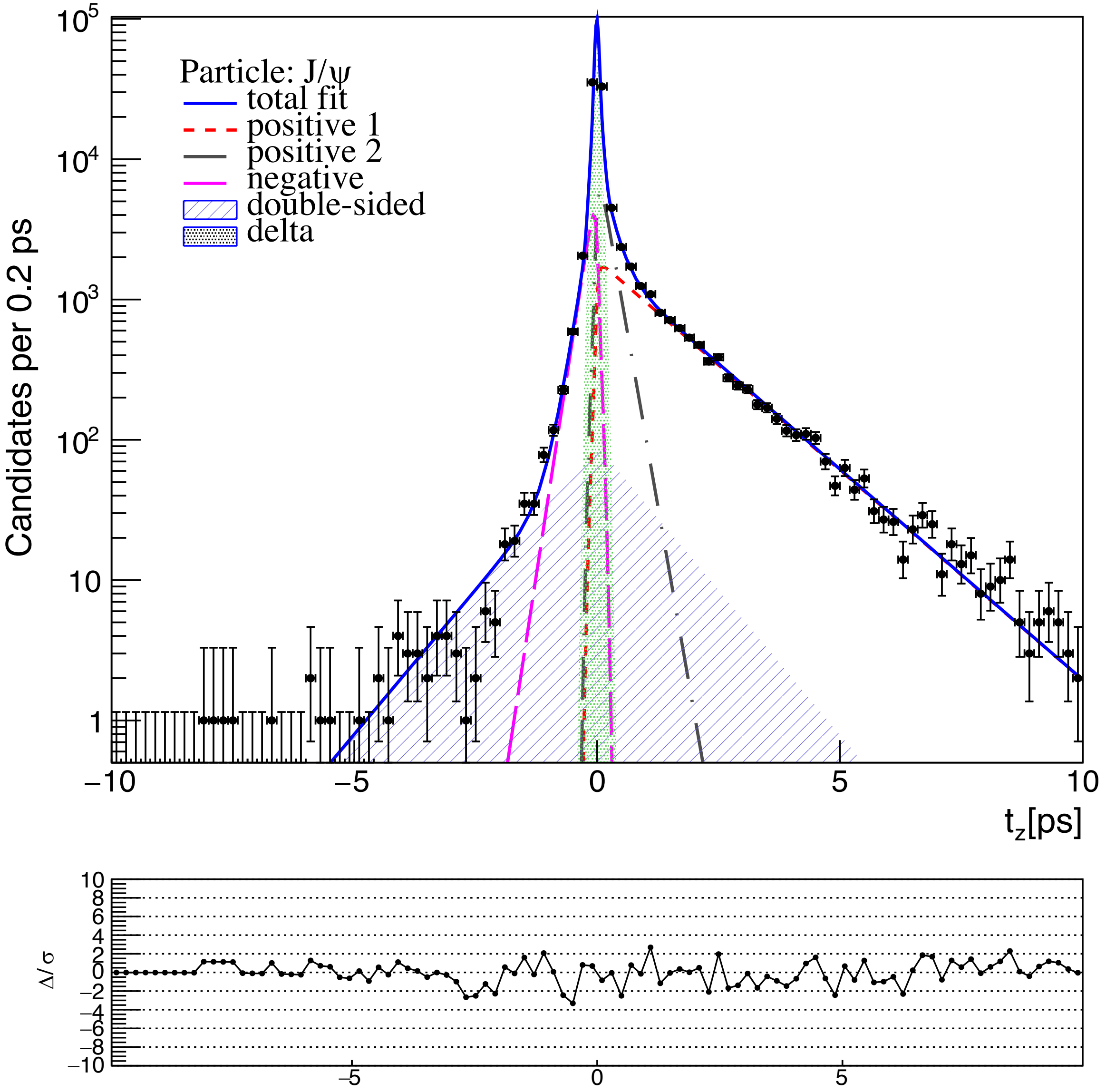

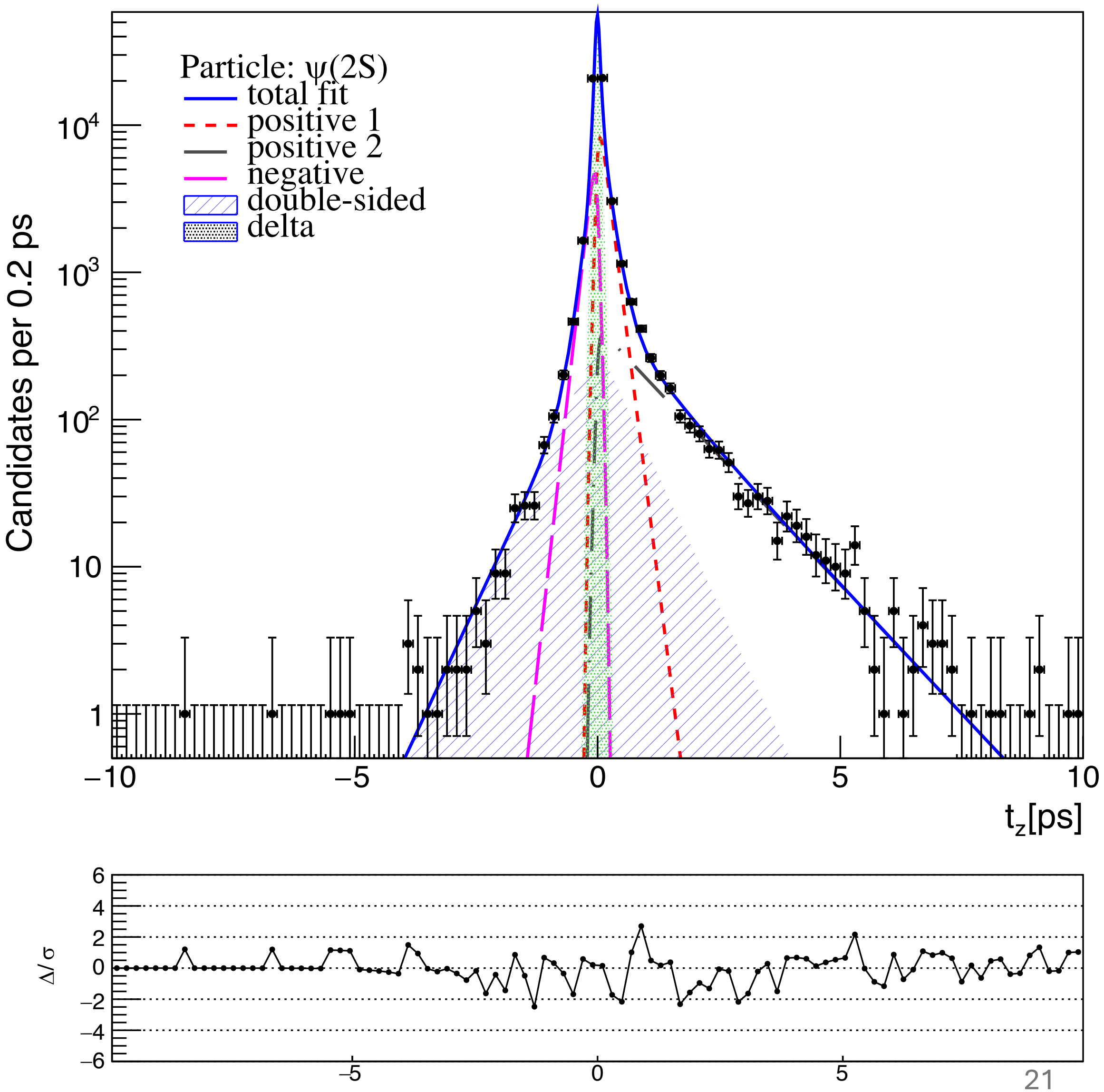

Total fit function

- Simultaneous unbinned extended maximum likelihood of $m(\mu^+\mu^-)$ and t_z is performed

$$f_{tz}\left(t_z; n_{prompt}, n_{tail}, n_{nonprompt}, n_{bkg}, \mu, \sigma_1^{res}, \sigma_2^{res}, \beta, \tau_b\right)$$
$$= \left(n_{prompt}\delta(t_z) + \frac{n_{nonprompt}}{\tau_b} e^{-\frac{t_z}{\tau_b}}\right) * f_{res}(t_z; \mu, \sigma_1^{res}, \sigma_2^{res}, \beta) + n_{tail} f_{tail}(t_z) + n_{kbg} f_{bkg}(t_z)$$

