J/ψ and ψ(2S) measurements in p+p collisions at √s = 200 and 500 GeV in the STAR experiment

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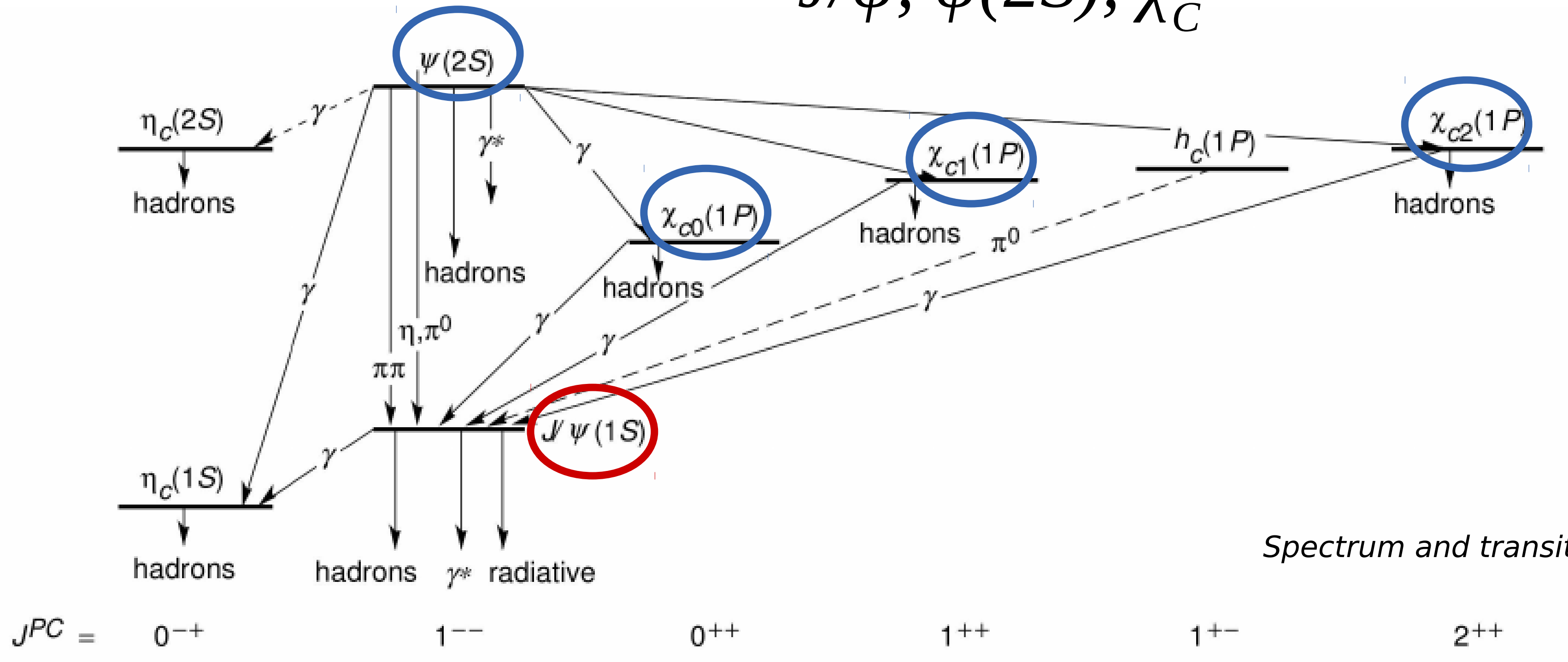
INVESTICE DO ROZVOJE VZDĚLÁVÁNÍ

Charmonia in p+p collisions

Charmonia - $c\bar{c}$ bound states

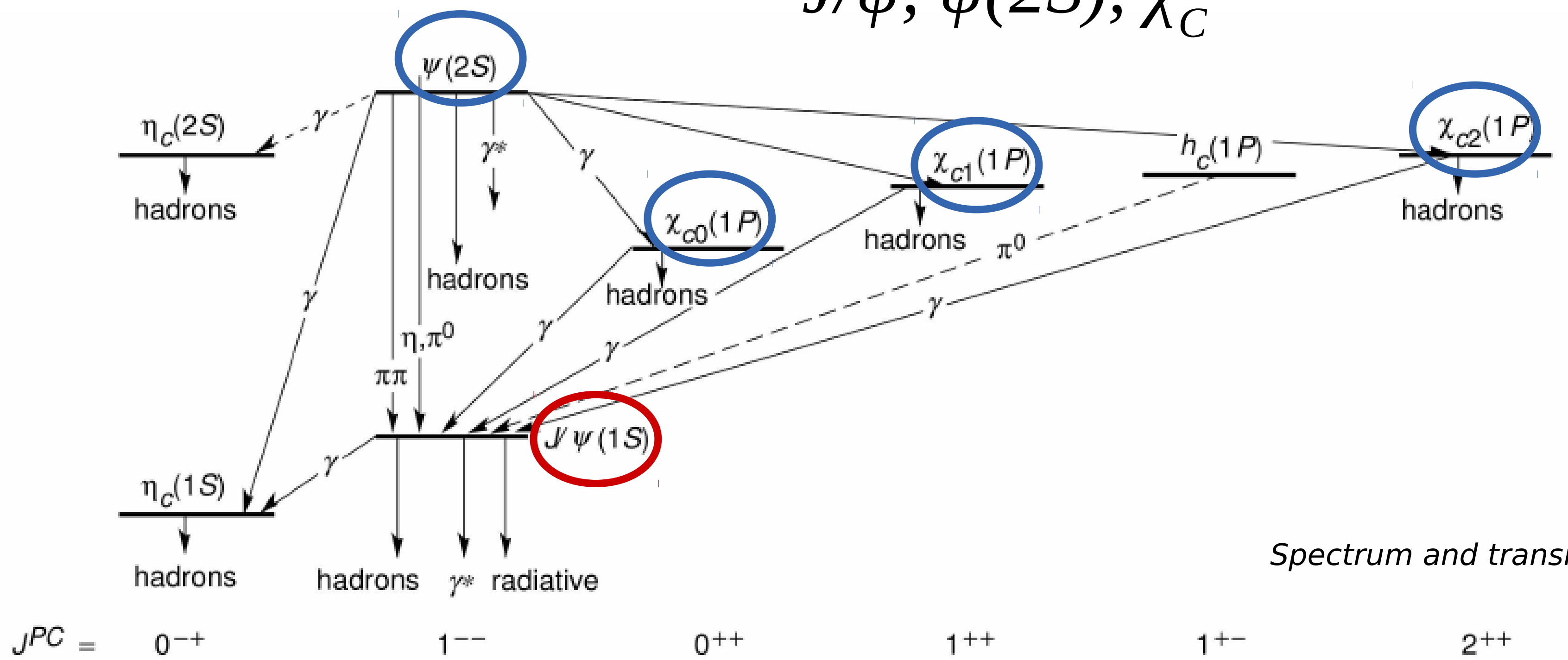
J/ψ, $\psi(2S)$, χ_C



Spectrum and transitions of the charmonium family

Charmonia in p+p collisions

Charmonia - $c\bar{c}$ bound states J/ψ, $\psi(2S)$, χ_C



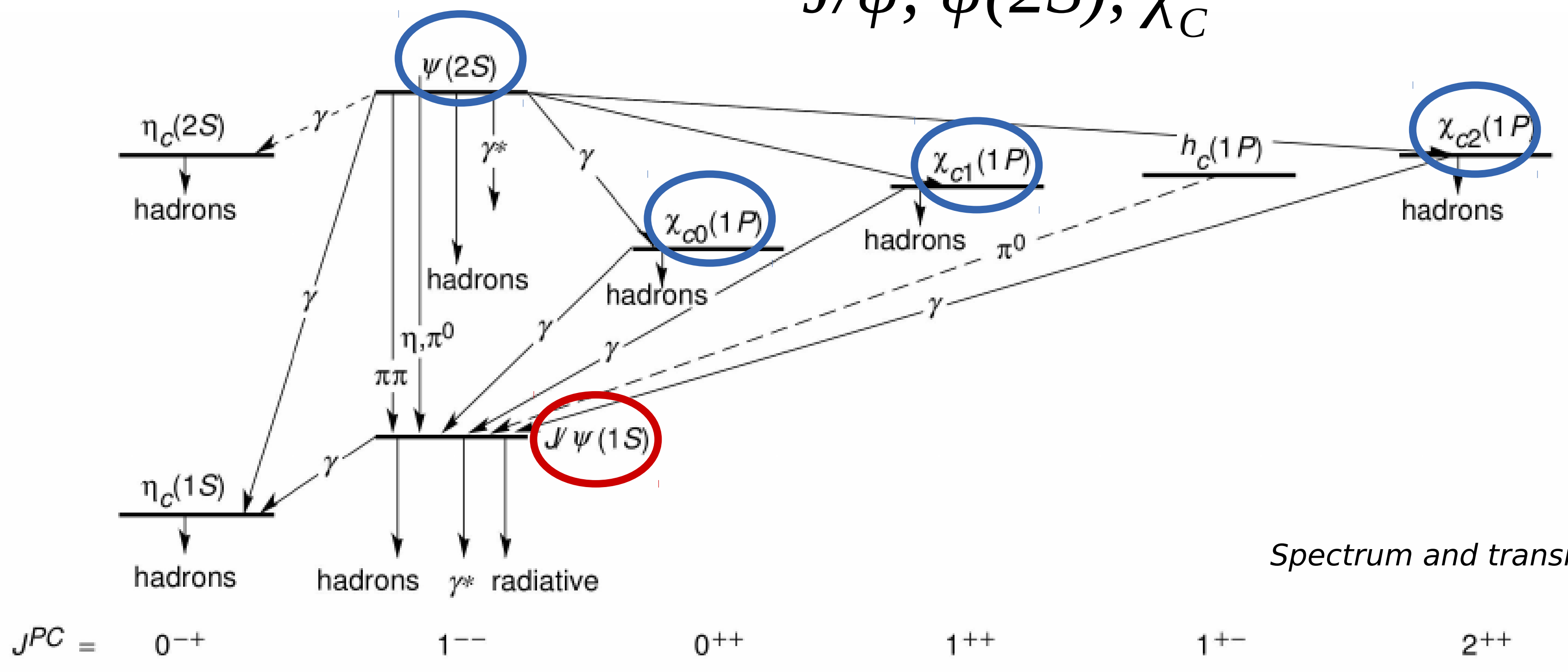
Spectrum and transitions of the charmonium family

- ***Production mechanism*** in elementary collisions is not fully understood
  - ➔ Color singlet vs color octet
- Color-singlet process: J/ψ is produced via intermediate color-neutral $c\bar{c}$ state with the same quantum numbers as the final J/ψ state
- Color-octet process: J/ψ is produced via intermediate colored $c\bar{c}$ state of any possible quantum numbers

➔ ***Quarkonium measurements - tests of different production models, help to understand QCD***

Charmonia in p+p collisions

Charmonia - $c\bar{c}$ bound states J/ψ, $\psi(2S)$, χ_C



Spectrum and transitions of the charmonium family

- ***Feed-down***

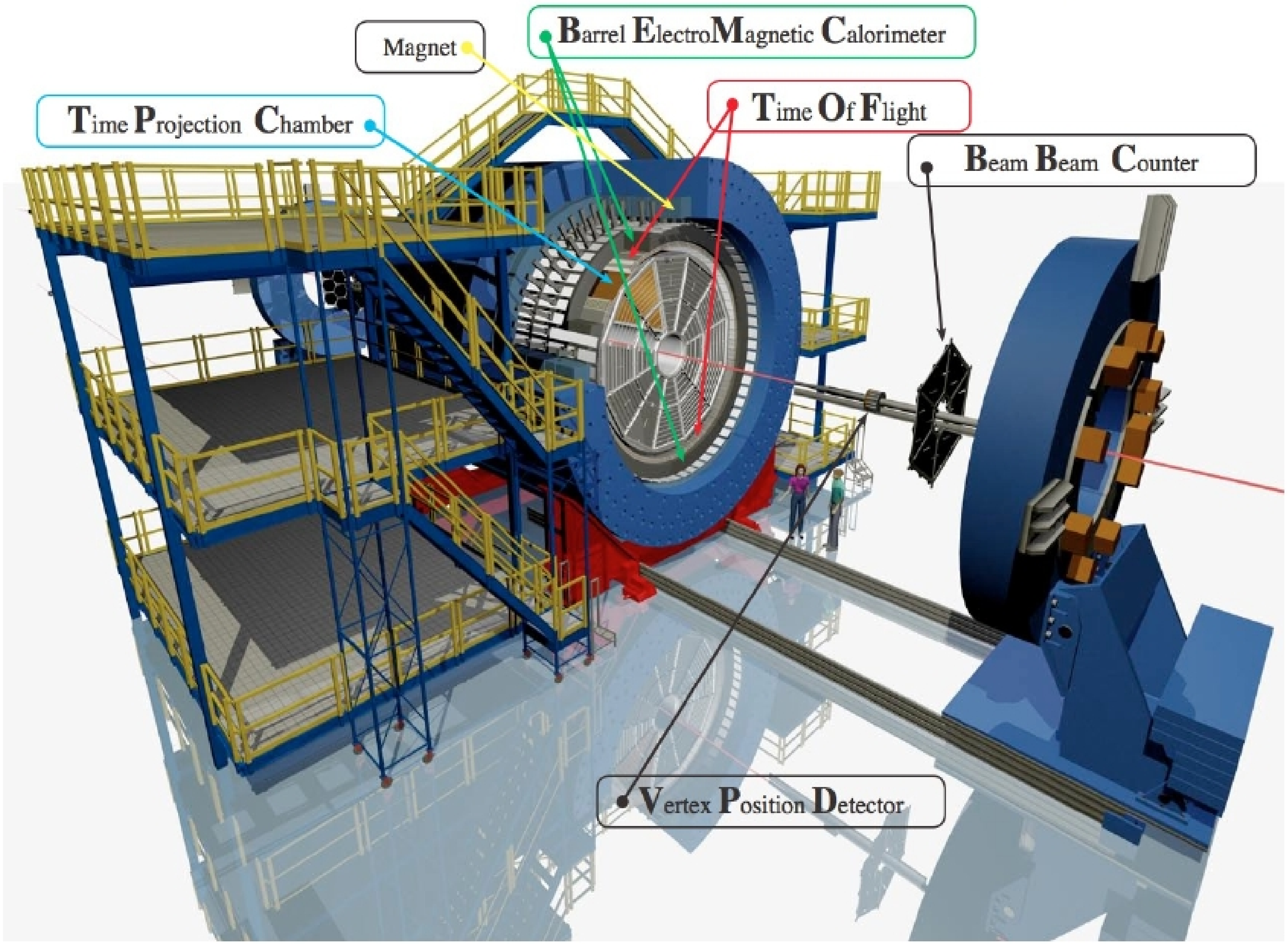
  Inclusive J/ψ production:

