Antiproton simulation with Geant4

Hailin Song[1], Xinnan Wang[2], Xiaorong Zhou[1], Huaimin Liu[2]

(On behalf of BESIII Collaboration)

[1]University of Science and Technology of China

[2] Institute of High Energy Physics

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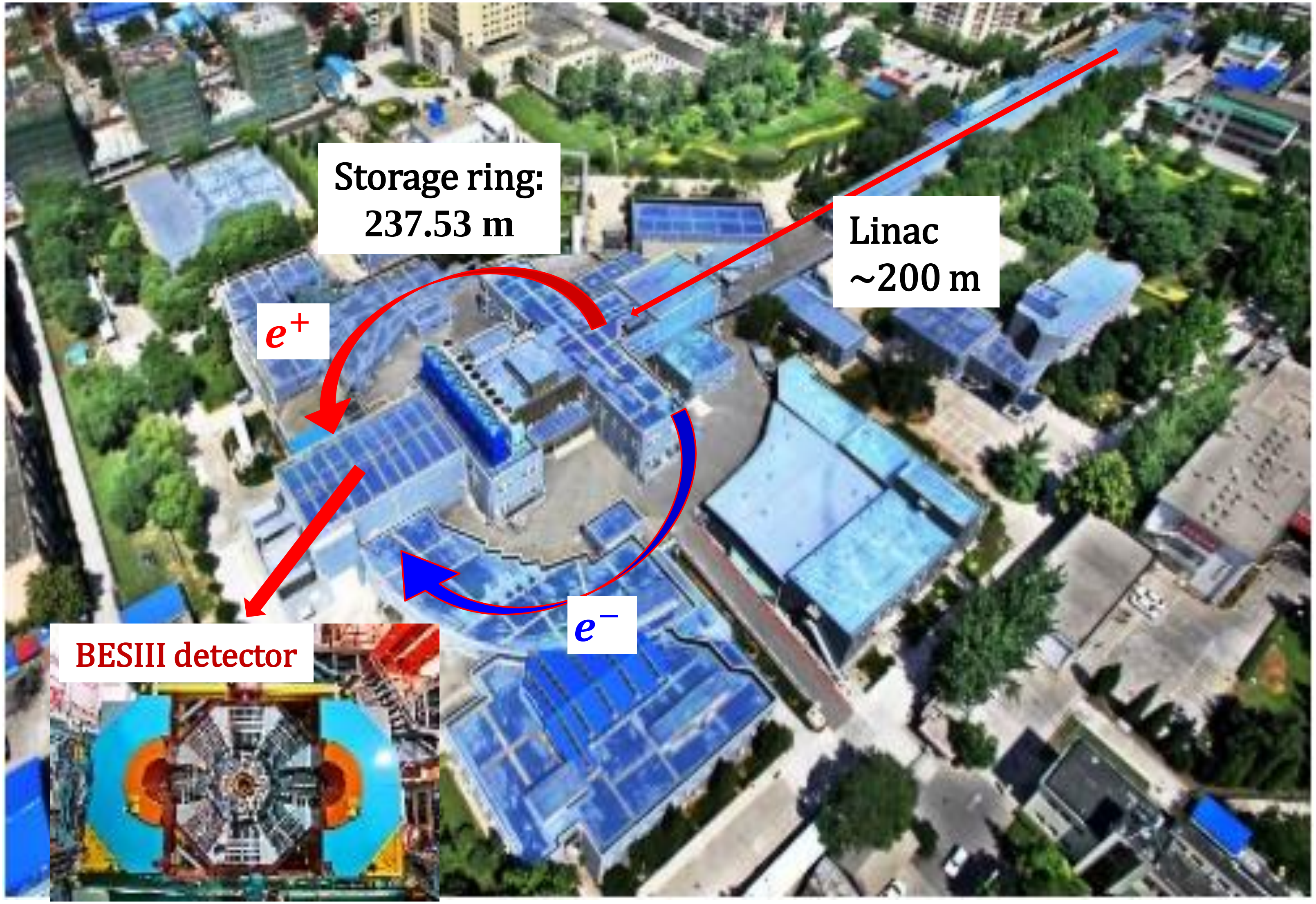
Outline

- BEPCII and BESIII
- Beam-pipe/MDC inner wall material of BESIII
- Antiproton samples at BESIII
- Comparison of data and simulated samples
- Summary and Prospect

Beijing Electron Positron Collider II (BEPCII)



BEPCII: a tau-charm factory

- $e^+ e^-$ collider
- Double ring, multiple bunch
- Crossing angle: 2×11 mrad
- Beam energy spread: 5×10^{-4}
- c.m. energy range: $1.84 - 4.95$ GeV
- Peak luminosity: $1.1 \times 10^{33} \mathrm{cm}^{-2} \mathrm{s}^{-1}$

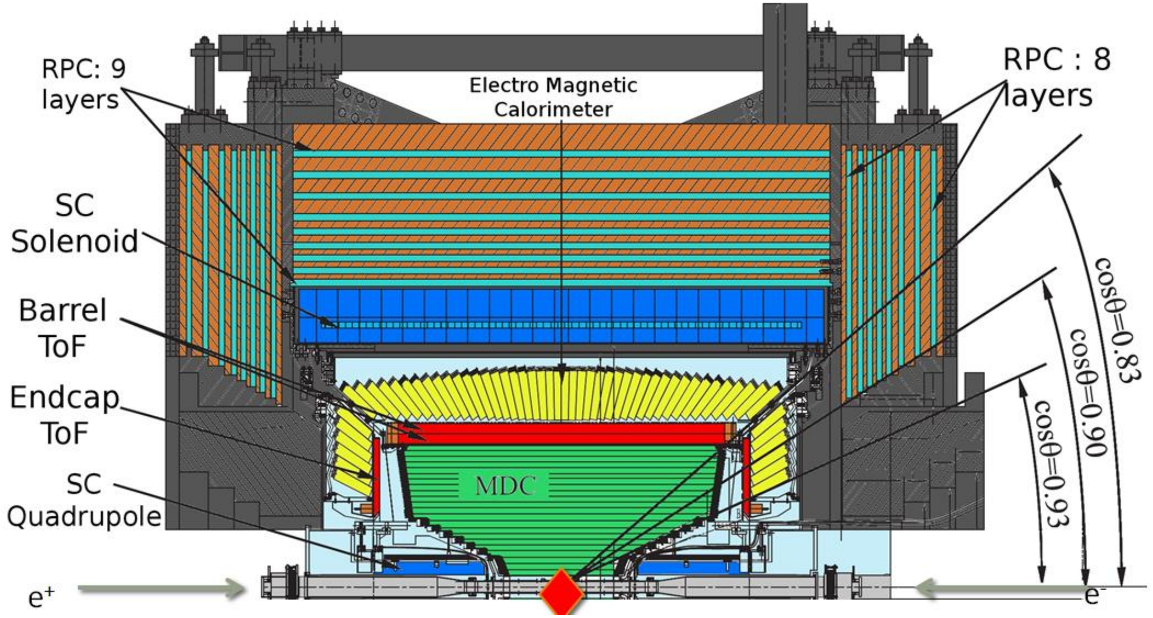
An upgrade of BEPCII is ongoing:

- Increase the luminosity by a factor of 3 above 4 GeV
- Extend the c.m. energy from 4.95 to 5.6 GeV

Beijing Spectrometer III (BESIII)

Electromagnetic Calorimeter
CsI(Tl): L=28 cm
Barrel σ_E=2.5%
Endcap σ_E=5.0%

Muon Counter
RPC
Barrel: 9 layers
Endcap: 8 layers
$\sigma_{spatial}$: 1.48 cm



Main Drift Chamber
Small cell, 43 layer
σ_{xy}=130 μm
dE/dx~6%
σ_p/p= 0.5% at 1 GeV

Time Of Flight
Plastic scintillator
σ_T(barrel): 68 ps
σ_T(endcap): 110 ps
(update to 60 ps with MRPC)

BESIII detector:

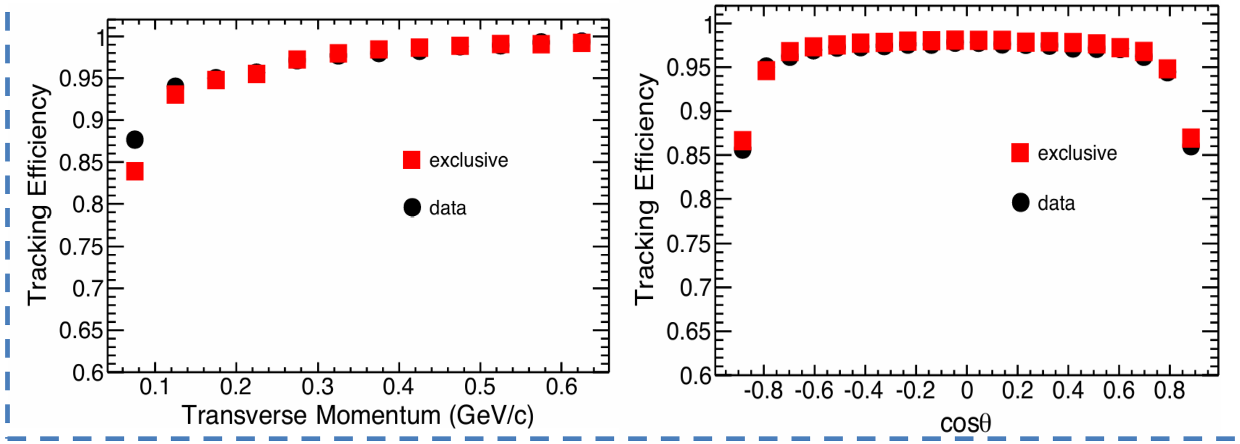
- Good tracking efficiency and momentum resolution for charged tracks
- Good π/K separation up to 1 GeV
- Good photon selection efficiency and energy resolution

Data samples:

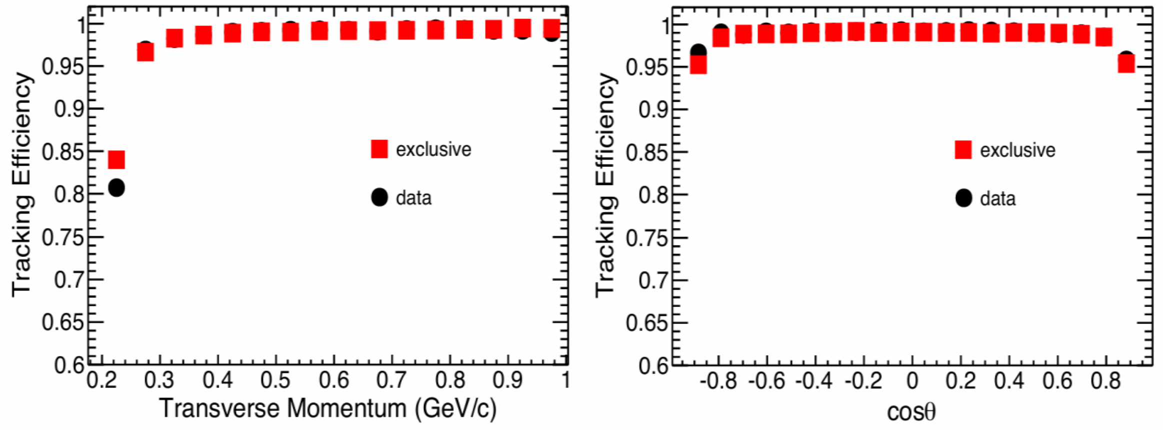
- Over 50 fb^{-1} data sample since 2009
- 10 billion J/ψ events
- 2.7 billion ψ(3686) events
- 20 fb^{-1} at ψ(3770) peak

BESIII Offline Software System

Tracking efficiency of π



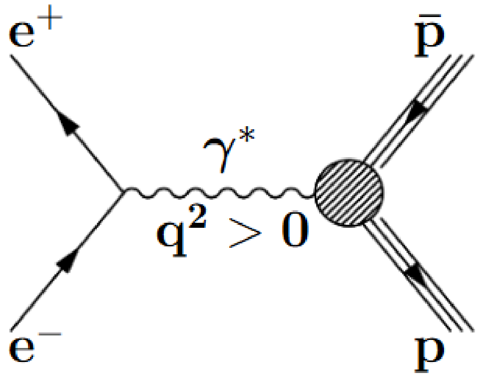
Tracking efficiency of p

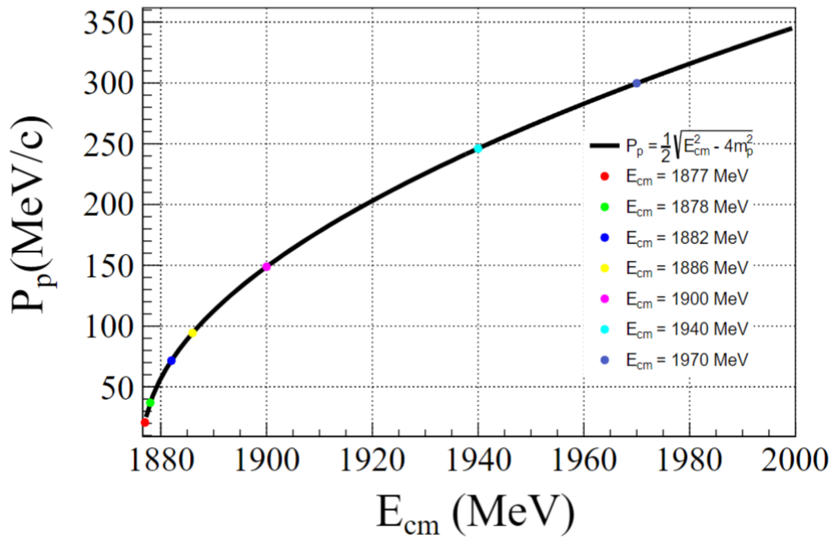


- BESIII uses a **Geant4-based simulation** software package
- **For most analysis**, benefit from the excellent performance of Geant4, the data and MC are **consistent well** with tracking uncertainty within 1%
- **No tracking efficiency** for **low-momentum proton/antiproton** due to large loss, **secondary products** are used to reconstruct tracks. Good agreement of antiproton interaction will improve the corresponding analysis significantly

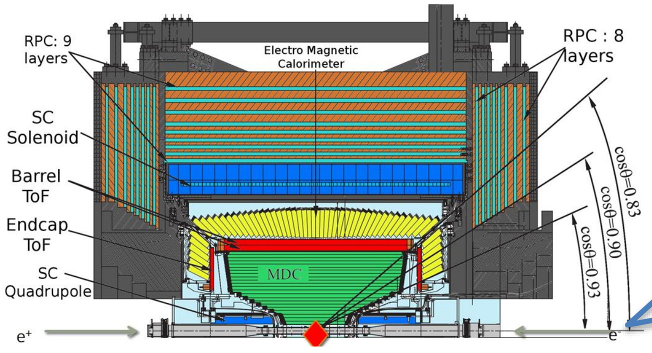
Why we are interested in low energy antiproton?