$$f_{total} = f_m(m; \mu_{mass}, \sigma_{mass}, p_0) + f_{tz}\left(t_z; n_{prompt}, n_{tail}, n_{nonprompt}, n_{bkg}, \mu, \sigma_1^{res}, \sigma_2^{res}, \beta, \tau_b\right)$$

- From n_{prompt} and $n_{nonprompt}$ statistical weights – sWeights – are extracted using sPlot technique

2D fit example - J/ψ

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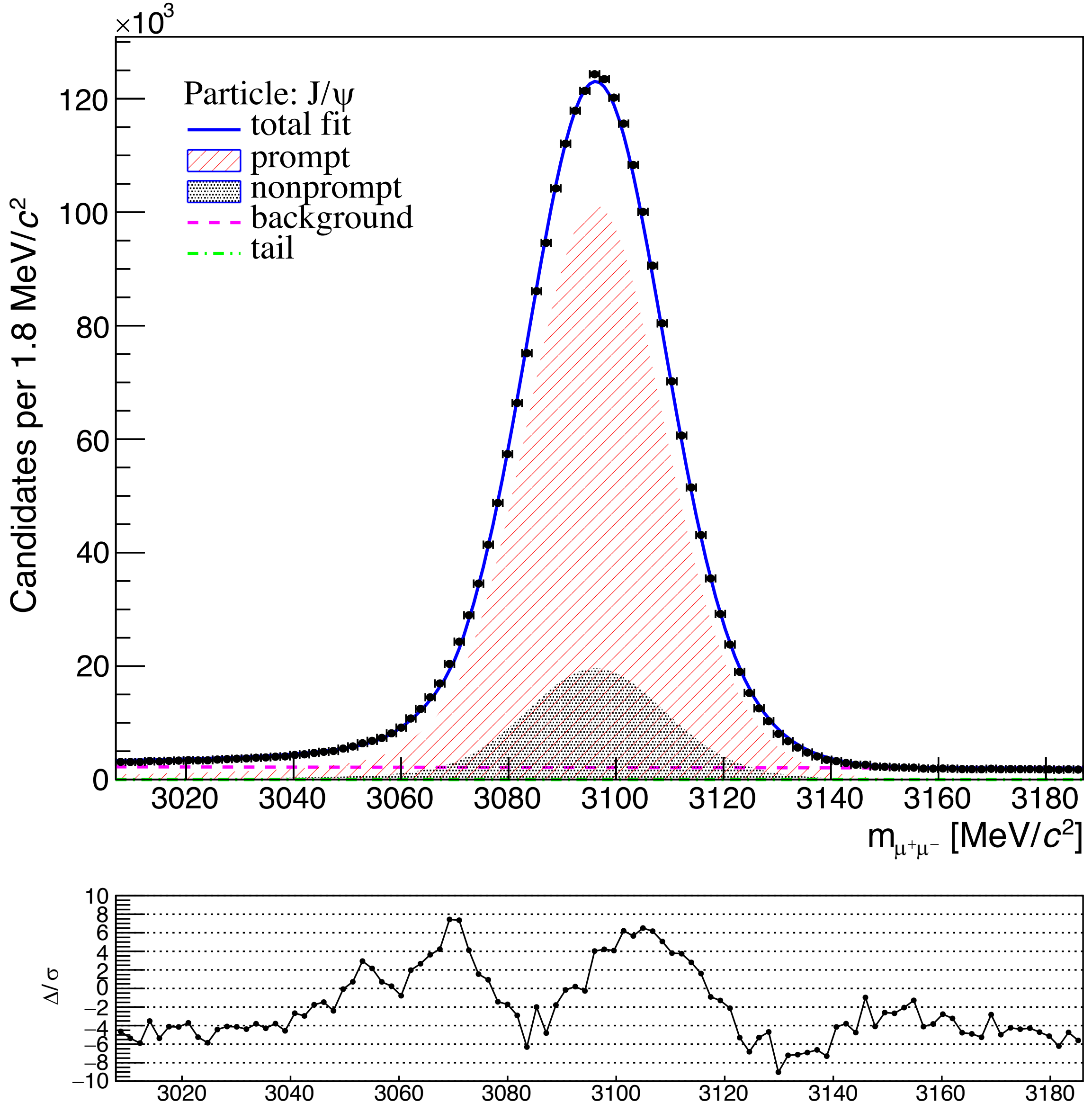