  - <u>prompt J/ψ</u>
    - direct J/ψ (~60%), feed down from ψ(2S) (~10%) and χ_C (~30%) decays
  - <u>non-prompt J/ψ</u>: B-mesons feed-down (10-25% at 4-12 GeV/c, STAR: Phys. Lett. B722 (2013) 55)

STAR Experiment at RHIC

$J/\psi,\ \psi(2S) \rightarrow e^+ e^-$

Large acceptance: $|\eta| < 1,\ 0 < \varphi < 2\pi$



- ✓ VPD - minimum bias trigger
- ✓ TPC
- ✓ TOF
- ✓ BEMC

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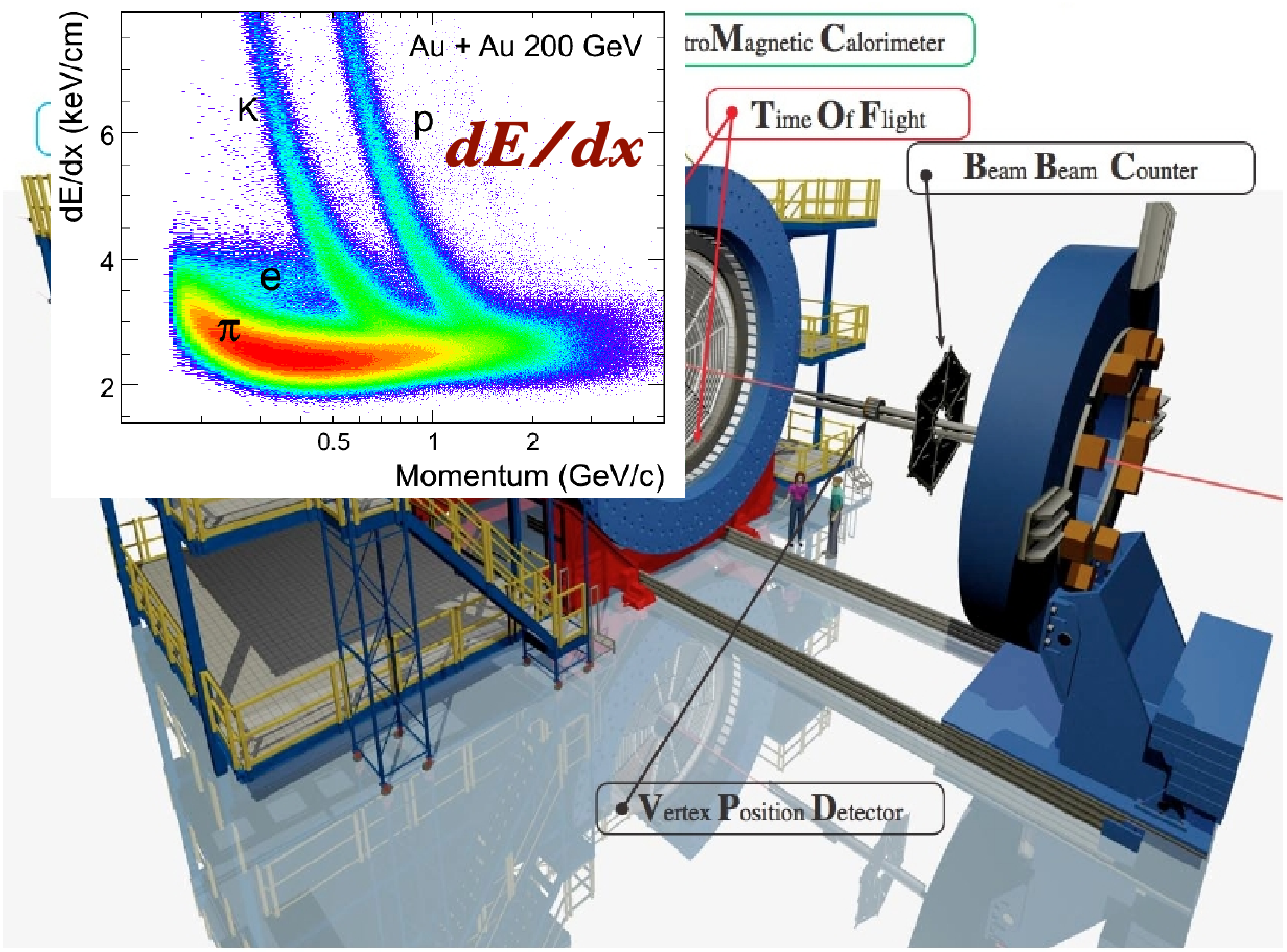

- ✓ VPD - minimum bias trigger
- ✓ TPC – tracking, **PID**: dE/dx
- ✓ TOF
- ✓ BEMC

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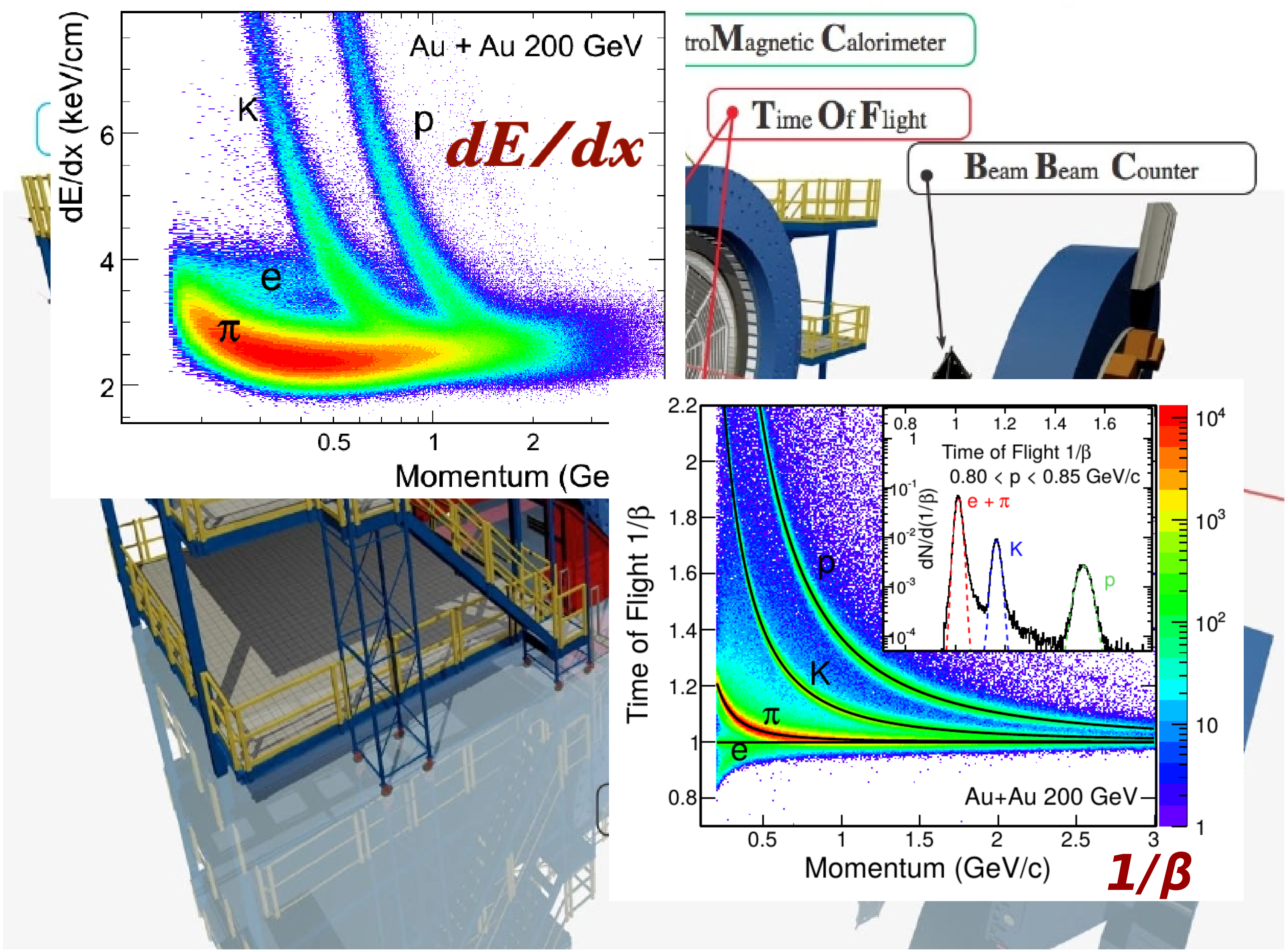

- VPD - minimum bias trigger
- TPC – tracking, **PID**: dE/dx
- TOF – time resolution < 100 ps **PID**: $1/\beta$
- BEMC

STAR Experiment at RHIC

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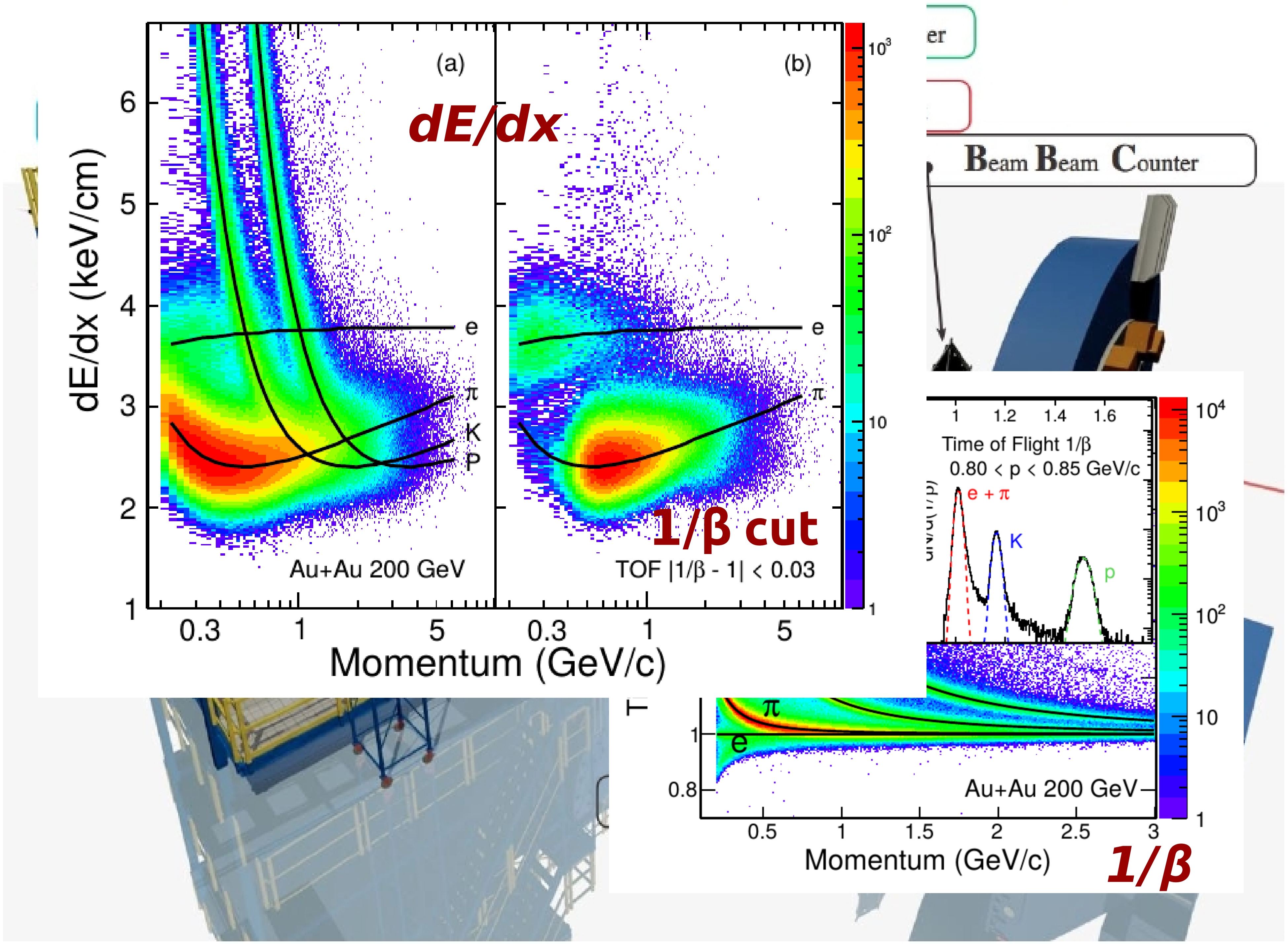