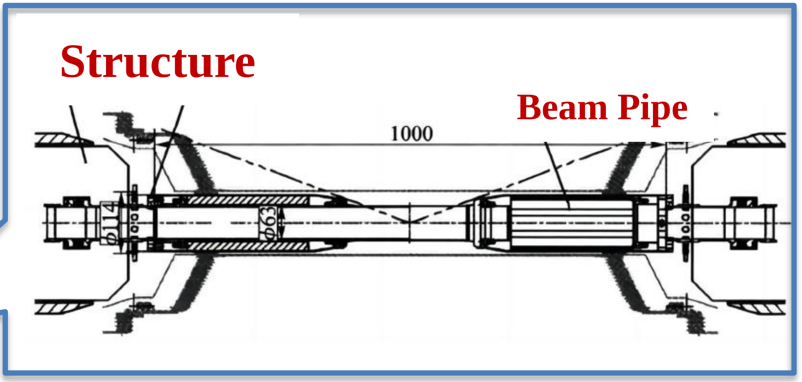
- Recently, BESIII collect data near $p\bar{p}$ mass threshold for cross-section measurement
  - Both p and $\bar{p}$ with momentum under 200 MeV/c cannot reach detector due to large energy loss.
  - The **only information comes from the $\bar{p}$ interaction with material** in front of the detector
- The simulation of low-energy antiprotons is important
  - However, we notice that pbar simulation models in Geant4 **changed significantly** from release 9 to release 10

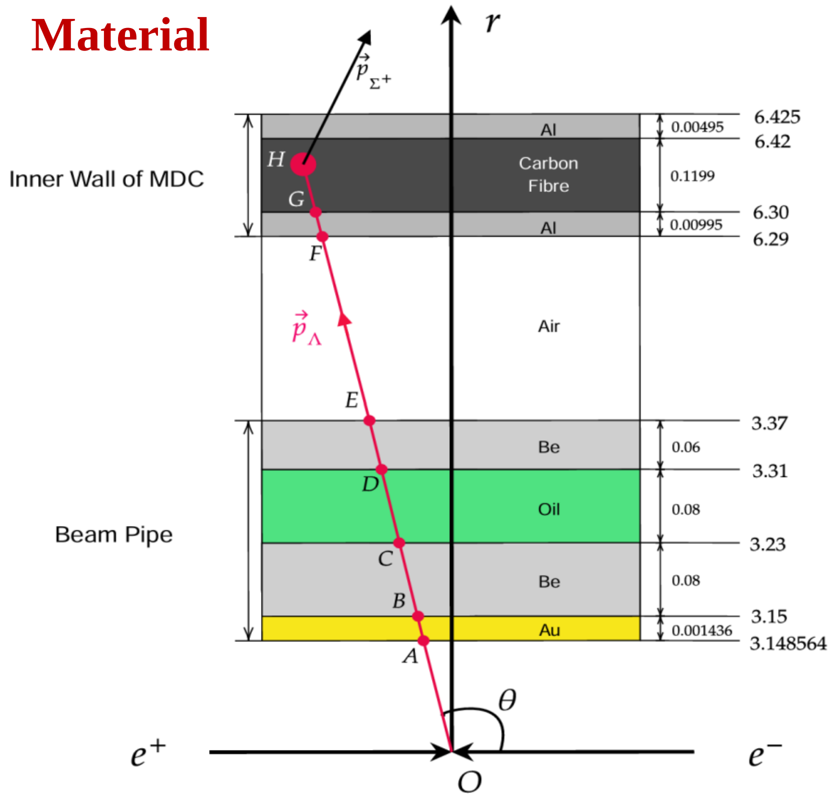


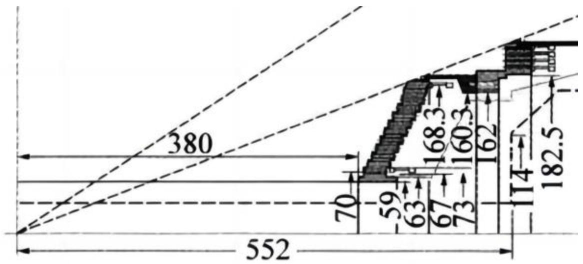


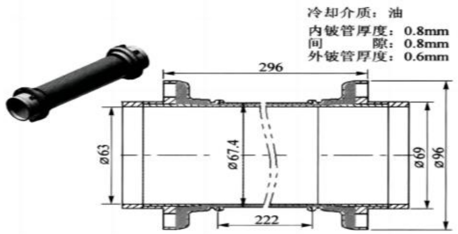
The beam pipe and Inner MDC wall of BESIII

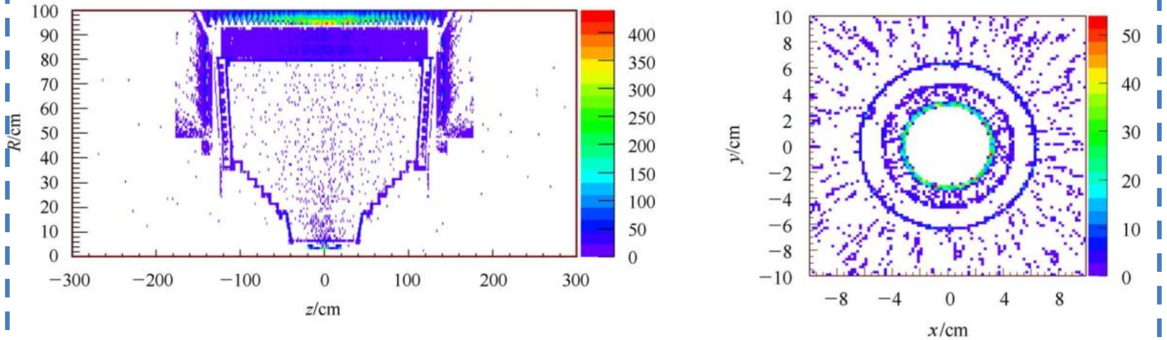








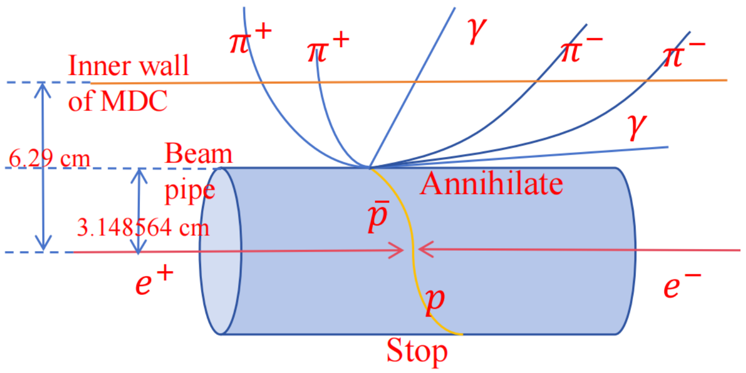




mapping of the BES detector using photon conversion

- Particle produced at IP must penetrate corresponds to **1.04%** (Be: 0.4%, gold: 0.44%, oil: 0.2%) of a **radiation length** at normal incidence