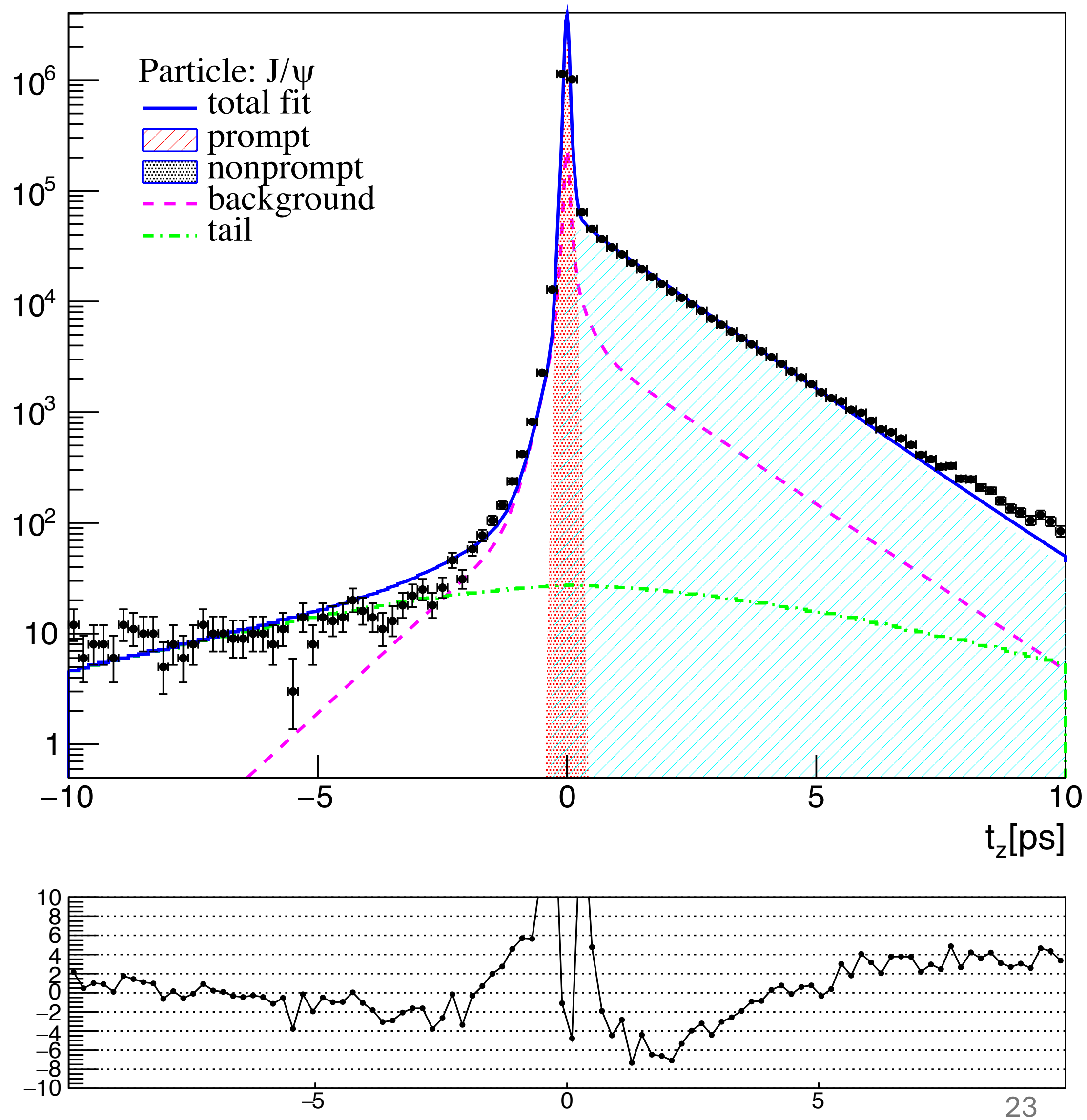

2D fit example - $\psi(2S)$

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