- VPD - minimum bias trigger
- TPC – tracking, **PID**: dE/dx
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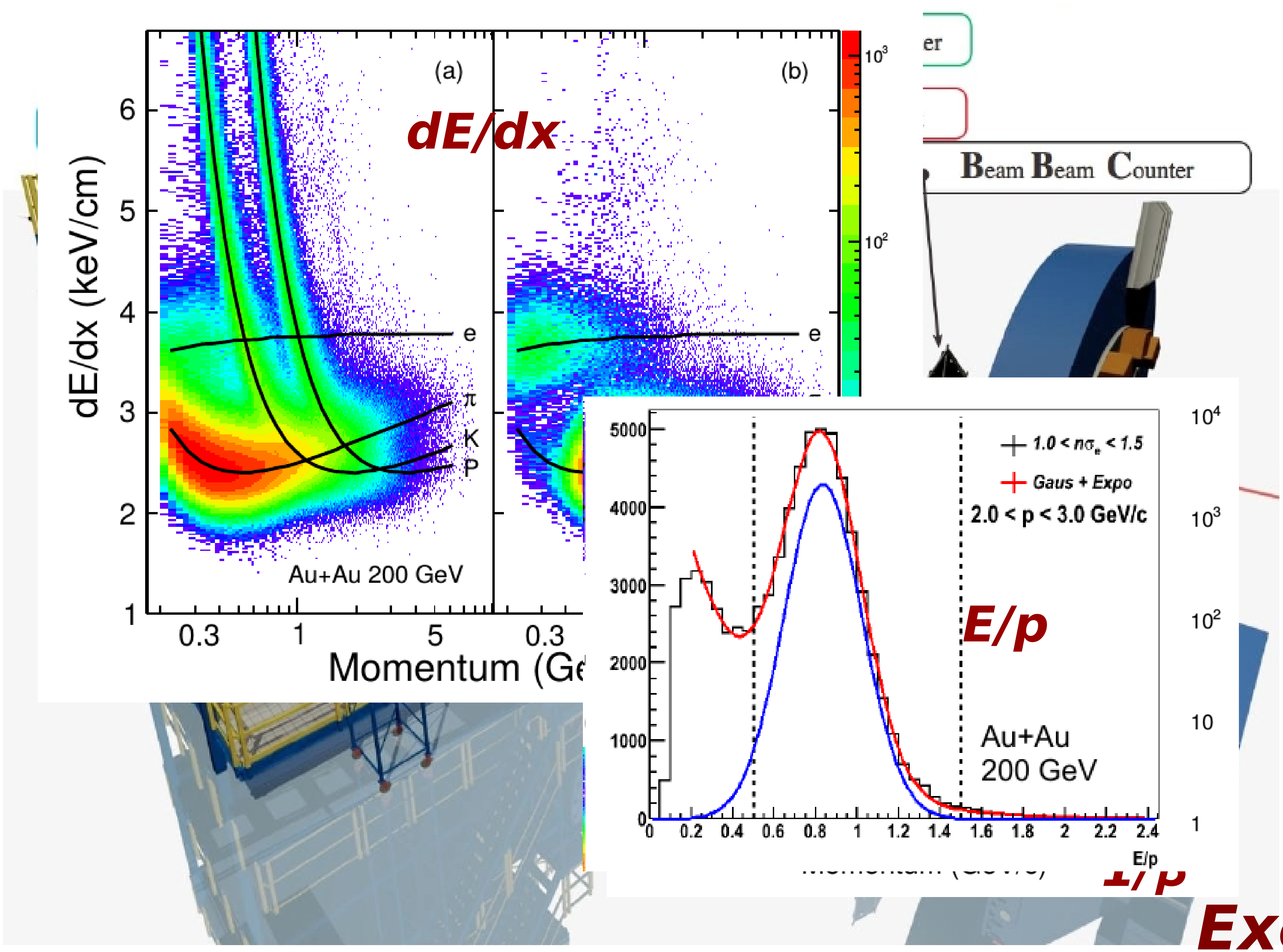
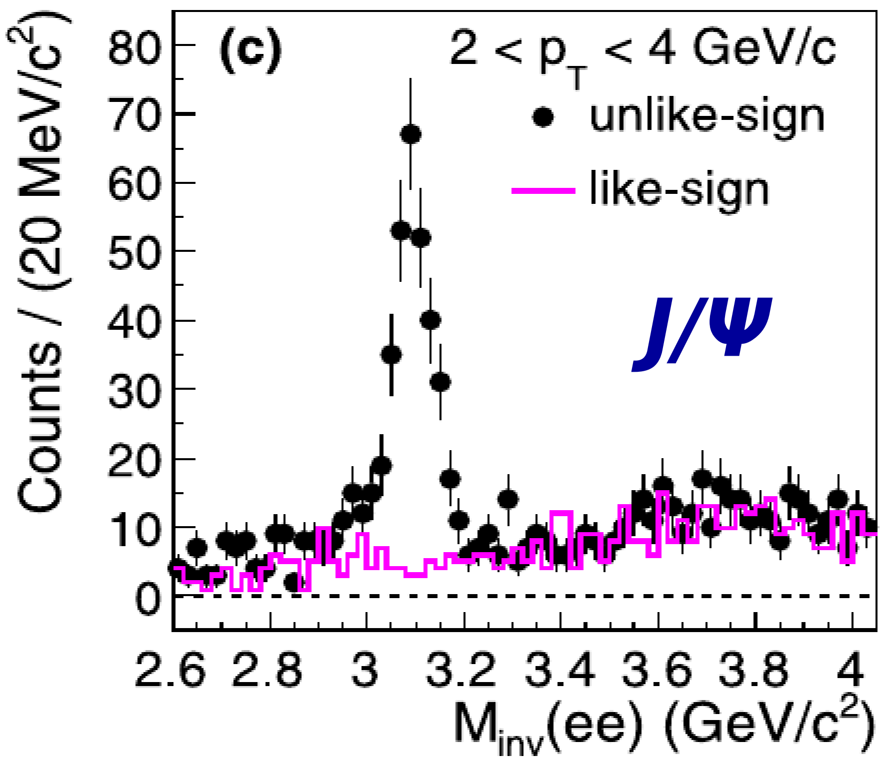


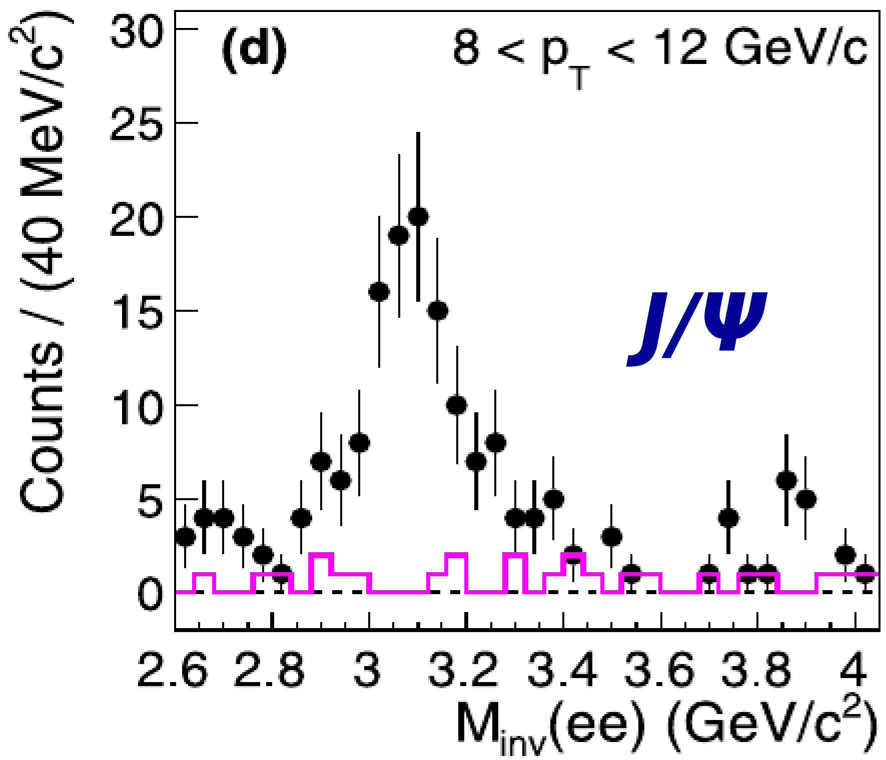
- ✓ VPD - minimum bias trigger
- ✓ TPC – tracking, **PID**: dE/dx
- ✓ TOF – time resolution < 100 ps **PID**: $1/\beta$
- ✓ BEMC – trigger, **PID**: E/p (~1 for electron)