Antiproton interacts at beam pipe/MDC inner wall



- The material budget **stops antiproton** with momentum **less than 200 MeV/c**
- Low-momentum **antiproton** interacts with **nucleon in nucleus**, while the **structure of nucleus** also matters

- $\bar{p}p \rightarrow Anything$

Annihilation frequencies of p̄p annihilation at rest in liquid H_2 into pionic final states (in units of 10^{-3}), from [2,48,216]

Physics Reports 413 (2005) 197 – 317

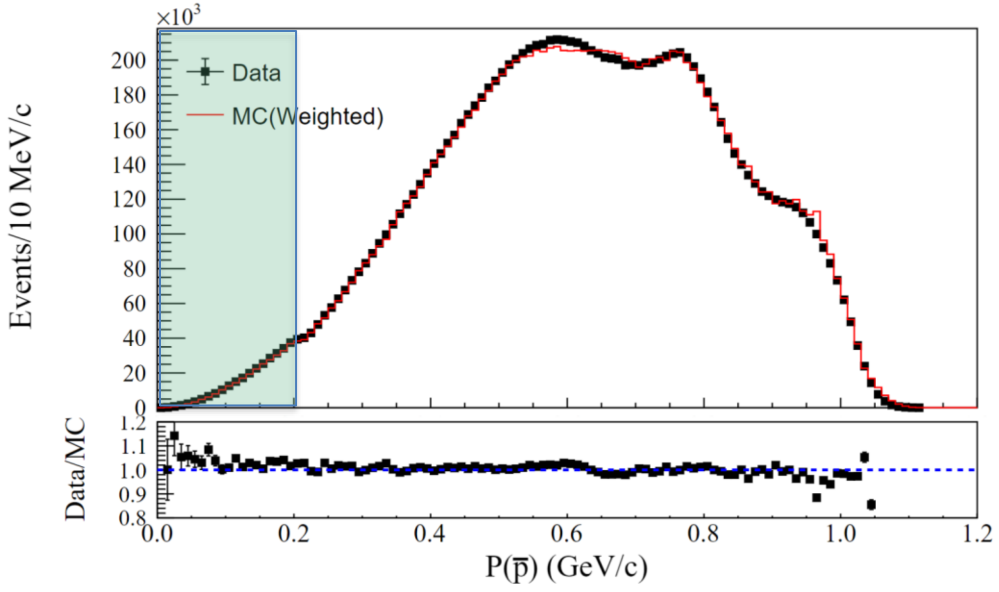
Final state	BNL	CERN	Crystal Barrel
All neutral	32 ± 5	41^{+2}_{-6}	35 ± 3
$2\pi^0$			0.65 ± 0.03
$3\pi^0$			7.0 ± 0.4
$4\pi^0$			3.1 ± 0.2
$5\pi^0$			9.2 ± 0.4
$6\pi^0$ (^{1})			0.12 ± 0.01
$7\pi^0$ (^{1})			1.3 ± 0.1
$8\pi^0$ (^{2})			0.012 ± 0.001
$9\pi^0$ (^{2})			0.025 ± 0.003
Non-multipion			15 ± 5
$\pi^+\pi^-$	3.2 ± 0.3	3.33 ± 0.17	3.14 ± 0.12
$\pi^+\pi^-\pi^0$	78 ± 9	69.0 ± 3.5	67 ± 10
$\pi^+\pi^-2\pi^0$			122 ± 18
$\pi^+\pi^-3\pi^0$			133 ± 20
$\pi^+\pi^-4\pi^0$			36 ± 5
$\pi^+\pi^-5\pi^0$ (^{1})			13 ± 2
$\pi^+\pi^-$MM	345 ± 12	358 ± 8	$65 \pm 20^*$
$2\pi^+2\pi^-$	58 ± 3	69 ± 6	56 ± 9
$2\pi^+2\pi^-\pi^0$	187 ± 7	196 ± 6	210 ± 32
$2\pi^+2\pi^-2\pi^0$			177 ± 27
$2\pi^+2\pi^-3\pi^0$			6 ± 2
$2\pi^+2\pi^-$MM	213 ± 11	208 ± 7	$30 \pm 15^*$
$3\pi^+3\pi^-$	19 ± 2	21.0 ± 2.5	
$3\pi^+3\pi^-\pi^0$	16 ± 3	8.5 ± 1.5	40 ± 3^a
$3\pi^+3\pi^-$MM	16 ± 3	3 ± 1	
Sum	954 ± 18	986 ± 6	970 ± 58

- $\bar{p}n \rightarrow Anything$

Final state	Frequency (in %)
$\pi^-n\pi^0$	16.4 ± 0.5
$\pi^-\pi^0$	0.40 ± 0.04
$\pi^-2\pi^0$	0.68 ± 0.07
$\pi^-4\pi^0$	1.32 ± 0.20
$2\pi^-\pi^+n\pi^0$	59.7 ± 1.2
$2\pi^-\pi^+$	1.57 ± 0.21
$2\pi^-\pi^+\pi^0$	21.8 ± 2.2
$2\pi^-\pi^+2\pi^0$	6.3 ± 1.1
$3\pi^-2\pi^+n\pi^0$	23.4 ± 0.7
$3\pi^-2\pi^+$	5.15 ± 0.47
$3\pi^-2\pi^+\pi^0$	15.1 ± 1.0
$4\pi^-3\pi^+n\pi^0$	0.39 ± 0.07
Sum	$95.5 \pm 1.5\%$
Final state	Frequency (in 10^{-4})

Antiproton sample at BESIII

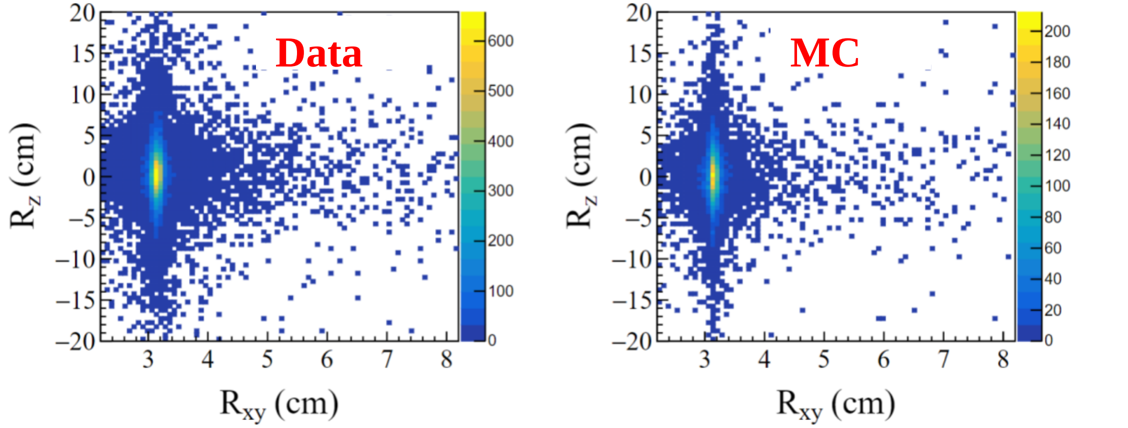
- The antiproton sample is selected from $J/\psi \rightarrow p\bar{p}\pi^{+}\pi^{-}$ with Br ~6×10^{-3}
- With 10 billion J/ψ at BESIII, millions antiproton sample with momentum range within 0-1.1 GeV/c with **99.65% purity**. **0.2 million antiproton** with momentum less than 200 MeV/c obtained
- To correctly simulate the signal process, an amplitude weight procedure is applied on the MC
- Geant4 physics list used:
  - 10.7.2 with FTFP_BERT (**default**)
  - 10.7.2 with FTFP_INCLXX
  - 9.3.1 with QGSP_BERT