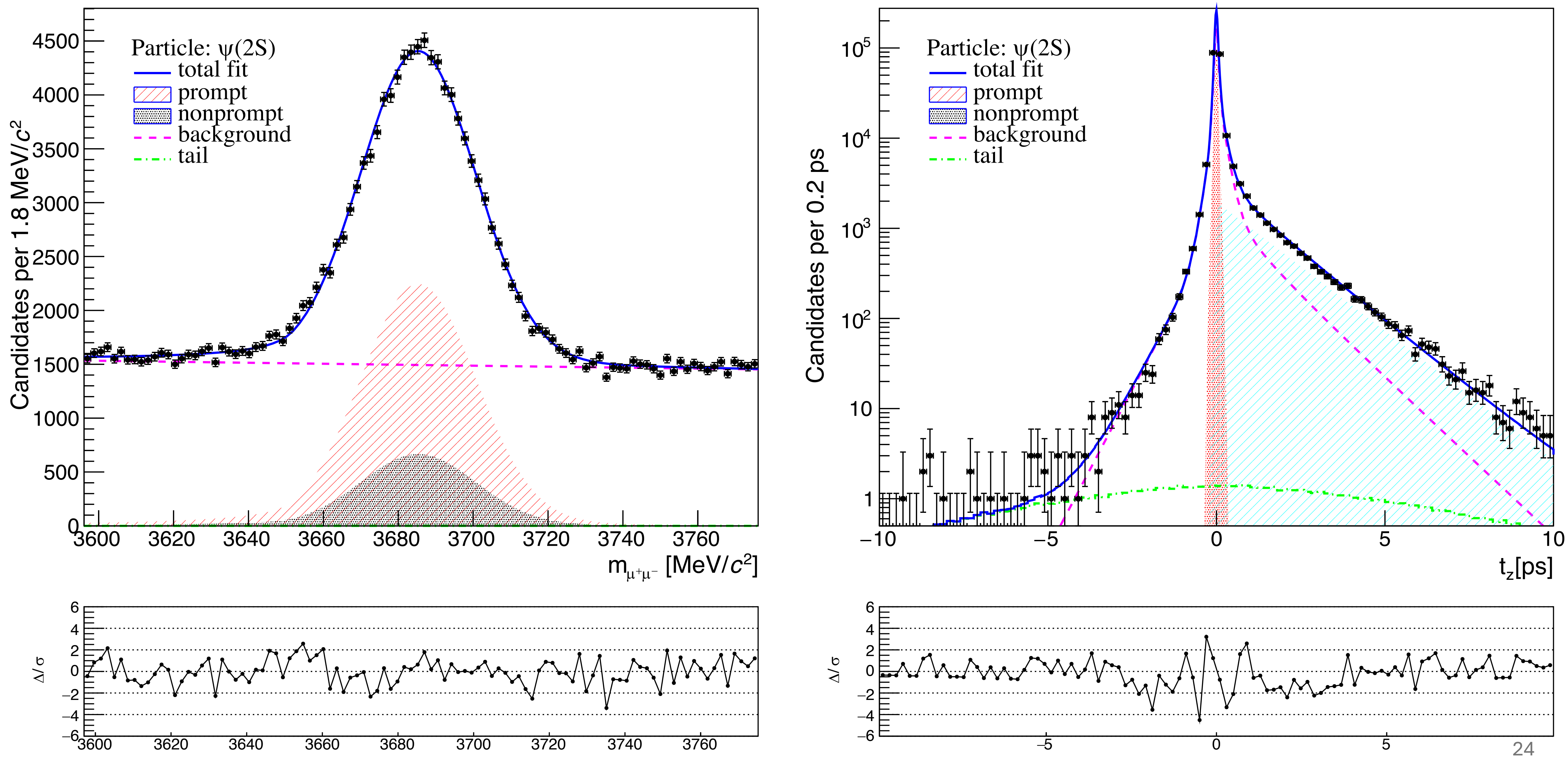
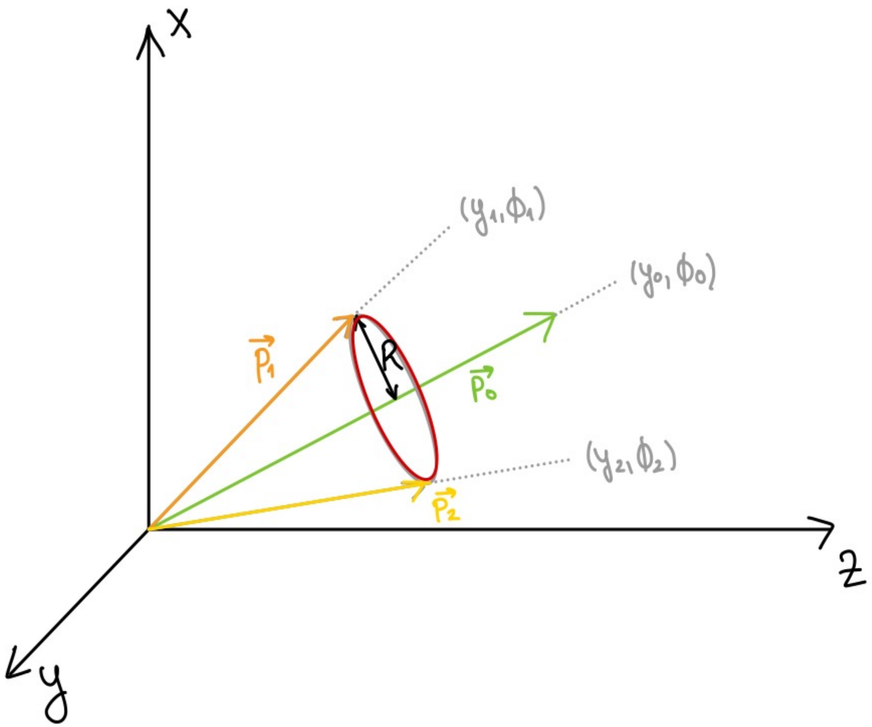
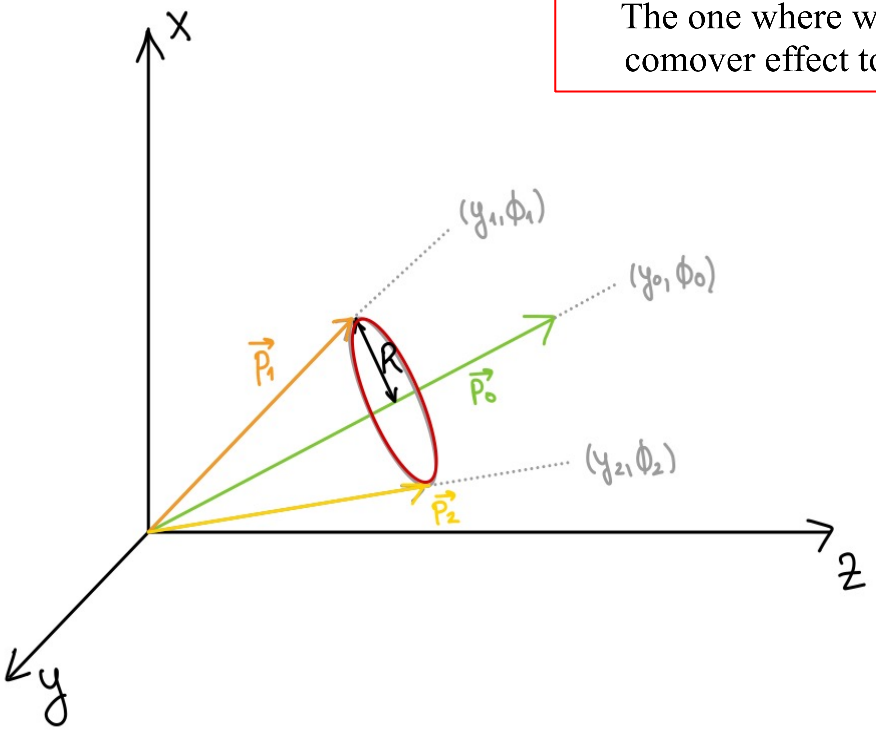