Excellent eID

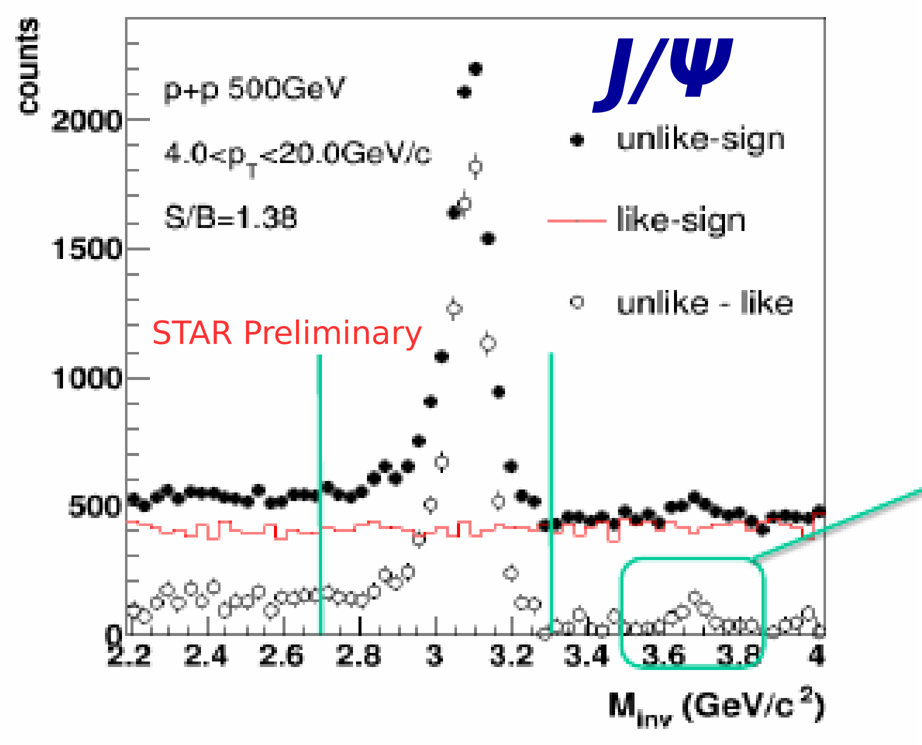
J/Ψ and Ψ(2S) signals

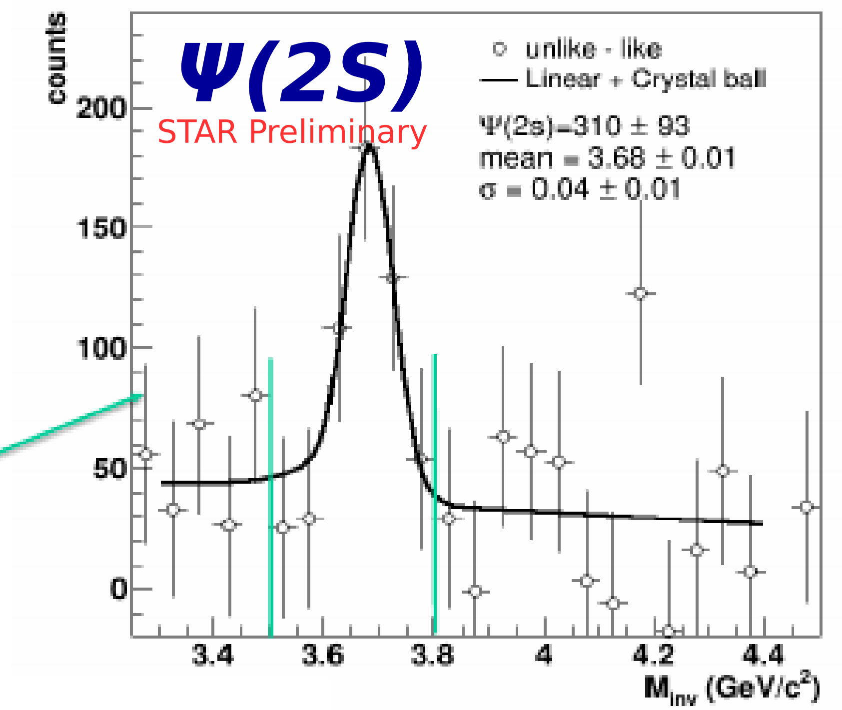
Phys. Lett. B 722 (2013) 55





p+p 200 GeV



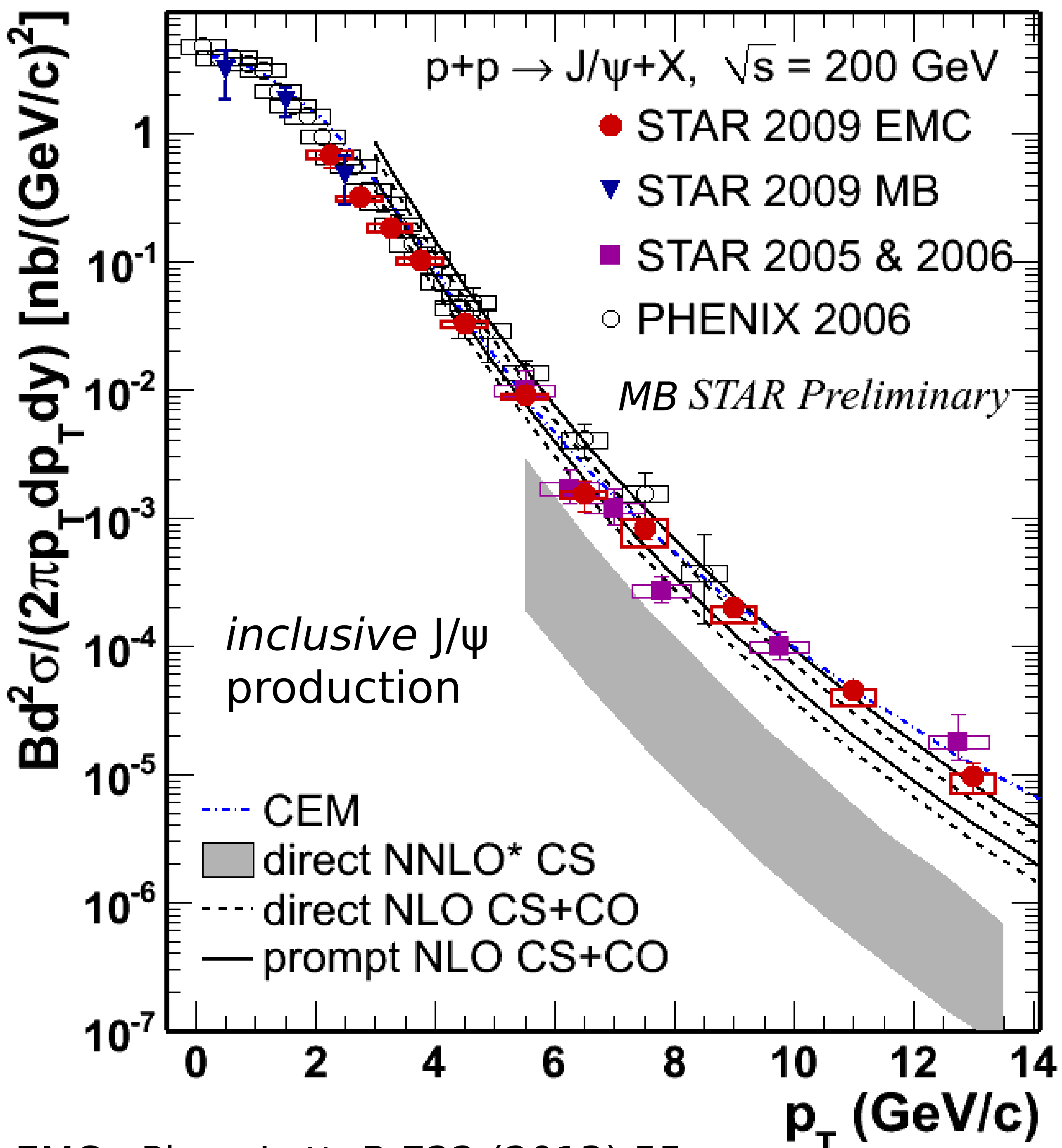


p+p 500 GeV

J/Ψ p_T spectrum in p+p 200 GeV

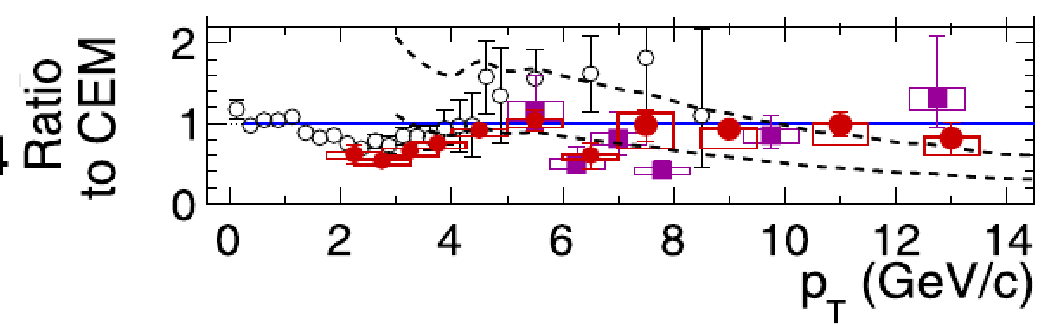
- Test of charmonium production models

STAR 2005&2006: Phys. Rev. C80, 041902(R) (2009)
PHENIX: Phys. Rev. D 85, 092004 (2012)
direct NNLO CS: P.Artoisenet et al., Phys. Rev. Lett. 101, 152001 (2008) and J.P.Lansberg private communication
NLO CS+CO: Y.-Q.Ma, K.Wang, and K.T.Chao, Phys. Rev. D 84, 51 114001 (2011) and private communication
CEM: A.D. Frawley, T Ullrich, R. Vogt, Pys. Rept. 462 (2008) 125, and R.Vogt private communication

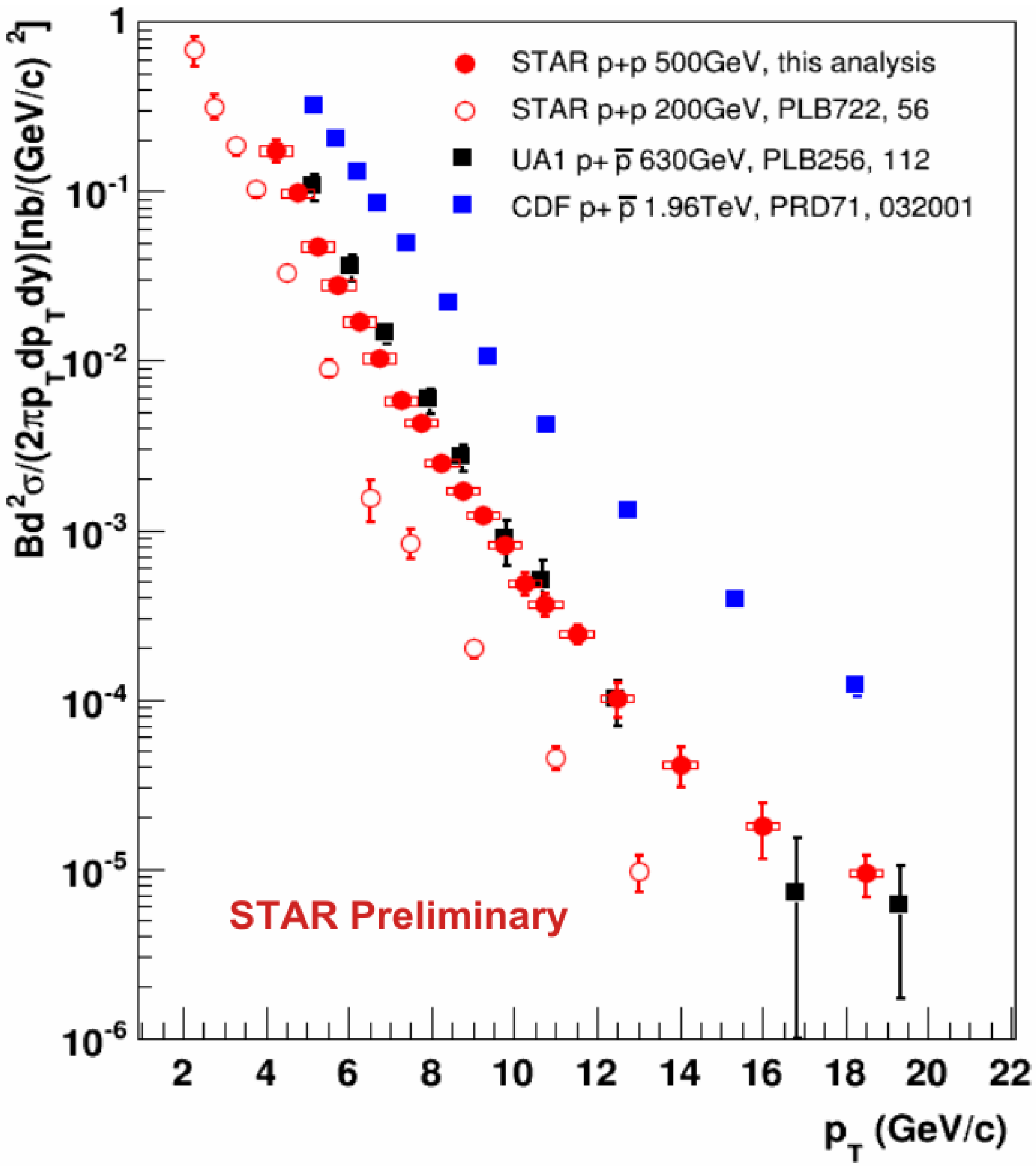


STAR EMC : Phys. Lett. B 722 (2013) 55
STAR MB: Acta Phys. Polonica B Vol.5, No 2 (2012), 543

- ✓ *prompt* NLO CS+CO model describes the data for $p_T > 4$ GeV/c
- ✓ *direct* NNLO* CS model misses high-p_T part
- ✓ *prompt* CEM model can reasonably well describe the p_T spectra (overpredicts the data at $p_T \sim 3$ GeV/c)