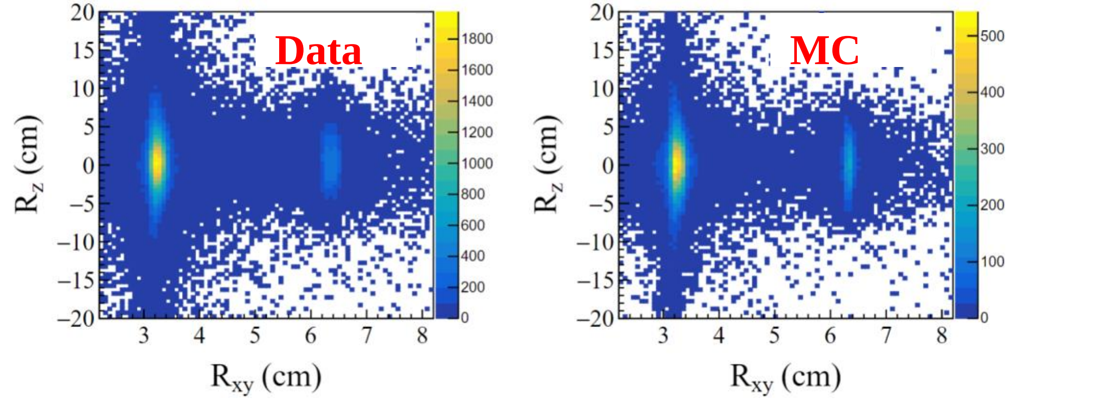
Comparison of data and simulated samples (1)

- **Position** (in xy plane and z direction) where antiproton stopped

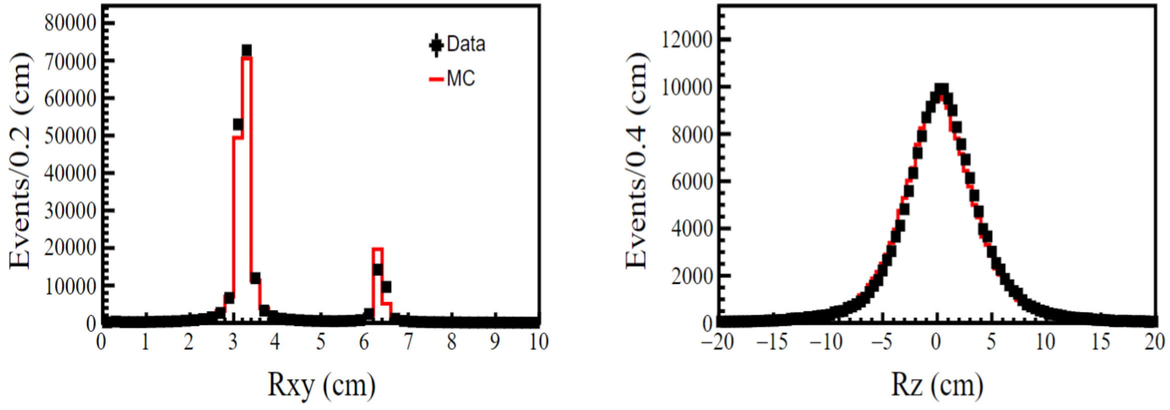
P <100 MeV/c



100<P <200 MeV/c

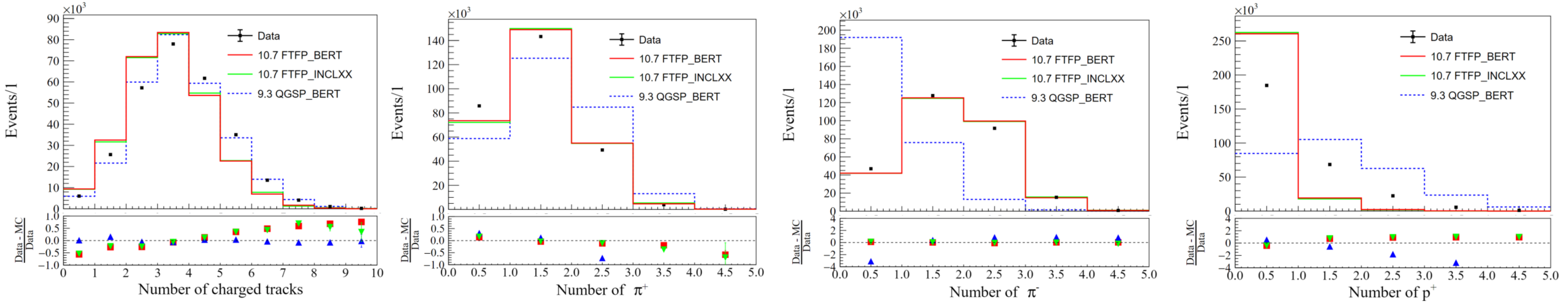


- **Good agreement** of the interaction vertex with respect of R_{xy} and R_z



Comparison of data and simulated samples (2)

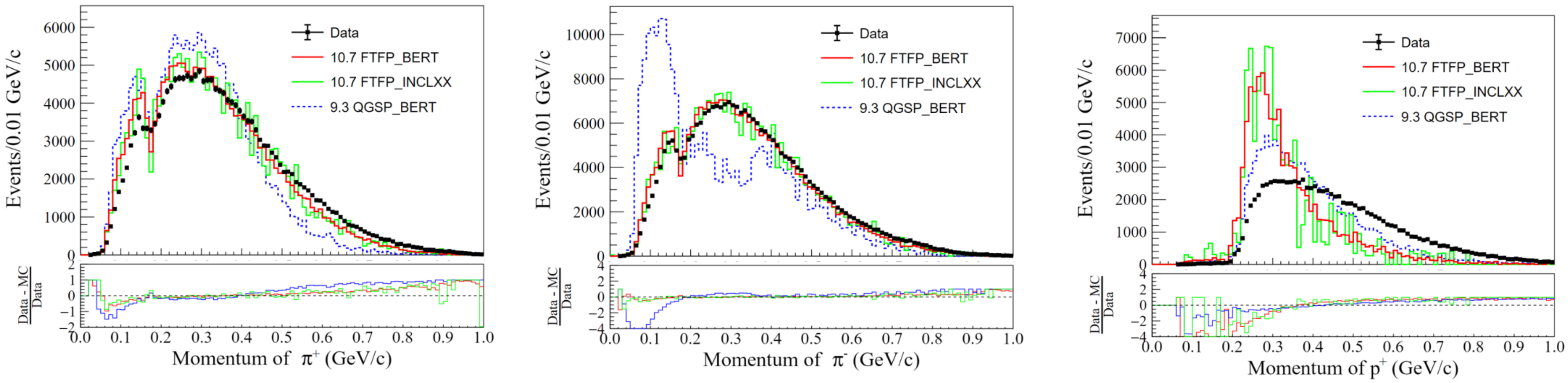
- **Multiplicity of products**



- **Significant improvement** of π^- **multiplicity** in 10.7 FTFP model
- Multiplicity of p^+ **is underestimated in 10.7 FTFP**, while overestimated in 9.3 QGSP