Back to the cone



Cone - since charmonium state and comovers originate from the same point

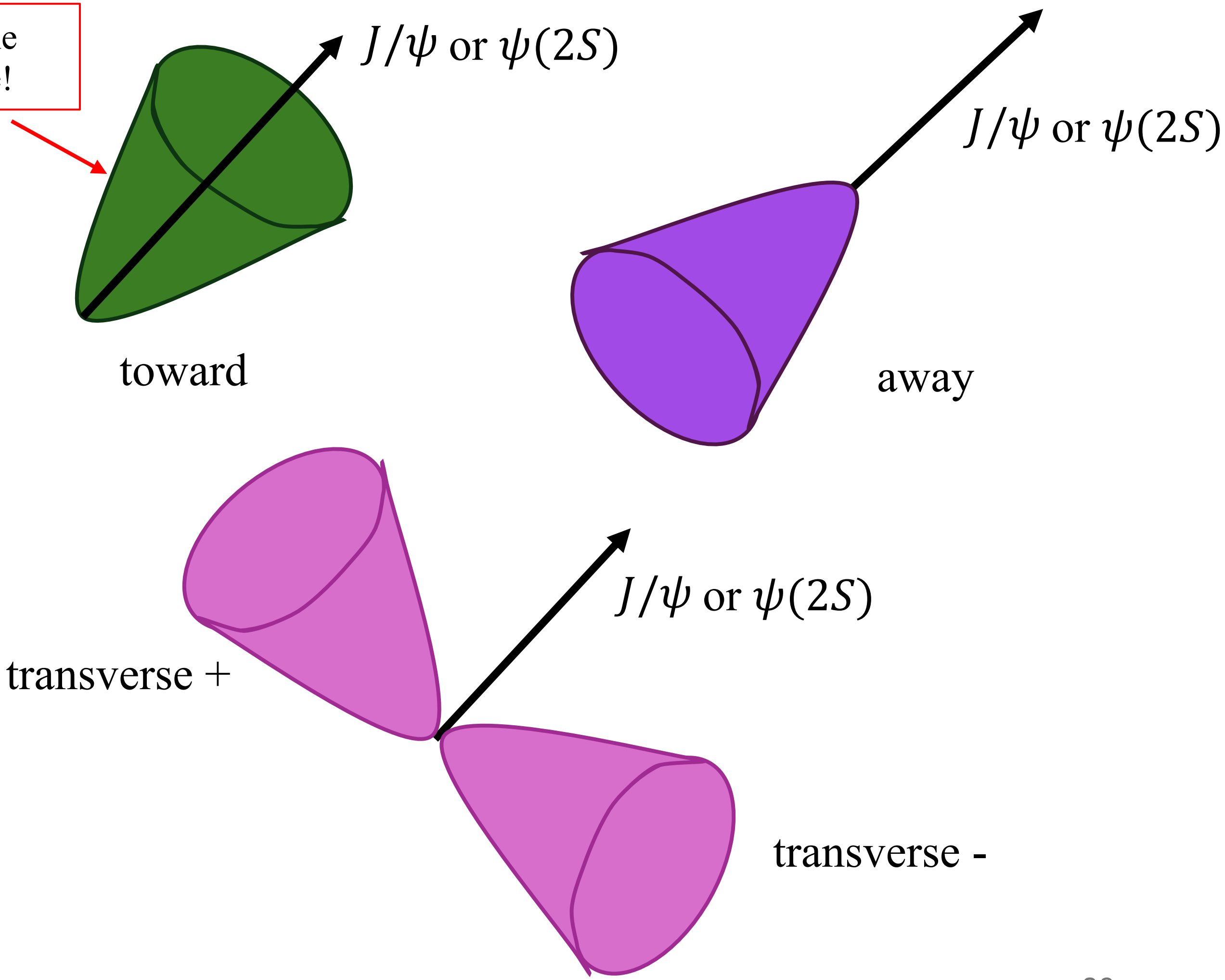
Back to the cone



Cone - since charmonium state and comovers originate from the same point

Various cones to consider:

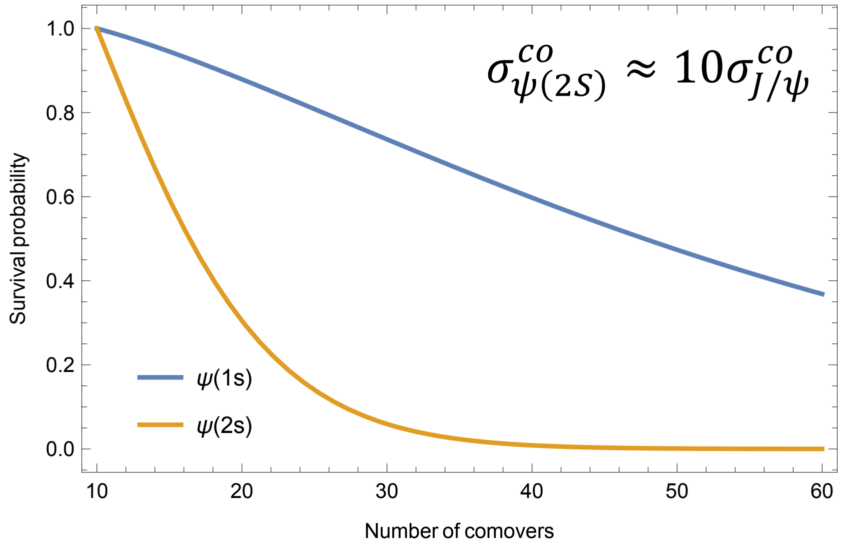
The one where we expect the comover effect to be visible!



Investigating the cone

What does our theoretical model predict?

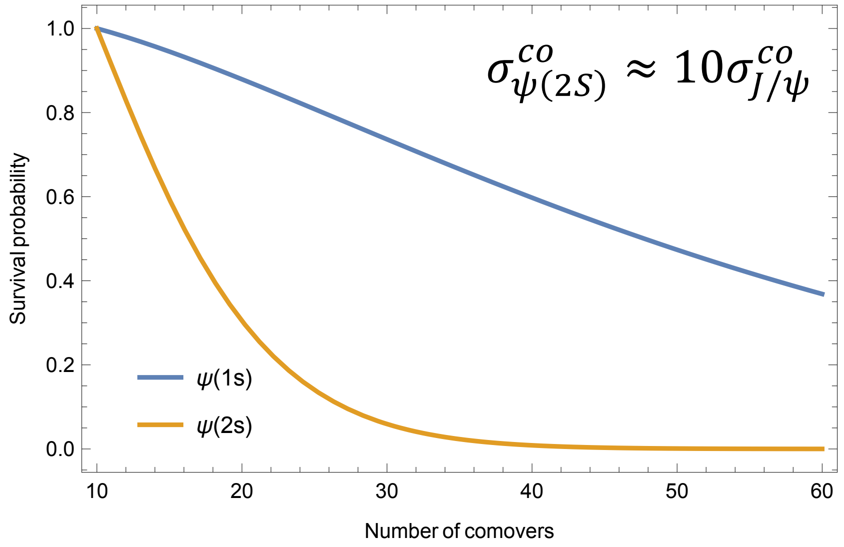
- Survival probability of charmonia based on the number of comovers around it



Investigating the cone

What does our theoretical model predict?