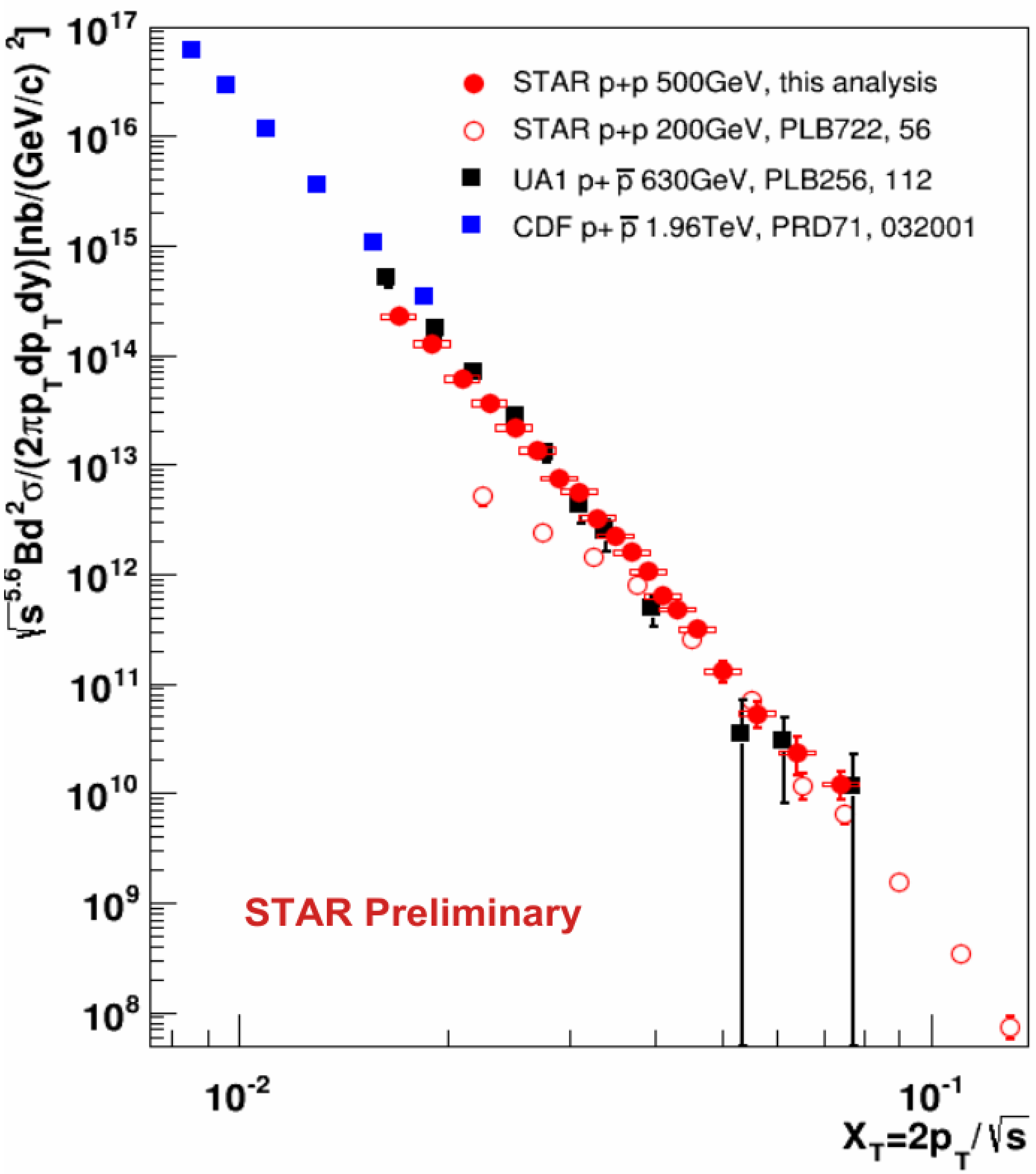


J/Ψ p_T spectrum in p+p 500 GeV



- ✓ Precise J/ψ measurement at new beam energy, up to p_T = 20 GeV/c

J/Ψ x_T scaling



$$x_T = 2p_T/\sqrt{s}$$

$$\frac{d^2\sigma}{2\pi\, p_T\, dp_T\, dy} = g(x_T)/(\sqrt{s})^n$$

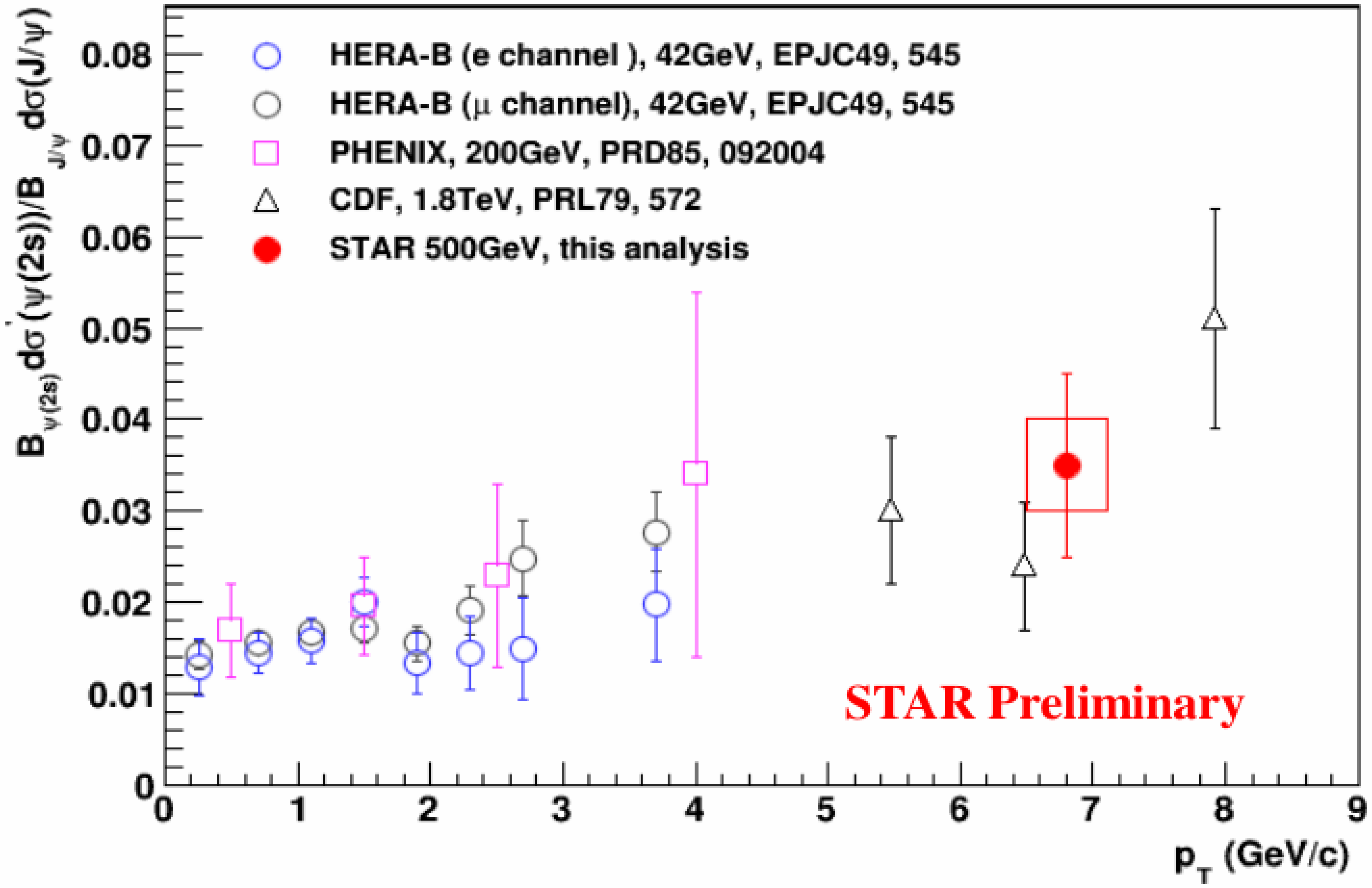
- ✓ p_T > 5 GeV/c – J/ψ production follows the x_T scaling of cross-section at mid-rapidity, with n = 5.6 (Phys. Rev. C 80, 041902 (2009))

→ x_T scaling breaking - transition from hard to soft process

n – number of constituents taking an active role in hadron production

Ψ(2S) in p+p 500 GeV

- Further test of charmonium production models
- Constrain ψ(2S) feed-down contribution to inclusive J/ψ production

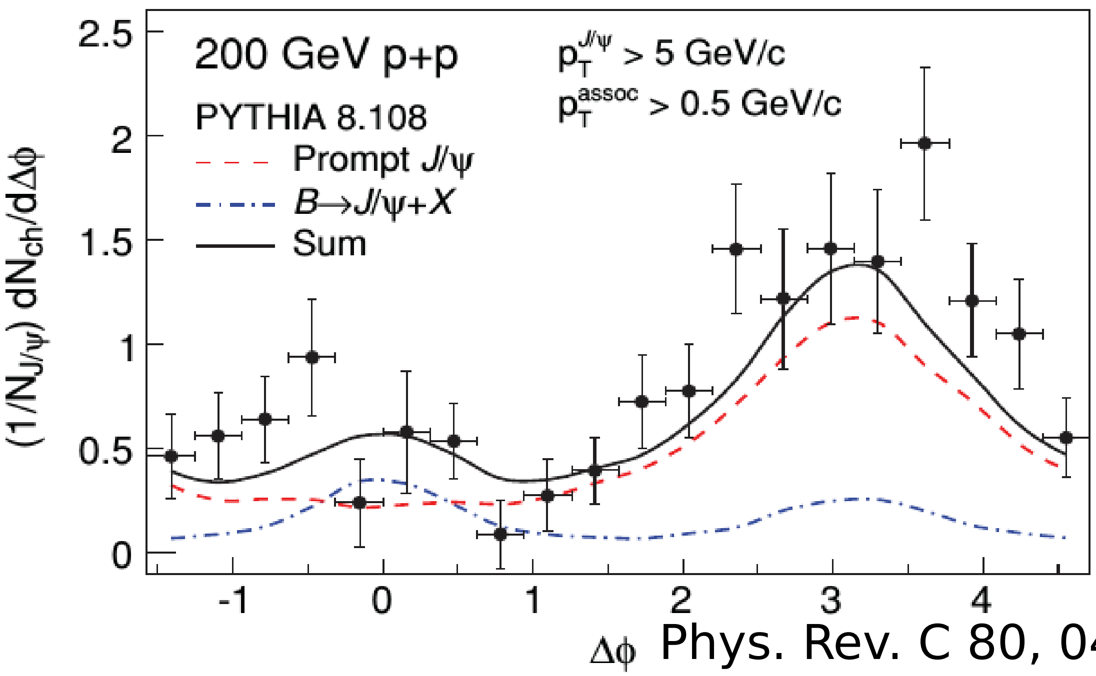


✓ First measurement of (ψ(2S) / J/ψ) ratio in p+p at 500 GeV

- Consistent with other experiments
- No collision energy dependence observed

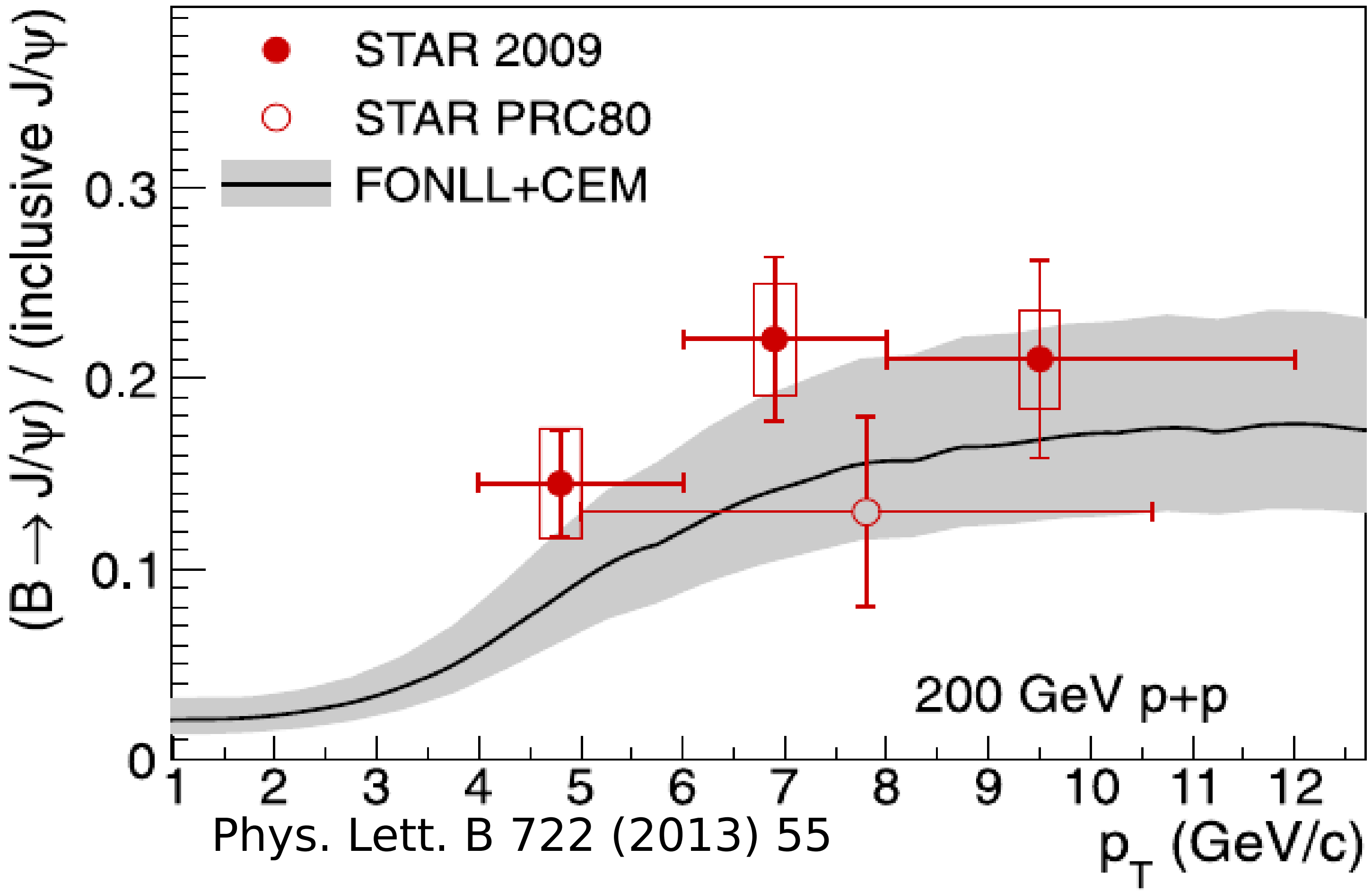
B -> J/Ψ fraction in p+p 200 GeV

- ✓ Measurement based on azimuthal angular correlations between high-p_T J/ψ and charged hadrons



Phys. Rev. C 80, 041902 (2009)

- ➔ B-hadron feed-down contribution: 10-25%, in the range 4 < p_T < 12 GeV/c
- ➔ Agreement with FONLL + CEM prediction



Phys. Lett. B 722 (2013) 55

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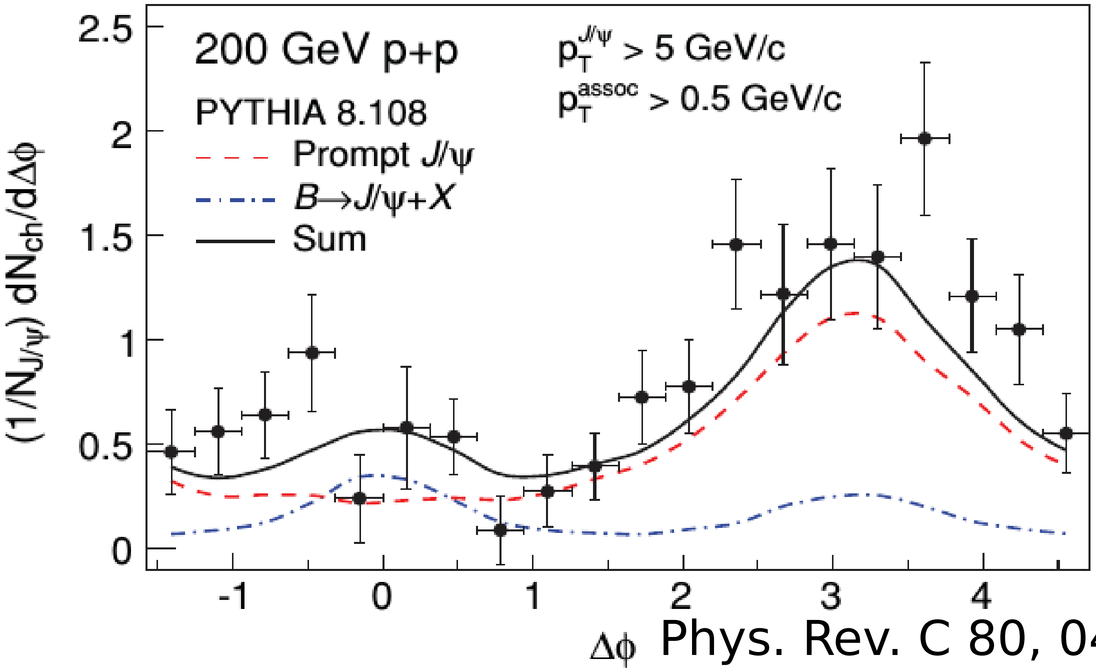