Comparison of data and simulated samples (3)

- **Momentum of products**

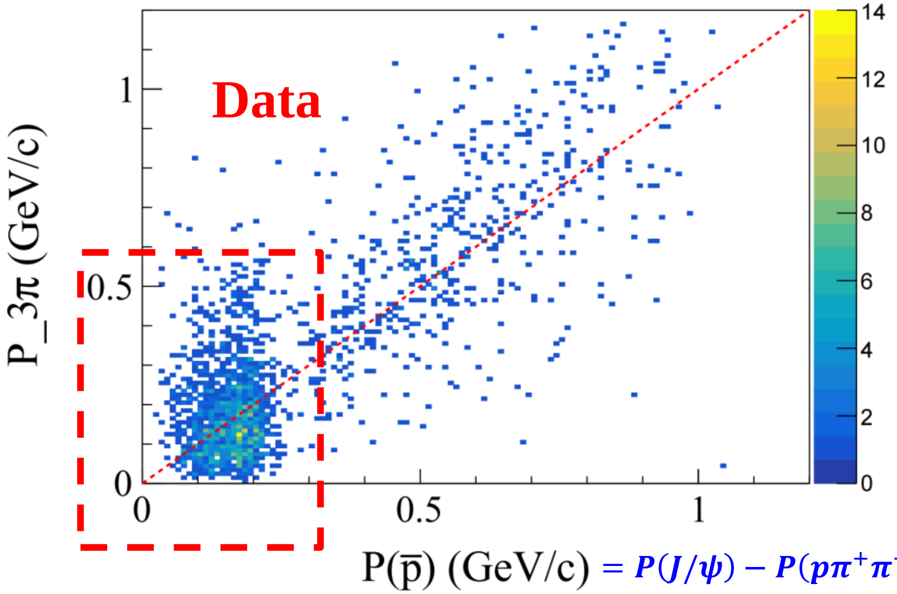


- Significant improvement of π^- momentum in 10.7 FTFP model
- **Momentum of p^+ is not consistent with data** for both 10.7 FTFP and 9.3 QGSP models

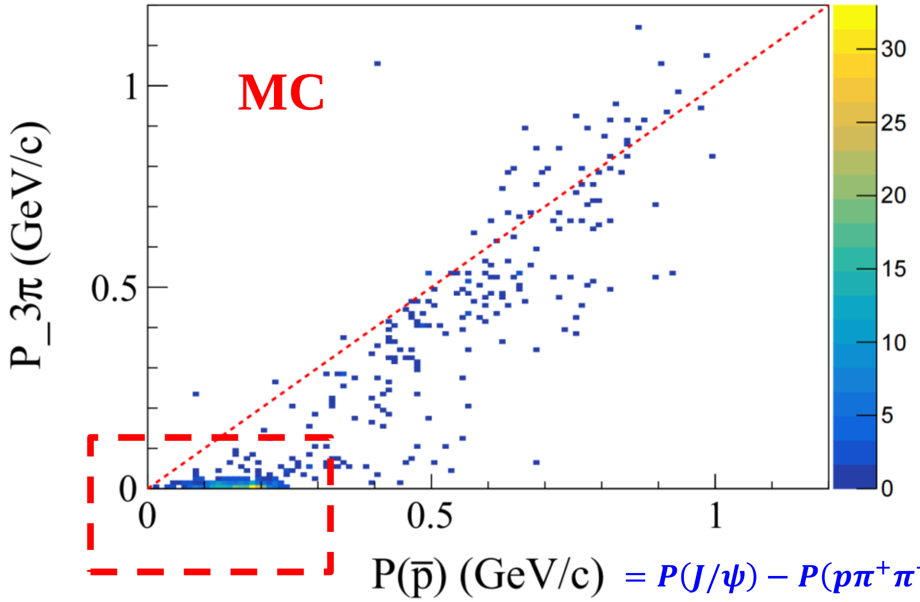
Comparison of data and simulated samples (4)

- Study the momentum of exclusive final states versus the initial momentum
  - **Is antiproton (p<200 MeV/c) at rest when interact?** Yes in simulation, no in data
  - **Is nucleon at rest in nucleus when it interacts with antiproton?** Yes in simulation, no in data

Select $\bar{p}n \rightarrow \pi^+\pi^-\pi^-$ process, study $\pi^+\pi^-\pi^-$ momentum versus momentum of antiproton under assumption that nucleon to be at rest



$= P(J/\psi) - P(p\pi^+\pi^-)$



$= P(J/\psi) - P(p\pi^+\pi^-)$

Summary and Prospect

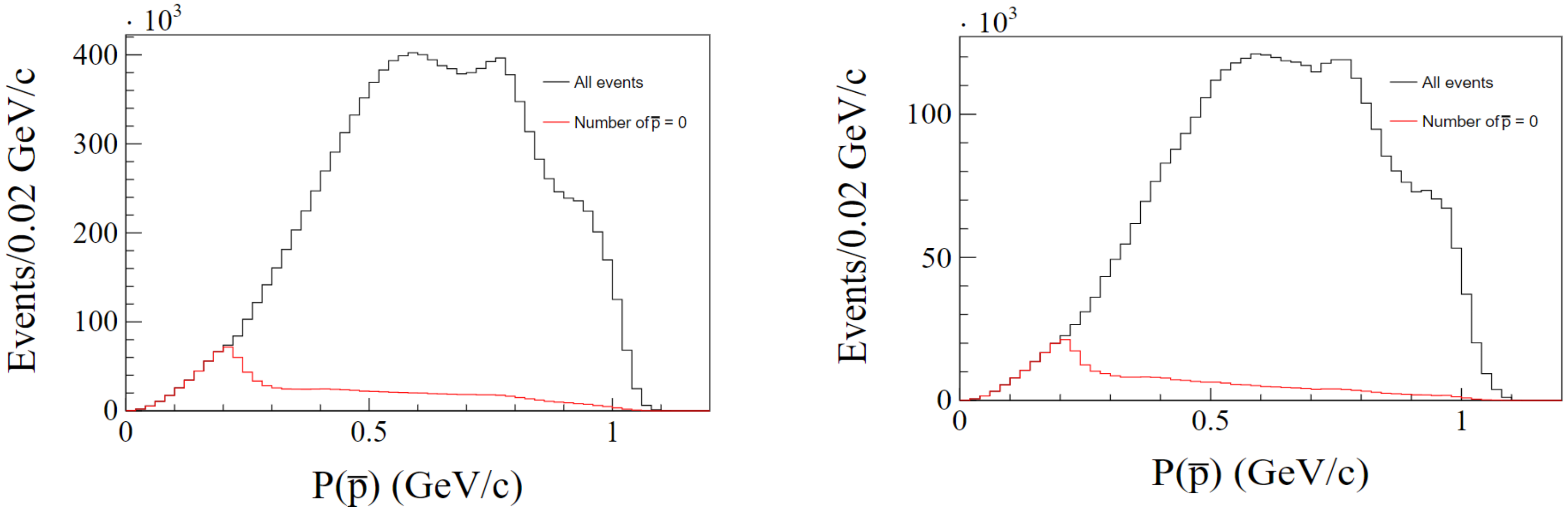
- Overall, the simulation of antiproton interaction is quite well. The **10.7 FTFP model** improves a lot on the π^- related variables, except
  - **multiplicity and momentum of secondary proton** are inconsistent
  - simulation treats **antiproton and nucleon at rest**, while data indicates a more complex case
- It is important to improve the antiproton interaction model at low momentum for the **BESIII physics research**
- On the other hand, BESIII **provides clean samples** for investigating the **low-energy particle interaction**, e.g. antineutron, hyperon, K_L etc.