- Survival probability of charmonia based on the number of comovers around it
- Number of comovers in the cone of a certain size around a charmonium state
- Ratio of this number for two states J/ψ and $\psi(2S)$



Investigating the cone

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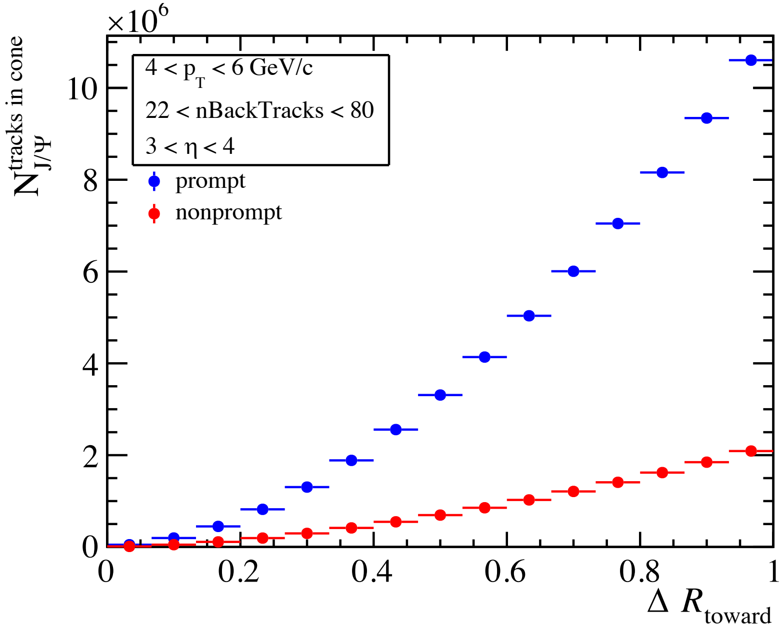
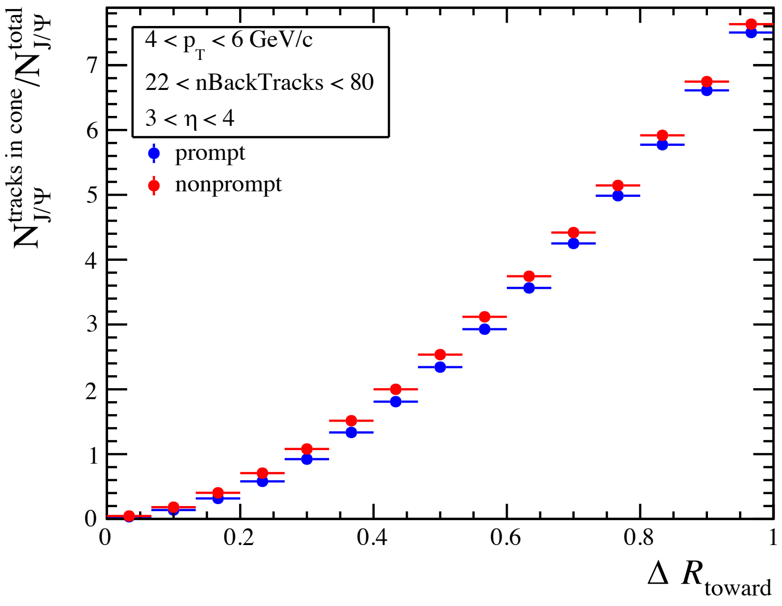
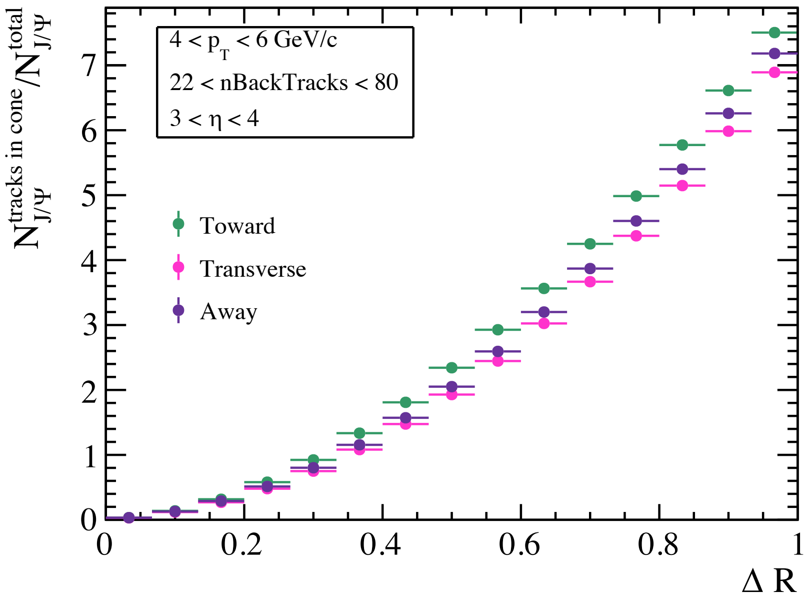


Unnormalized number of **prompt and nonprompt** tracks in one cone type



Normalized number of **prompt and nonprompt** tracks in one cone type



Normalized number of **prompt** tracks in various cone types

Investigating the cone

What does our theoretical model predict?