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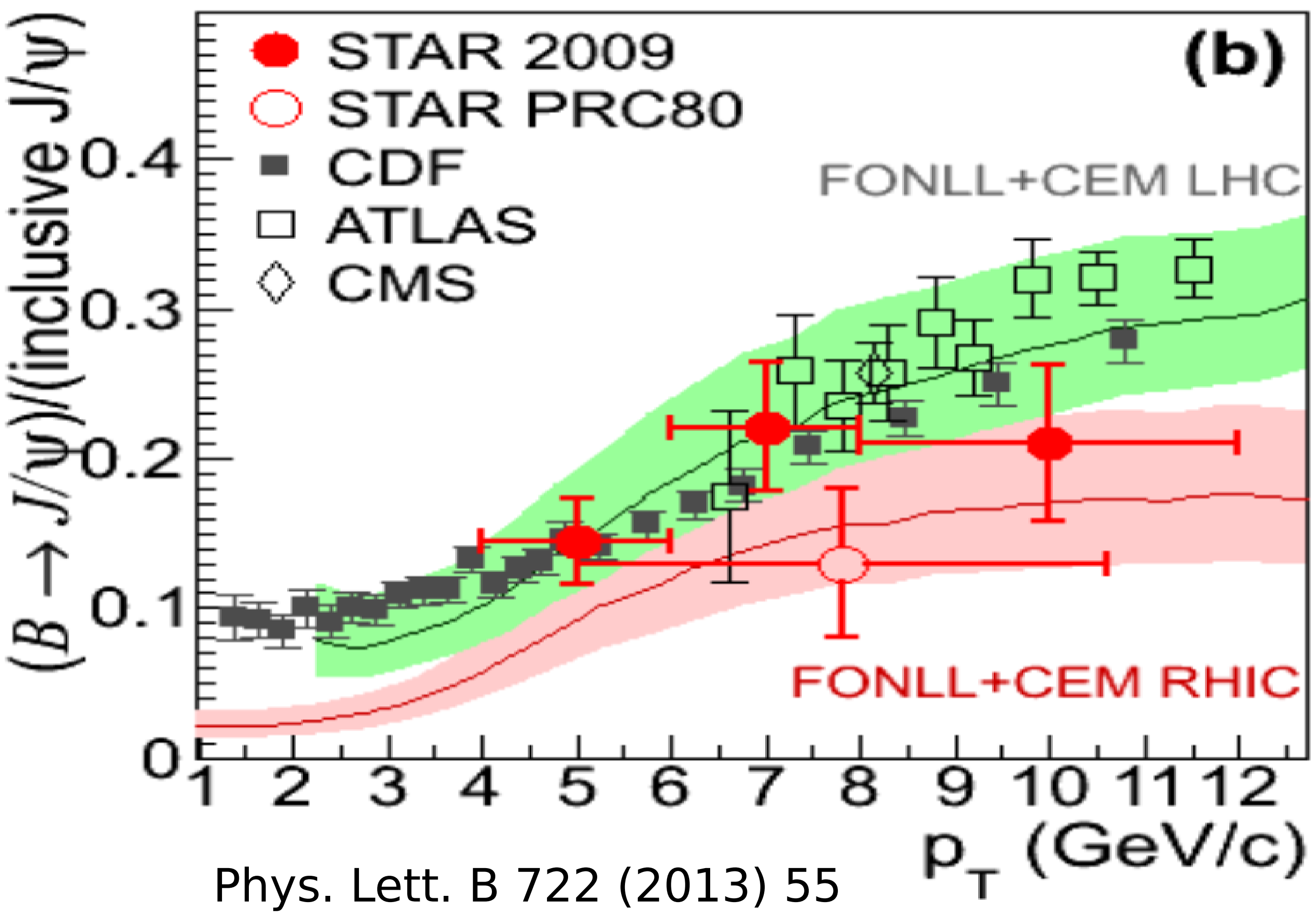
➔ B-hadron feed-down contribution: 10-25%, in the range 4 < p_T < 12 GeV/c

➔ Agreement with FONLL + CEM prediction and with measurements from other experiments



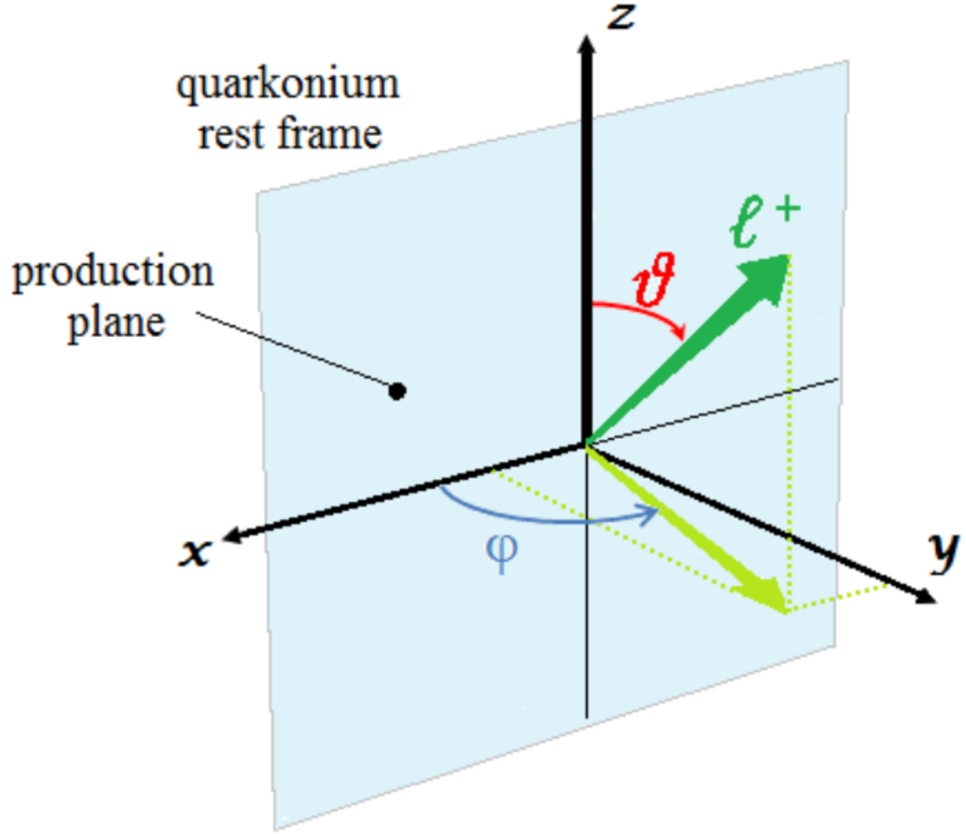
Phys. Lett. B 722 (2013) 55

J/Ψ polarization

- Discrimination power between different J/ψ production models
  - Competing mechanisms domination in different theoretical approaches lead to different expected polarization

J/ψ polarization can be analyzed via the angular distribution of the decay lepton pair

$$\frac{d\sigma}{d(cos\theta)d\phi} \propto 1 + \lambda_\theta cos^2\theta + \lambda_{\theta\phi} sin(2\theta) cos\phi + \lambda_\phi sin^2\theta cos(2\phi)$$



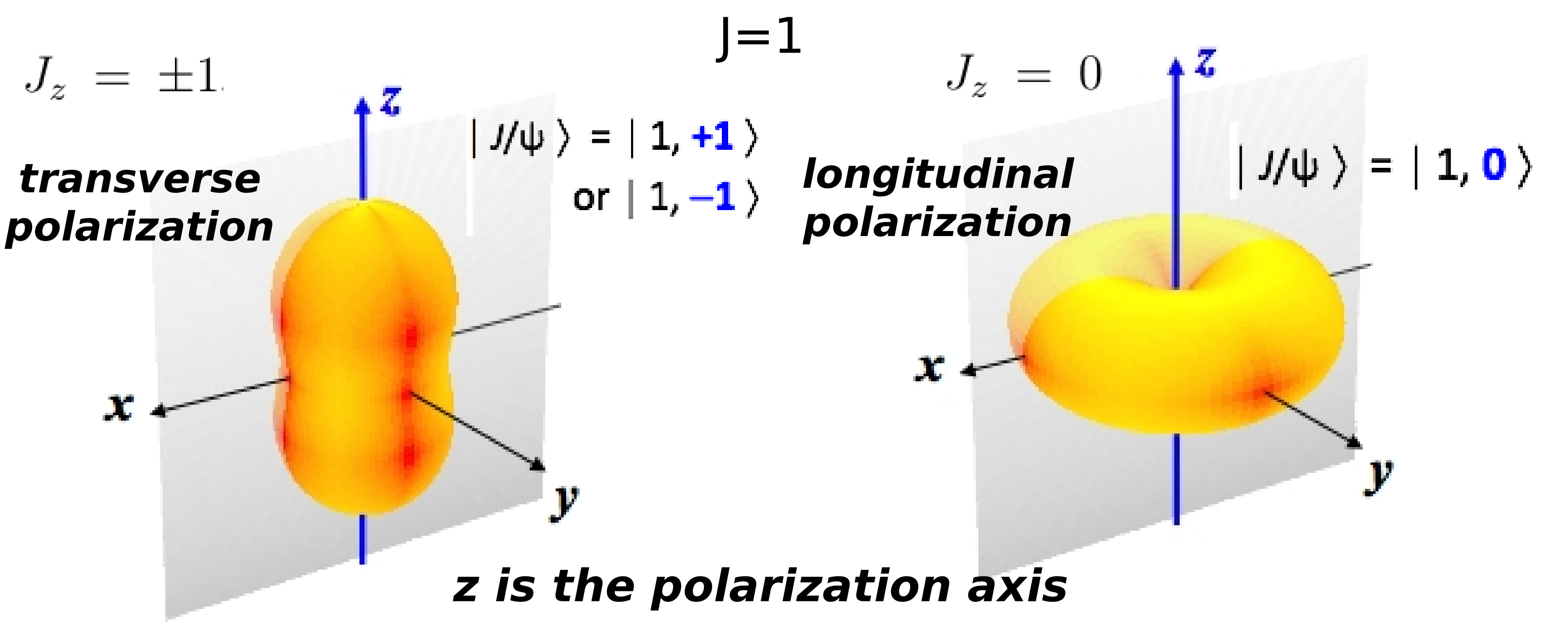
- **θ** - polar angle between momentum of a positive lepton in the J/ψ rest frame and the polarization axis *z*
- **φ** - corresponding azimuthal angle

In the ***helicity frame*** *z* axis is defined along the J/ψ momentum in the center of mass frame

J/Ψ polarization

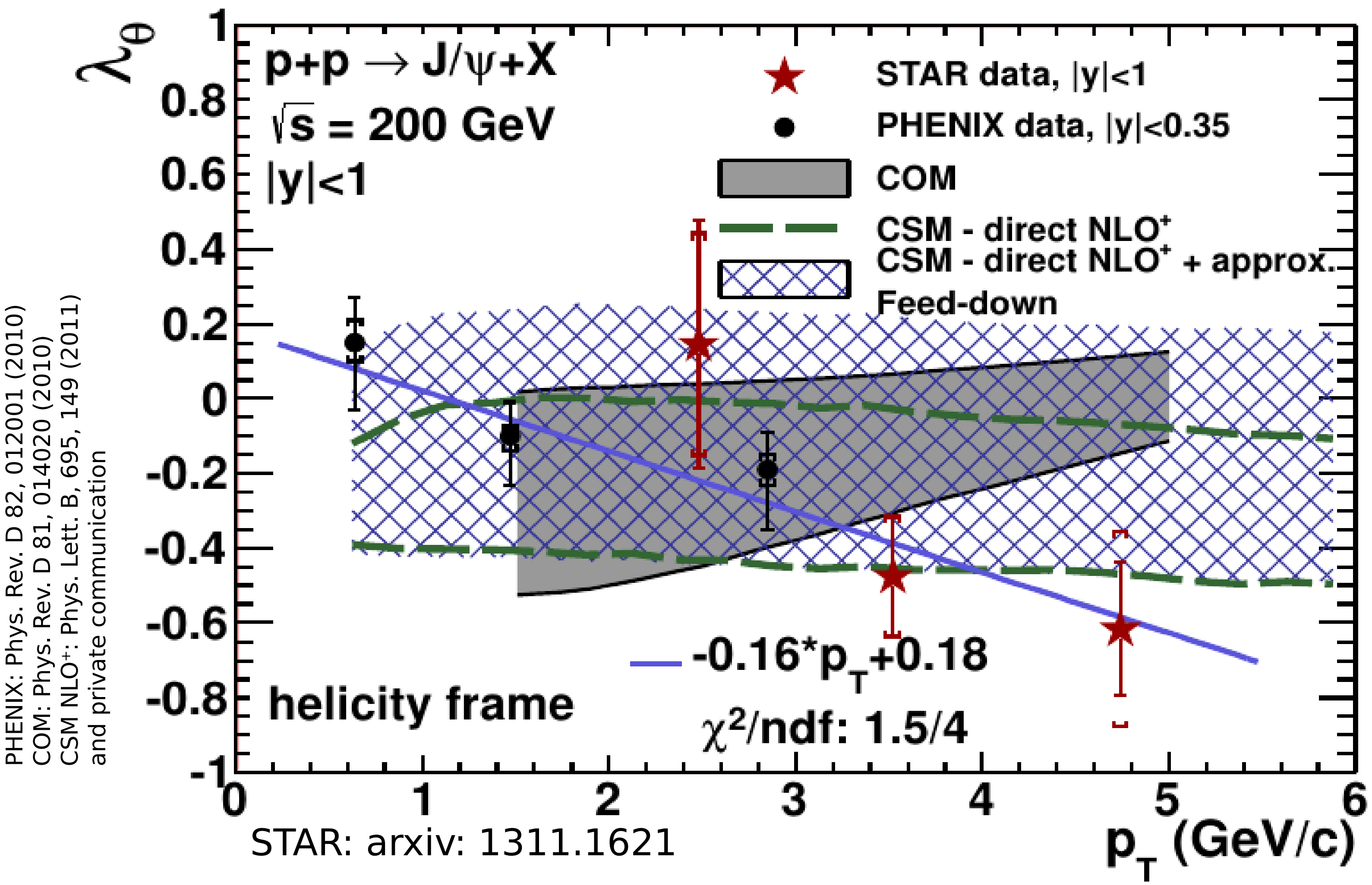
- Discrimination power between different J/ψ production models
  - Competing mechanisms domination in different theoretical approaches lead to different expected polarization