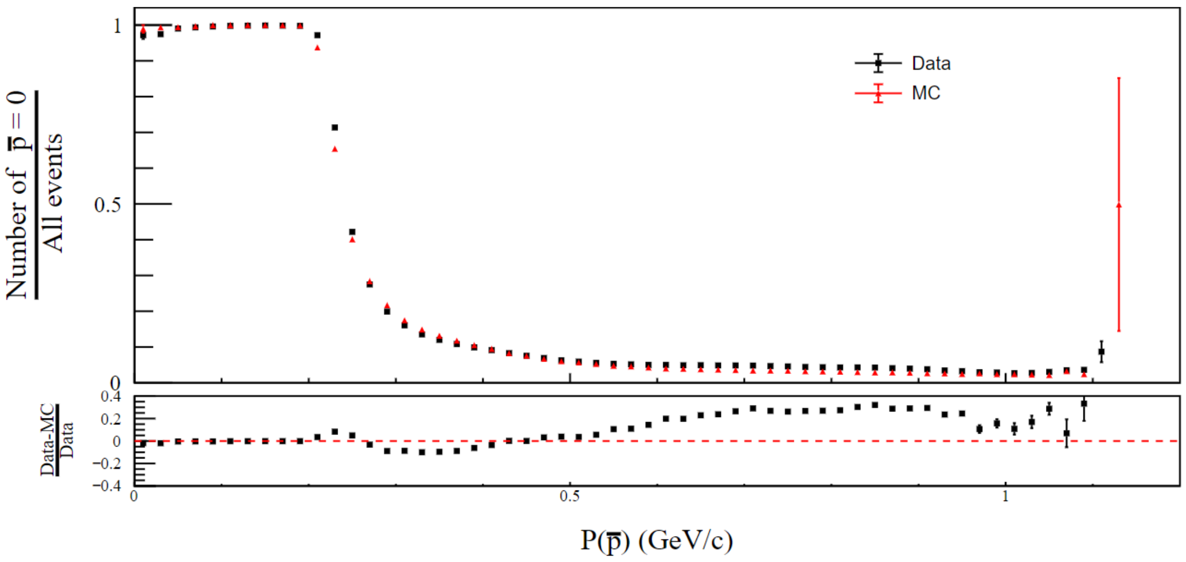
Thanks for your listening and
thanks for all the efforts of Geant4 team!

Release notes since Geant4 10.7

- Geant4 11.1 Release note:
  - Hadronic physics: Improved FTF fragmentation to better describe the production of strange mesons and baryons in proton-proton interactions. Revised the mixing probability between vector mesons as well as the probabilities for the ratios between pseudo-scalar and vector meson production for both FTF and QGS string fragmentations.
- Geant4 11.2 Release note:
  - Hadronic physics: **Major extension of the INCLXX model to handle antiproton annihilation at rest and in-flight.** All INCLXX-based physics lists now use INCLXX for the antiproton annihilation at rest. Note that, for the time being, for in-flight antiproton annihilation, FTFP is still used in all physics list.
- Geant4 11.3 Release note:
  - Hadronic physics: Since Geant4 11.2, the physics list QGSP_BERT_HP has a treatment of low energy neutrons which is not the same for the other HP-based reference physics list.