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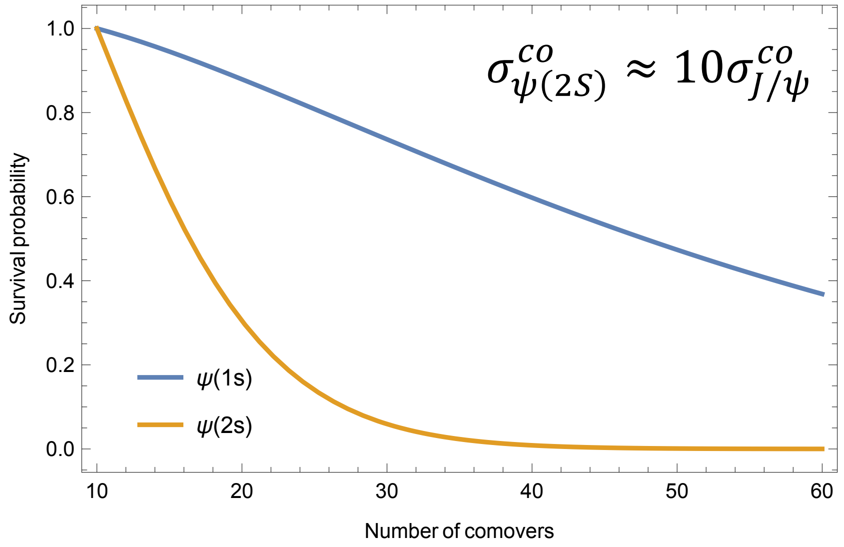
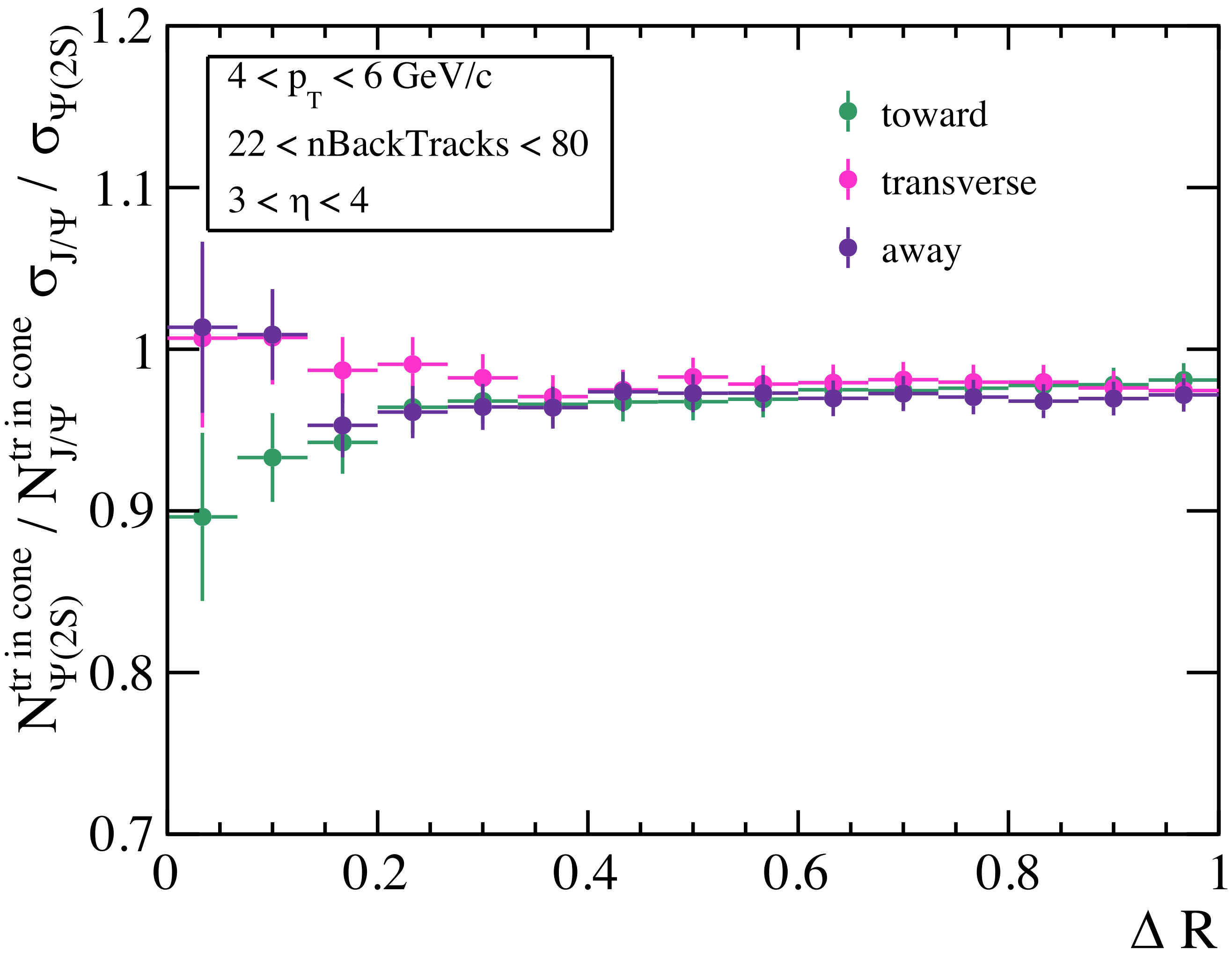
- Ratio of this number for two states J/ψ and $\psi(2S)$