***J* = 1** → three J_z eigenstates |**1, +1**〉, |**1, 0**〉, |**1, -1**〉



P. Faccioli, C. Laorenco, J. Seixas, H.K. Wohri, Eur. Phys. J. C 69, 657 (2010)

J/Ψ polarization in p+p 200 GeV



STAR: arxiv: 1311.1621

The angular distribution integrated over the azimuthal angle:

$$W(cos\theta) \propto 1 + \lambda_\theta cos^2\theta$$

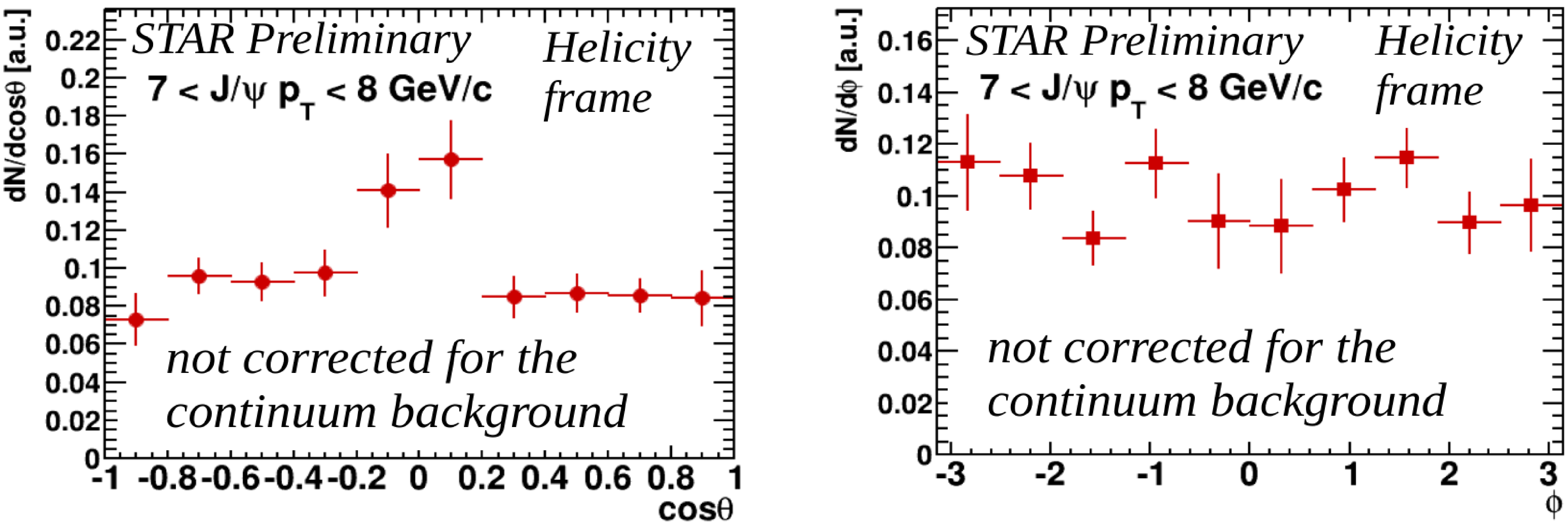
λ_θ – *polarization parameter*

λ_θ = -1- longitudinal polarization
λ_θ = 1 - transverse polarization

- ✓ Polarization parameter λ_θ is measured in the helicity frame at |y| < 1 and 2 < p_T < 6 GeV/c
  - ➔ RHIC data indicate trend towards longitudinal polarization with increasing p_T
  - ➔ The result is consistent with NLO+ CSM

J/Ψ polarization in p+p 500 GeV

- Information about full decay angular distribution
  - ✓ Measurement in progress, larger statistics ~22 pb^{-1} vs ~1.8 pb^{-1}



  - ✓ Reconstruction of both θ and φ angles
  - ✓ J/ψ signal up to p_T ~ 15 GeV/c, can be divided into ~ 5 p_T bins

Upgrades

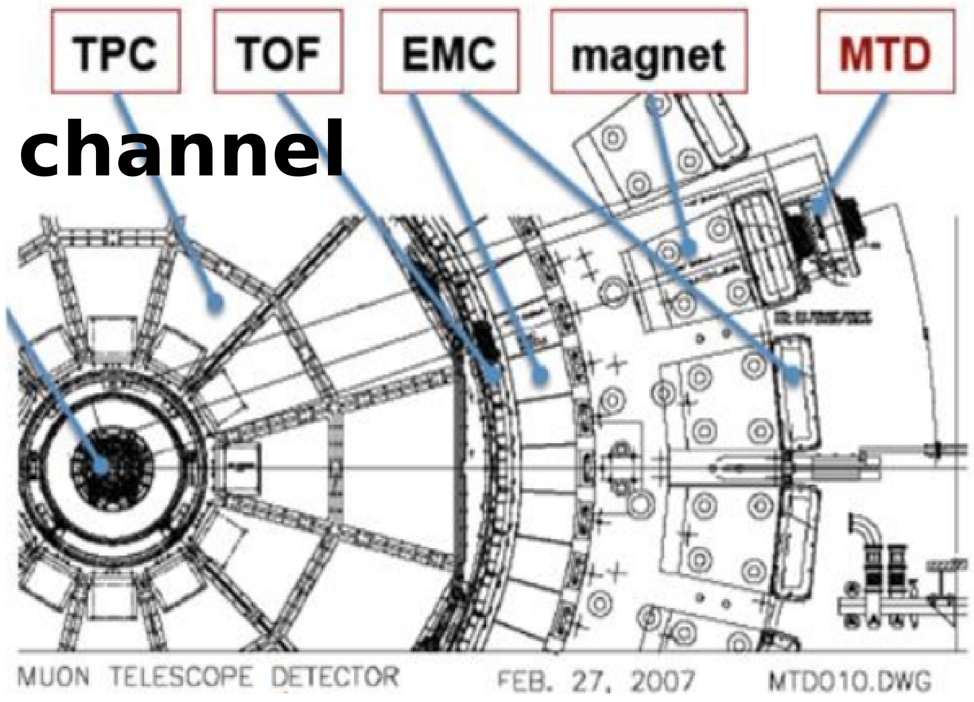
Fully installed and take data since 2014

Muon Telescope Detector (MTD)

Precision quarkonium measurements via di-μ channel

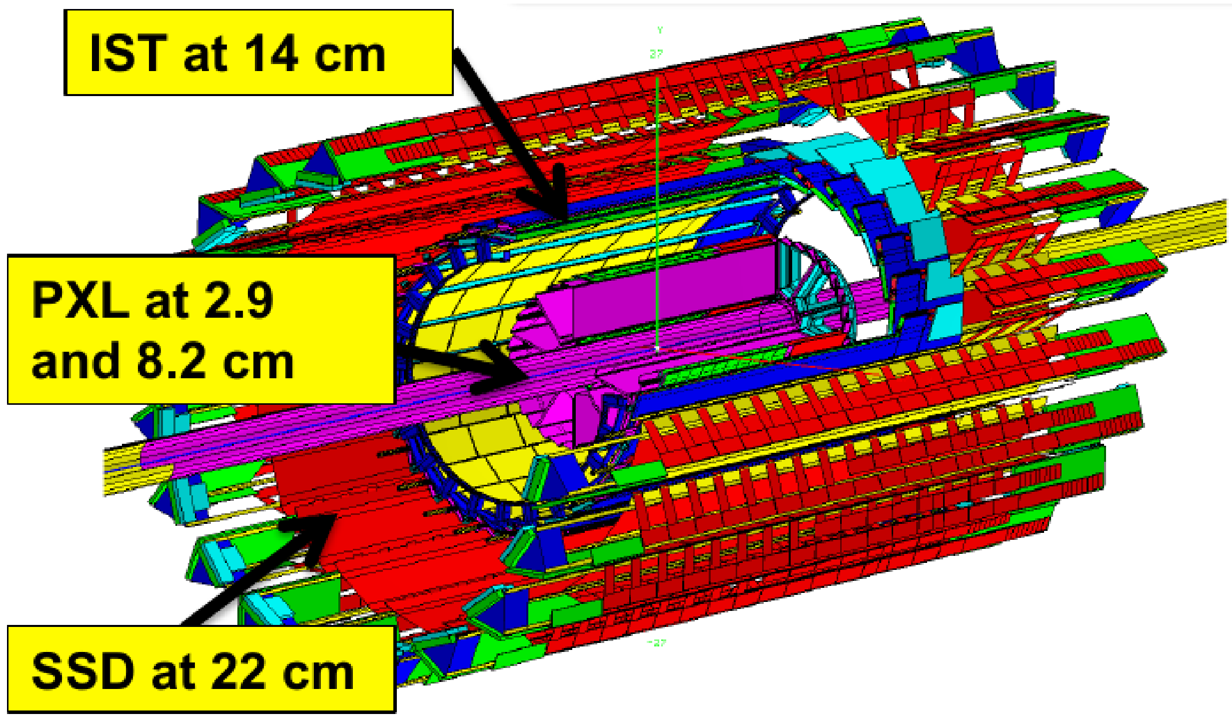
μ advantages over e:

- No γ conversion
- Much less Dalitz decay contribution
- Less affected by radiative loses in the detector material



- Acceptance: 45% at $|\eta| < 0.5$
- Multi-gap Resistive Plate Chamber (MRPC) - gas detector
- Long-MRPCs

Heavy Flavor Tracker (HFT)



Inner tracking system with 3 sub-systems

Precise pointing resolution

$$B \rightarrow J/\psi + X$$

Summary

- NLO CS+CO and CEM models describe the J/ψ p_T spectrum in p+p 200 GeV
- New J/ψ measurement in p+p 500 GeV – production follows x_T scaling at high p_T
- First ψ(2S) / J/ψ measurement in p+p at 500 GeV – no collision energy dependence observed
- J/ψ polarization in p+p 200 GeV consistent with the NLO$^+$ CSM prediction
- Measurement of J/ψ polarization in p+p 500 GeV in progress

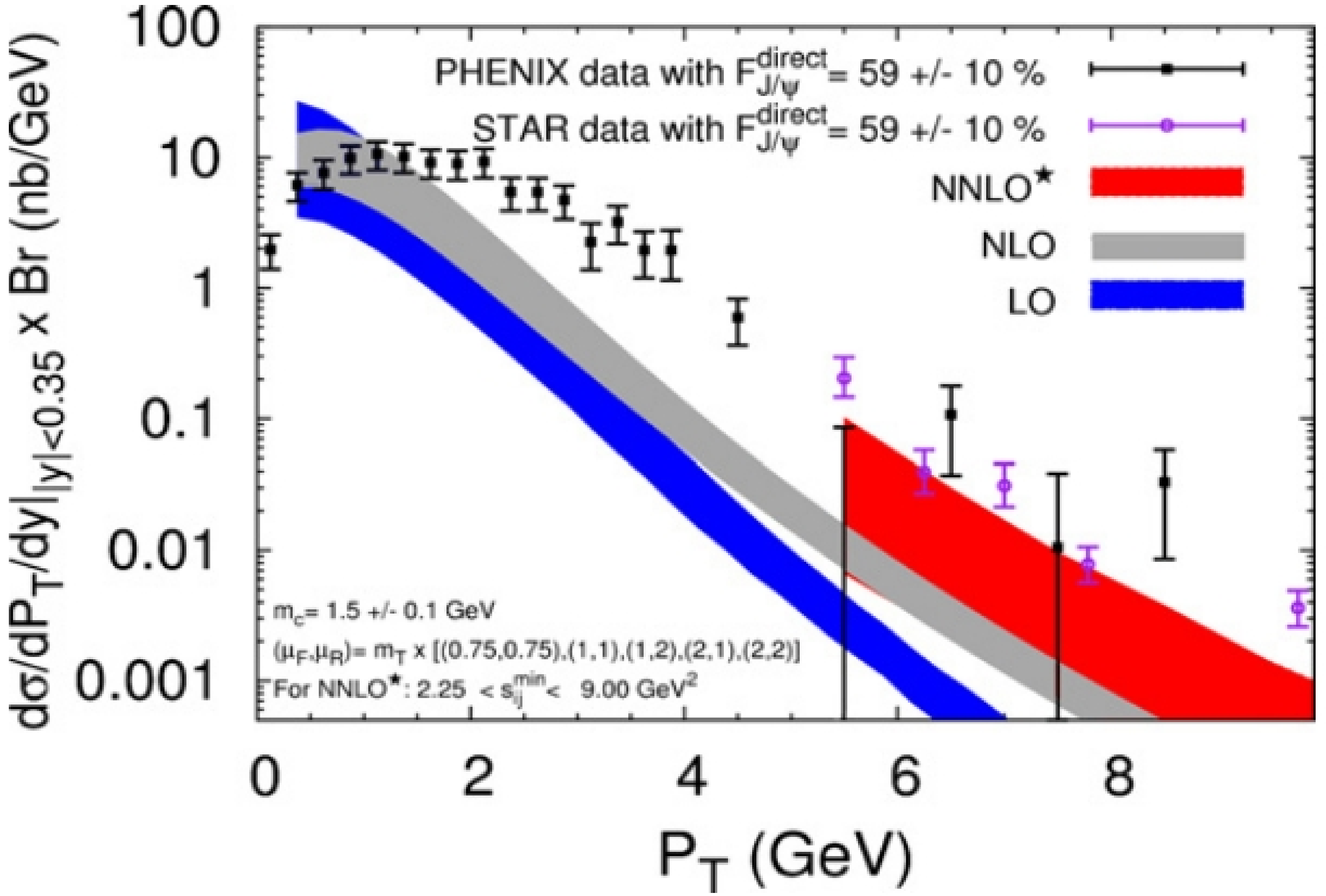
➔ *HFT and MTD since 2014 – significant improvement of quarkonium measurements*

Czech Technical University in Prague
Faculty of Nuclear Science and Physical Engineering
Project „ Support of inter-sectoral mobility and quality enhancement of research teams at Czech Technical University in Prague “
CZ.1.07/2.3.00/30.0034

Thank you !