$\bar{p}N$ interaction rate

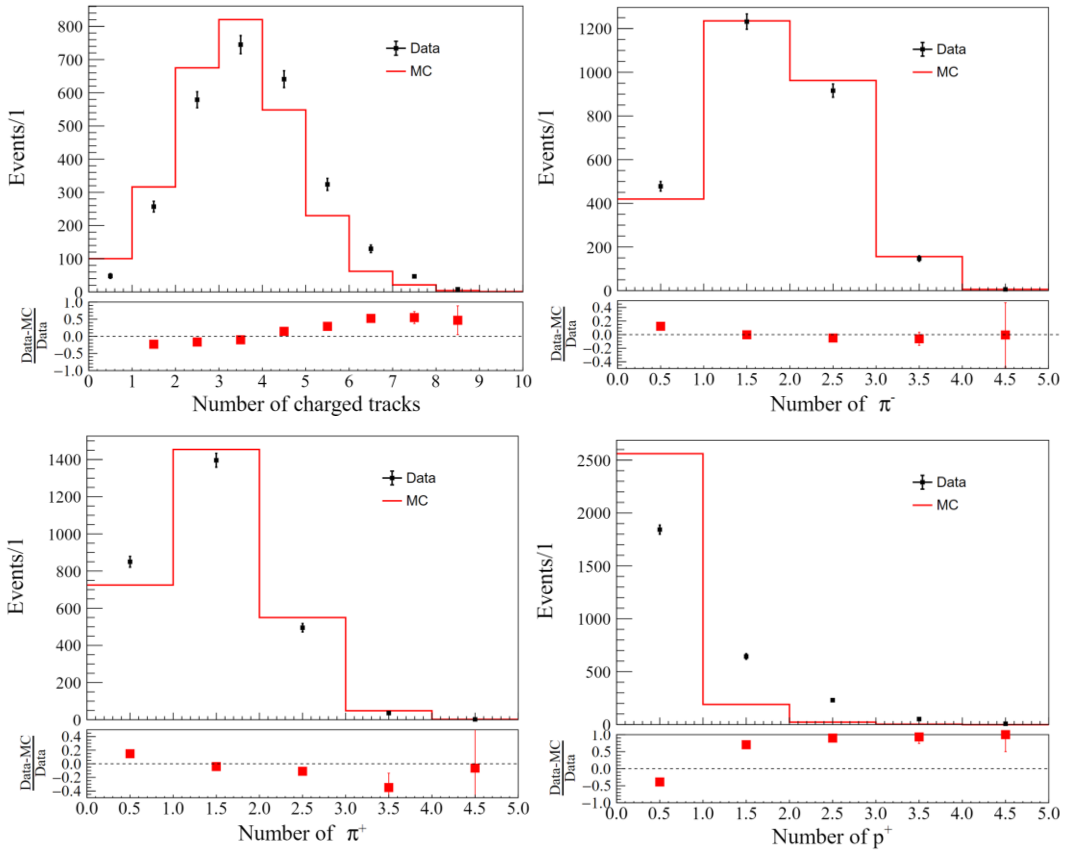


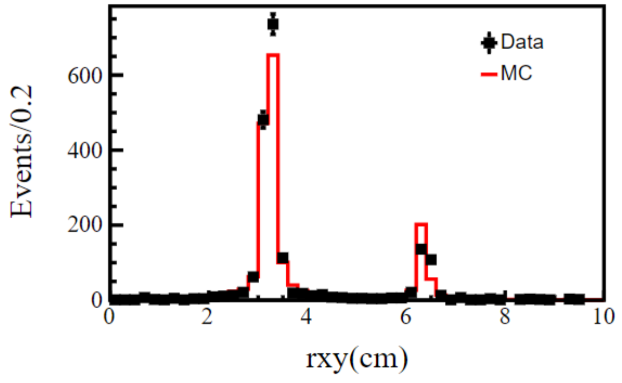


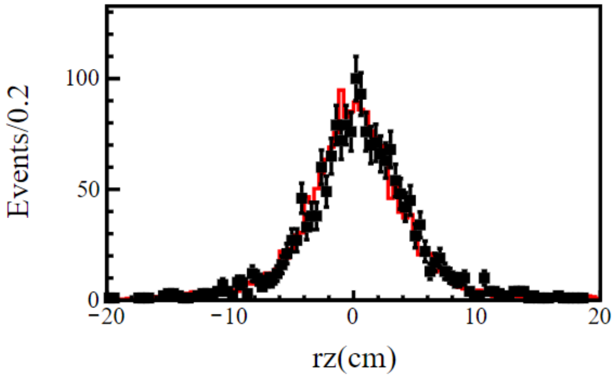
- Consistency interaction rate between $\bar{p}N$
- Below 200 MeV/c, almost 100% $\bar{p}$ interacts

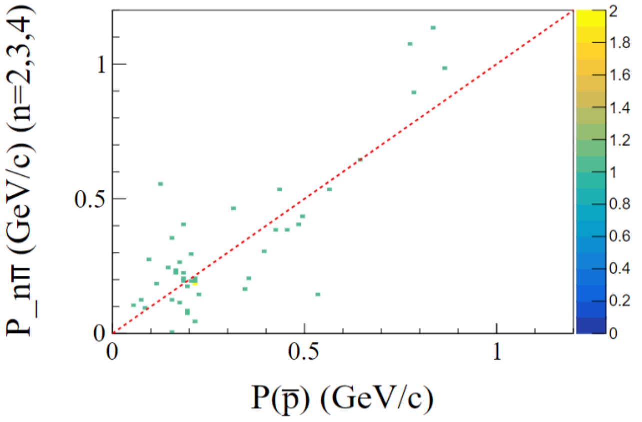
Cross check with $J/\psi \to \bar{p}K^{+}\Lambda$

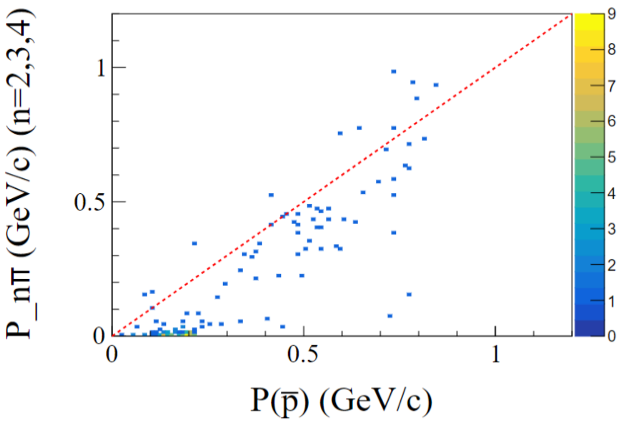
- The antiproton control sample is selected from the channel: $J/\psi \to \bar{p}K^{+}\Lambda$
- Signal MC $J/\psi \to \bar{p}K^{+}\Lambda$
  - ➢ 1.5 million with PWA results, using geant4-10-07-patch-02 with physicsList: FTFP_BERT











Reactions in generator

G4-10-07

- hFritiofCaptureAtRest:
  - $\bar{p} + {}^{9}_{4}Be \rightarrow \pi^{+}\pi^{-}3\pi^{0} + p3n + {}^{4}_{2}\alpha + 4e^{-}7\gamma$
  - $\bar{p} + {}^{197}_{79}Au \rightarrow 2\pi^{+}2\pi^{-} + 6n + {}^{190}_{78}Pt + e^{-}12\gamma$
  - $\bar{p} + {}^{27}_{13}Al \rightarrow \pi^{+}2\pi^{-}2\pi^{0} + {}^{26}_{13}Al + 2e^{-}7\gamma$
  - $\bar{p} + {}^{12}_{6}C \rightarrow \pi^{+}\pi^{-}2\pi^{0}\eta' + p2n + 2{}^{4}_{2}\alpha + 6e^{-}\gamma$
  - ……
- anti_protonInelastic:
  - $\bar{p} + {}^{9}_{4}Be \rightarrow \pi^{-}\pi^{0}2K^{0}_{L} + pn + {}^{4}_{2}\alpha{}^{2}_{1}D$
  - $\bar{p} + {}^{107}_{47}Ag \rightarrow \bar{p}4n + {}^{4}_{2}\alpha{}^{99}_{45}Rh + e^{-}12\gamma$
  - $\bar{p} + {}^{9}_{4}Be \rightarrow \pi^{+}\pi^{-}3\pi^{0} + n + {}^{3}_{1}T{}^{4}_{2}\alpha$
  - $\bar{p} + {}^{12}_{6}C \rightarrow K^{+}K^{-}\pi^{-}\eta + p + {}^{10}_{5}B + 2\gamma$
  - ……
- Others: hadElastic

G4-09-03

- CHIPSNuclearCaptureAtRest:
  - $\bar{p} + X \rightarrow 3\pi^{+}\pi^{-}3\pi^{0} + 3p8n$
  - $\bar{p} + X \rightarrow 2\pi^{+} + 9p15n + {}^{2}_{1}D$
  - $\bar{p} + X \rightarrow \pi^{+}2\pi^{0} + 2p6n$
  - $\bar{p} + X \rightarrow 2\pi^{+}2\pi^{0} + p7n$
  - ……
- CHIPS_Inelastic:
  - $\bar{p} + {}^{17}_{8}O \rightarrow 2\pi^{+}3\pi^{-}3\pi^{0} + pn + 3{}^{4}_{2}\alpha{}^{2}_{1}D$
  - $\bar{p} + {}^{197}_{79}Au \rightarrow 2\pi^{+}2\pi^{-}2\pi^{0} + p5n + {}^{190}_{77}Ir$
  - $\bar{p} + {}^{9}_{4}Be \rightarrow 2\pi^{+}3\pi^{-}2\pi^{0} + 2p2n + {}^{4}_{2}\alpha$
  - ……
- Others:
  - Transportation

Hadronic Processes