Investigating the cone



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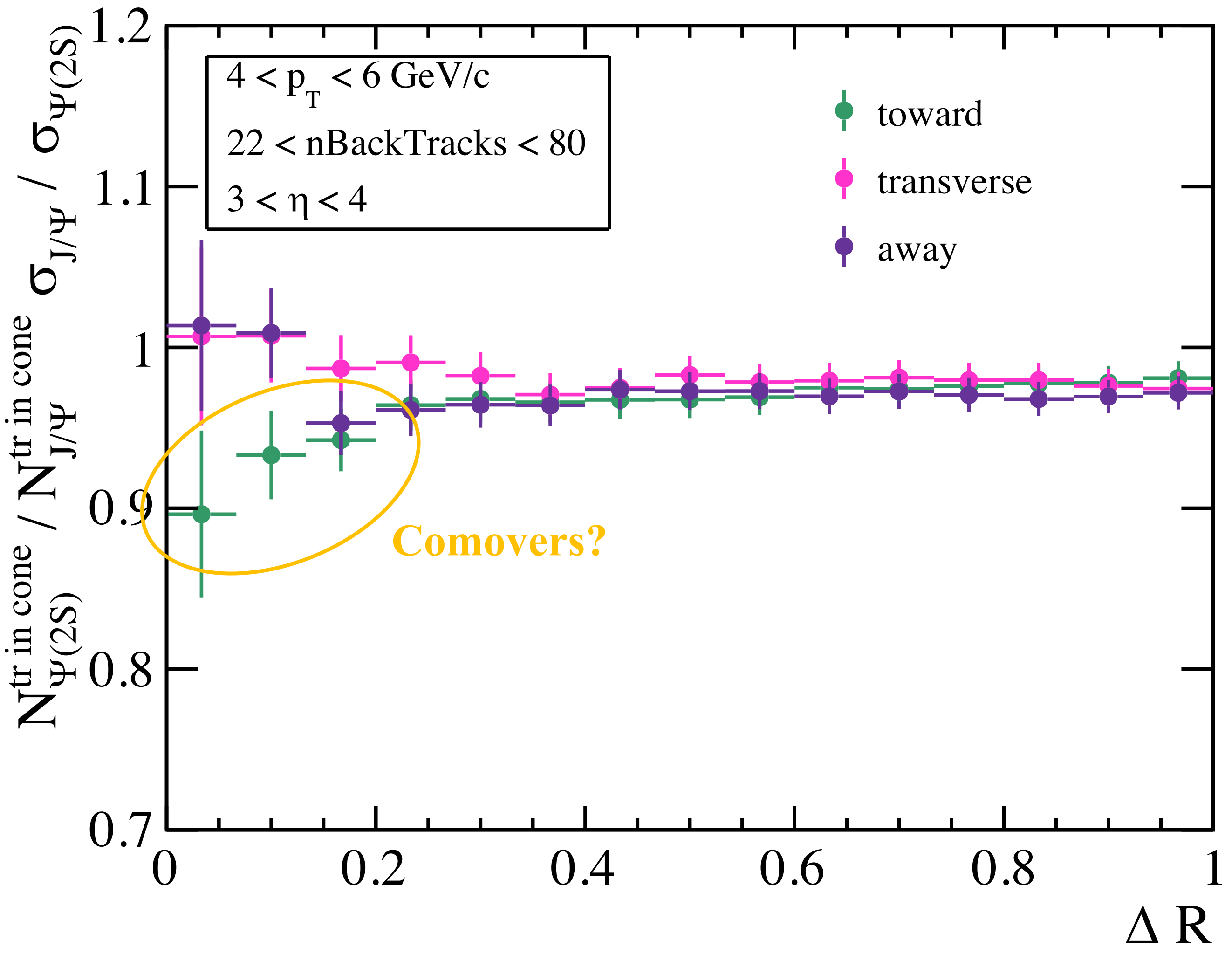

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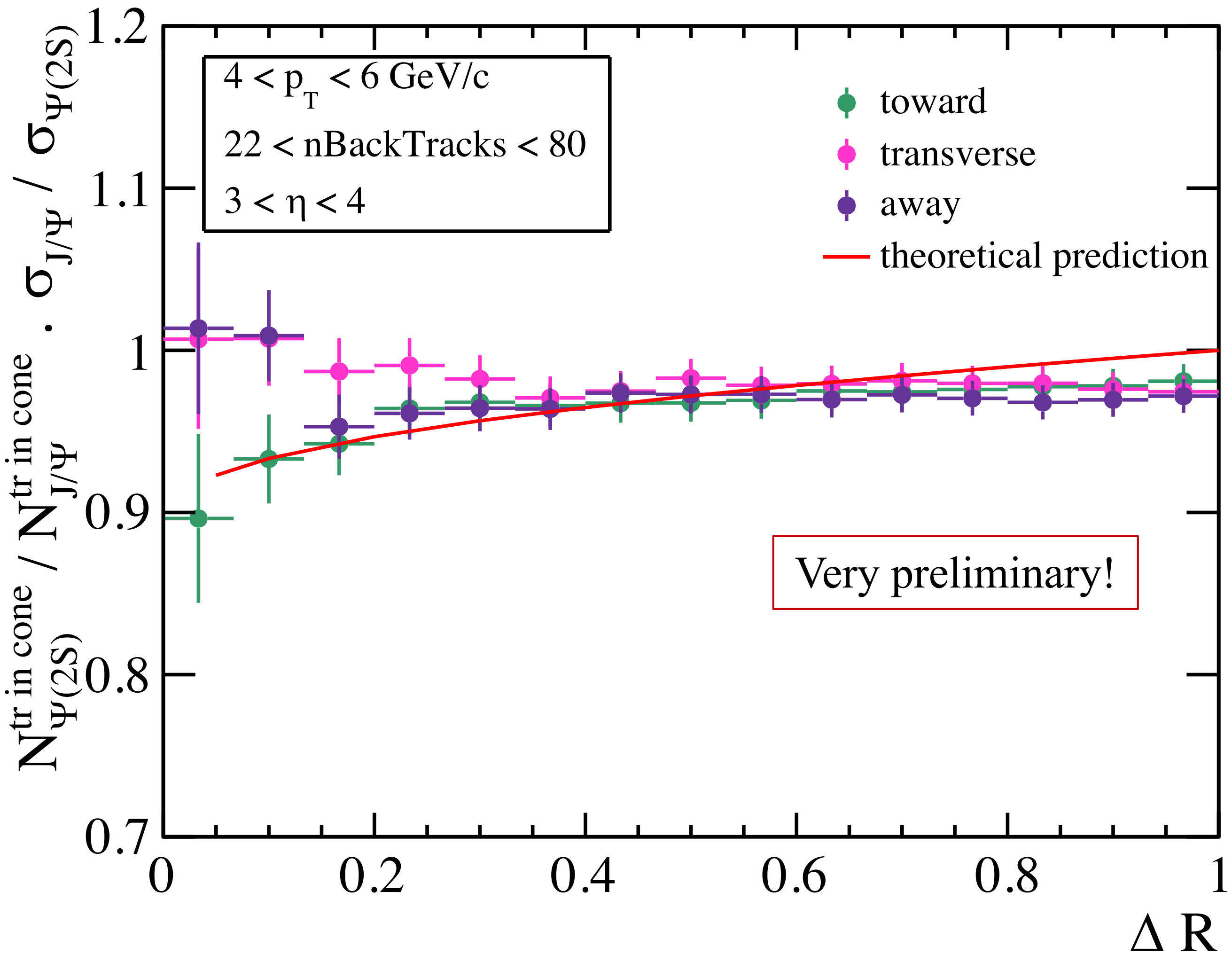

Conclusions

Idea: Current model takes into account the whole space. Only comovers close to the quarkonium state can break it => localized approach for improving precision.

This work presents the start of the **first ever** study of quarkonia suppression due to comover interactions inside a cone around it, and preliminary analysis results show a **promising match** with recently developed theoretical model.

In the next month: Deeper investigation into relevant variables for the comover effect, normalization, correlation between different cone types…

After: Finalizing the analysis by computing efficiencies and applying corrections, finalizing the theoretical model.

Thank you for your attention!