J/Ψ production mechanism - CSM

- Comparison of CSM to RHIC data

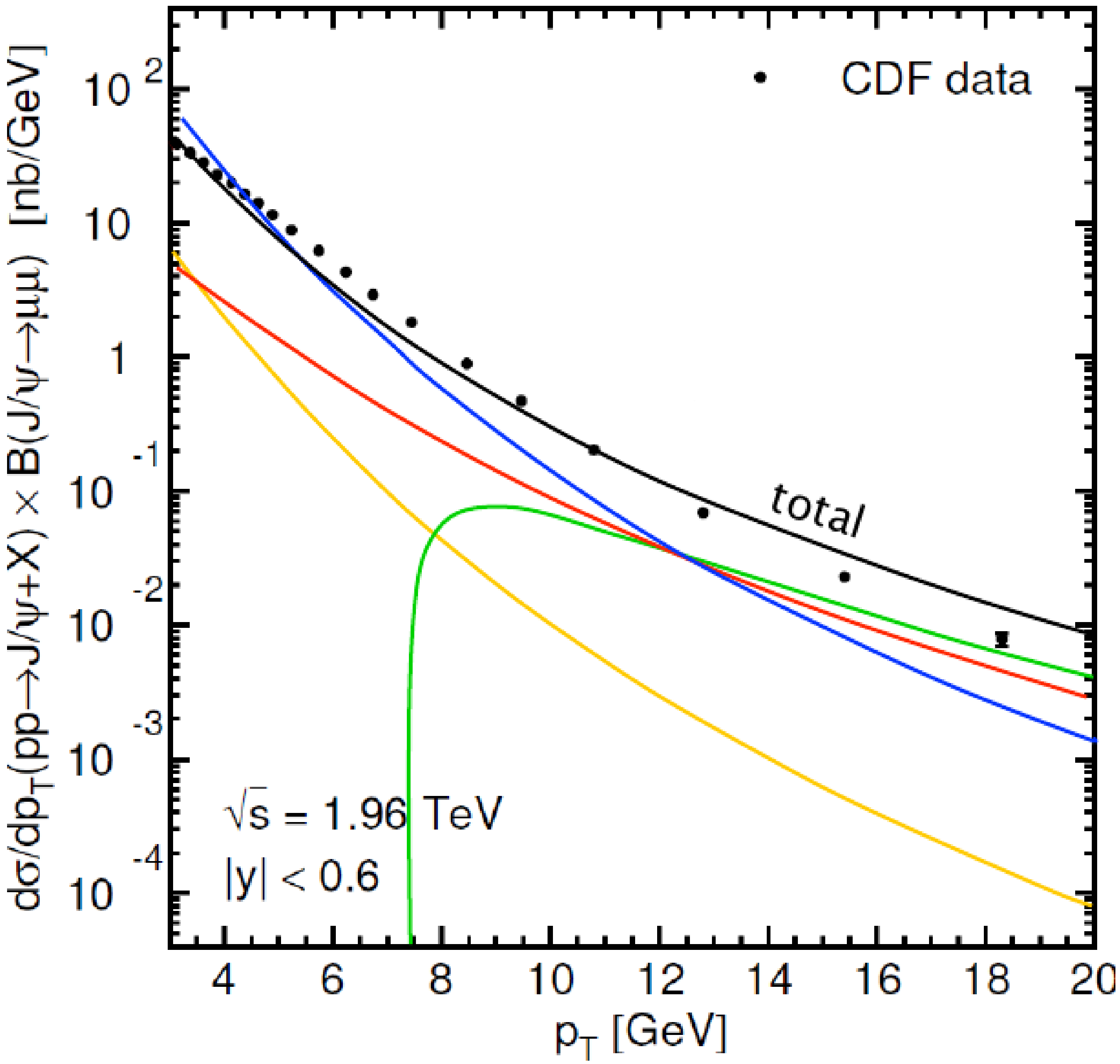


(a) central

J.P. Lansberg, Phys.Lett.B 695 (2011) 149

J/Ψ production mechanism - NRQCD

Each color singlet and octet term has a specific polarization associated



colour-singlet $^3S_1$

$\lambda_\theta = +1$ at LO to $\lambda_\theta = -1$ at NLO

tiny fraction of the total cross section

octet $^1S_0$ → $\lambda_\theta = 0$ at LO, NLO

octet $^3S_1$ → $\lambda_\theta = +1$ at LO, NLO, at high p_T

octet ^3P_J → $\lambda_\theta >> +1$ at NLO at LO it is 0

Dominance of the $^3S_1$ and ^3P_J octet terms

→ $\lambda_\theta \approx +1$,

for high-p_T S-wave quarkonia

C. Lourenço et al., Hard Probes 2013

Color-octet contributions have fixed shape but adjustable normalizations (LDMEs)

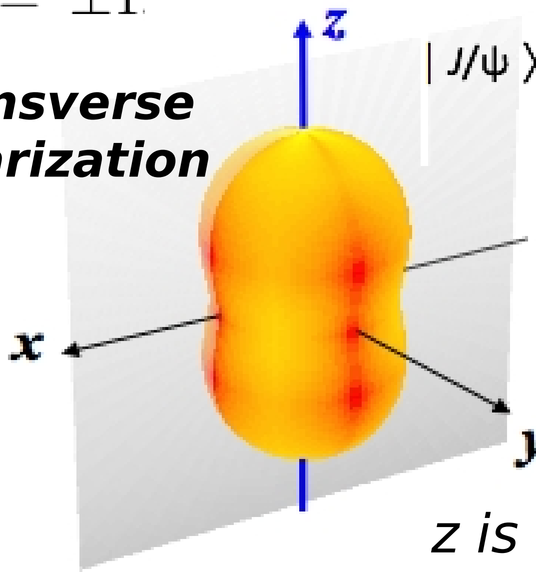
J/Ψ polarization – observation frames

J=1

$J_z = \pm 1$

transverse polarization

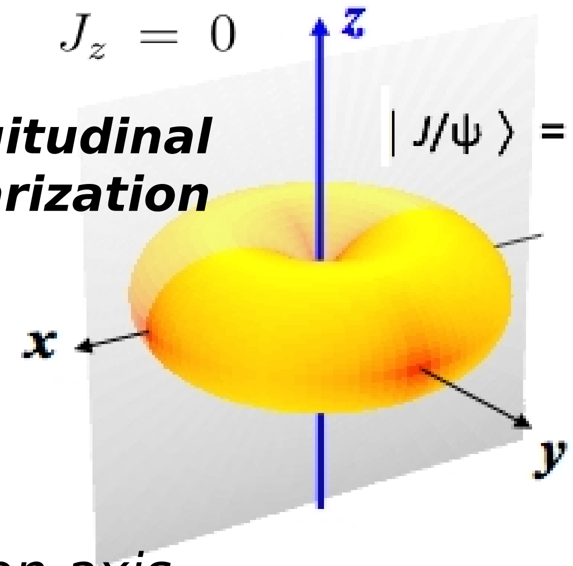
$|J/\psi\rangle = |1, +1\rangle$ or $|1, -1\rangle$



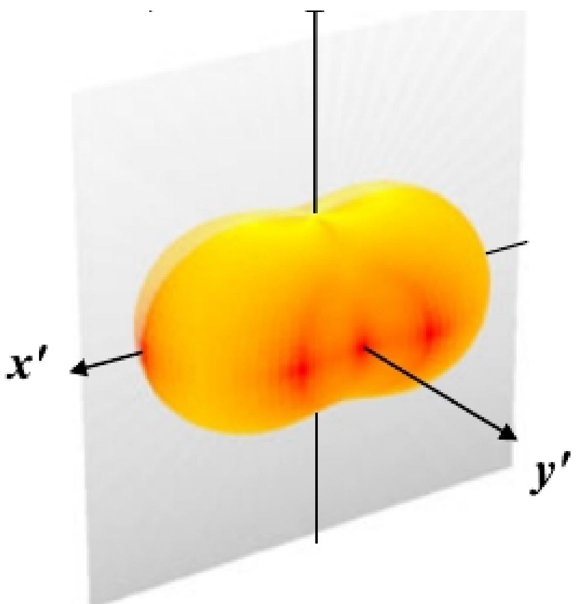
$J_z = 0$

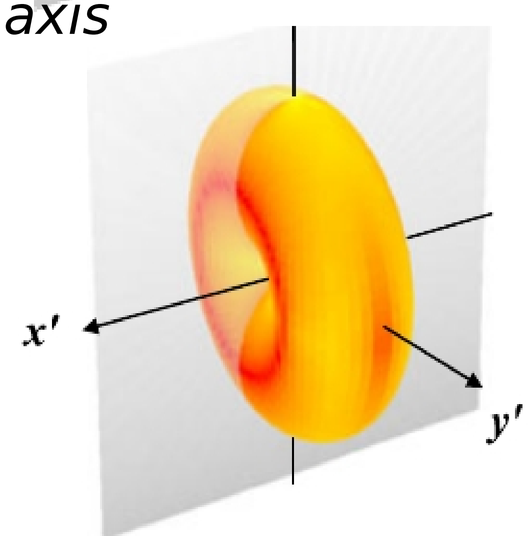
longitudinal polarization

$|J/\psi\rangle = |1, 0\rangle$



z is the polarization axis





"natural" fame

$$\lambda_\vartheta = +1 \qquad \lambda_\vartheta = -1$$

$$\lambda_\varphi = \lambda_{\vartheta\varphi} = 0$$

observation axis perpendicular to the natural axis

$$\delta = \pm 90^\circ$$

$$\lambda'_\vartheta = -1/3 \qquad \lambda'_\vartheta = +1$$

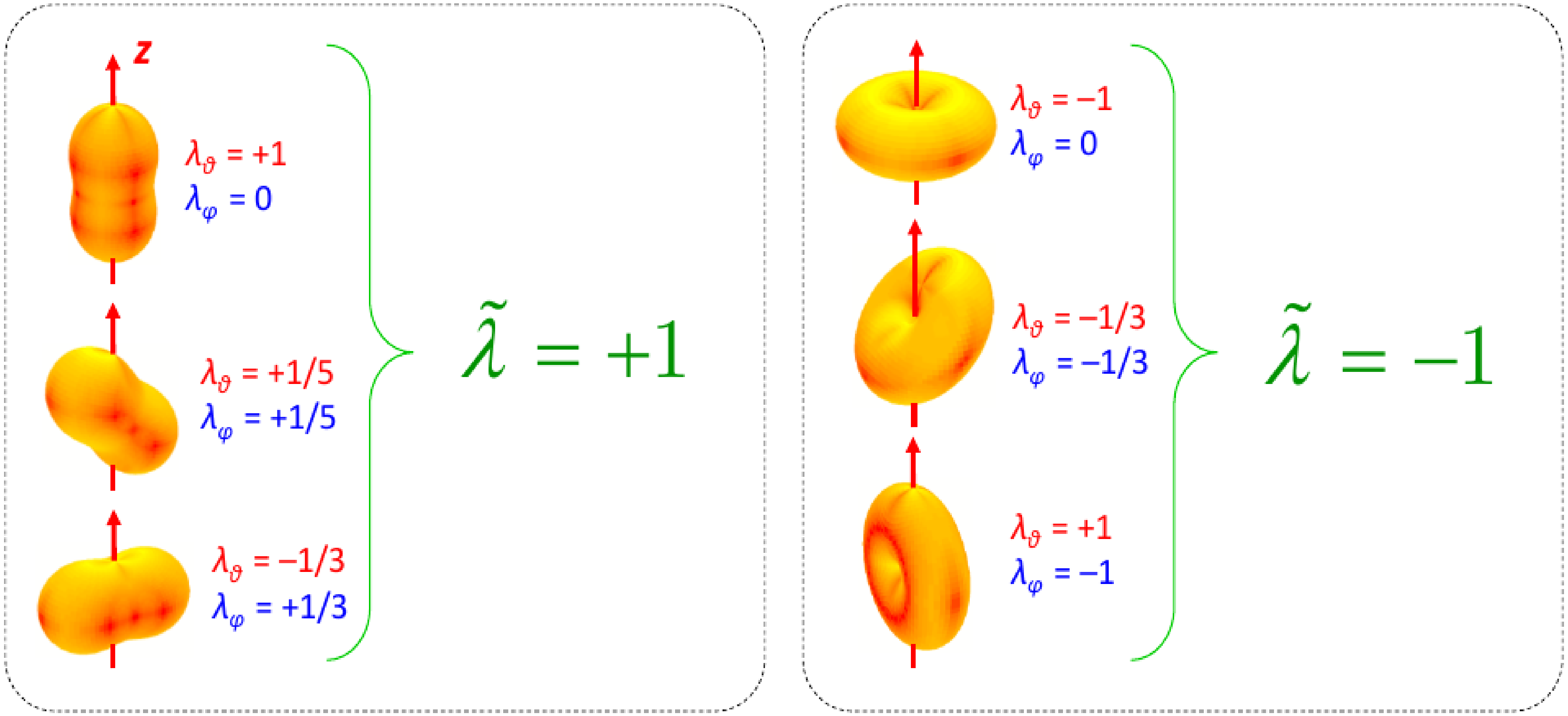
$$\lambda'_\varphi = 1/3 \qquad \lambda'_\varphi = -1$$

P. Faccioli, C. Laorenco, J. Seixas, H.K. Wohri, Eur. Phys. J. C 69, 657 (2010)

J/Ψ polarization – frame invariant approach

- Frame invariant quantity:

$$\tilde{\lambda} = \frac{\lambda_\theta + 3\lambda_\phi}{1 - \lambda_\phi}$$



Any arbitrary choice of the experimental observation frame will give the same value of this quantity

P. Faccioli, C. Laorenco, J. Seixas, H.K. Wohri, Eur. Phys. J. C 69, 657 (2010)