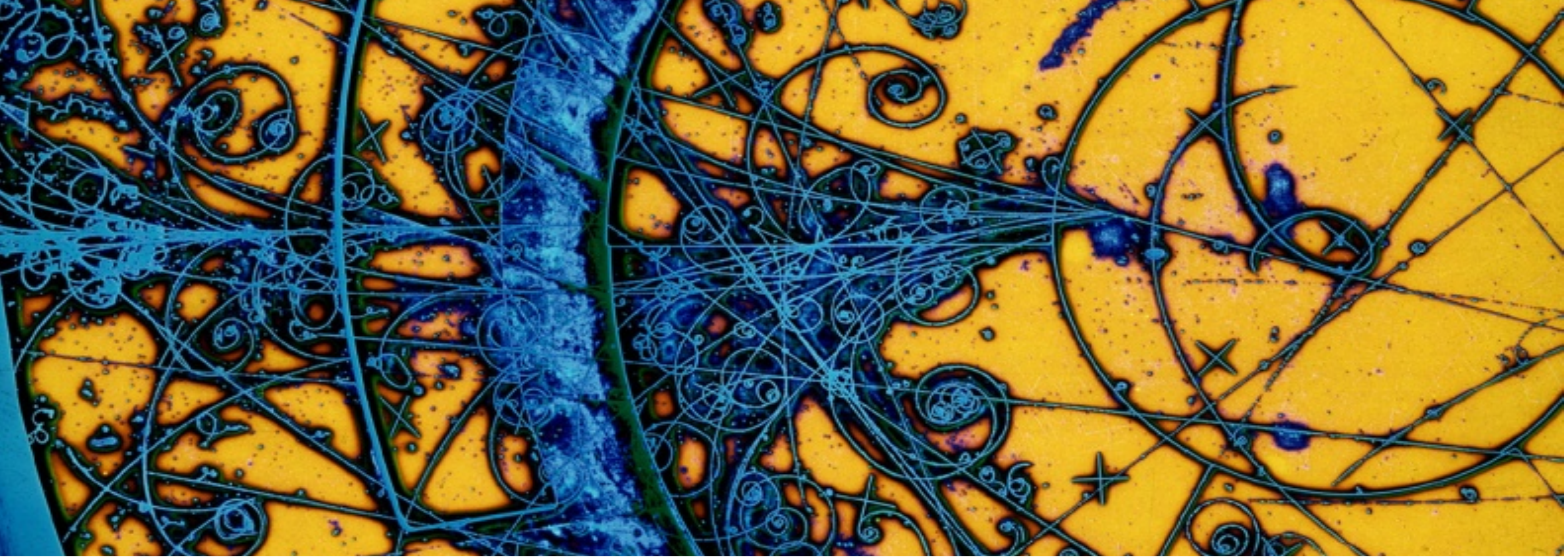


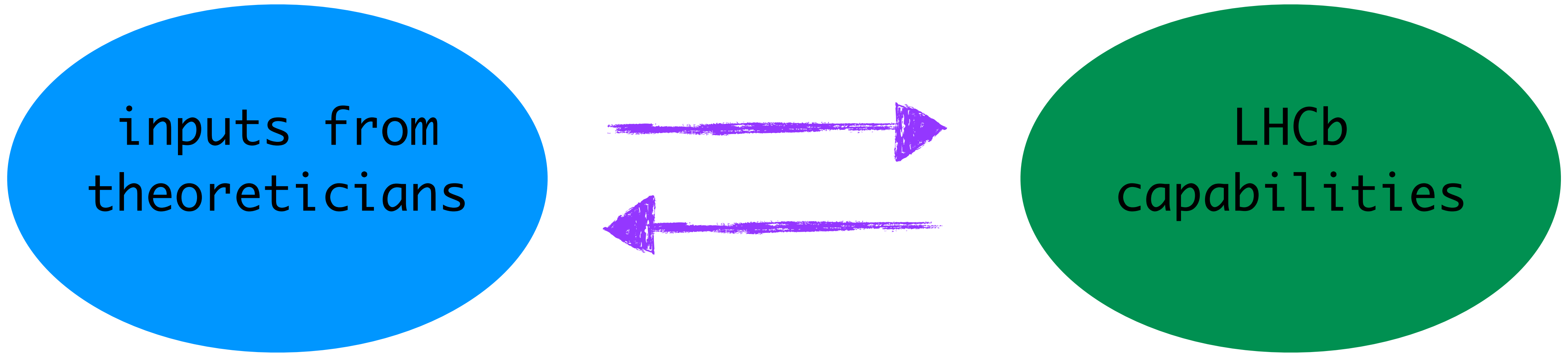
Physics channels at LHCspin

Marco Santimaria
LHCspin kick-off meeting, 18/12/2023

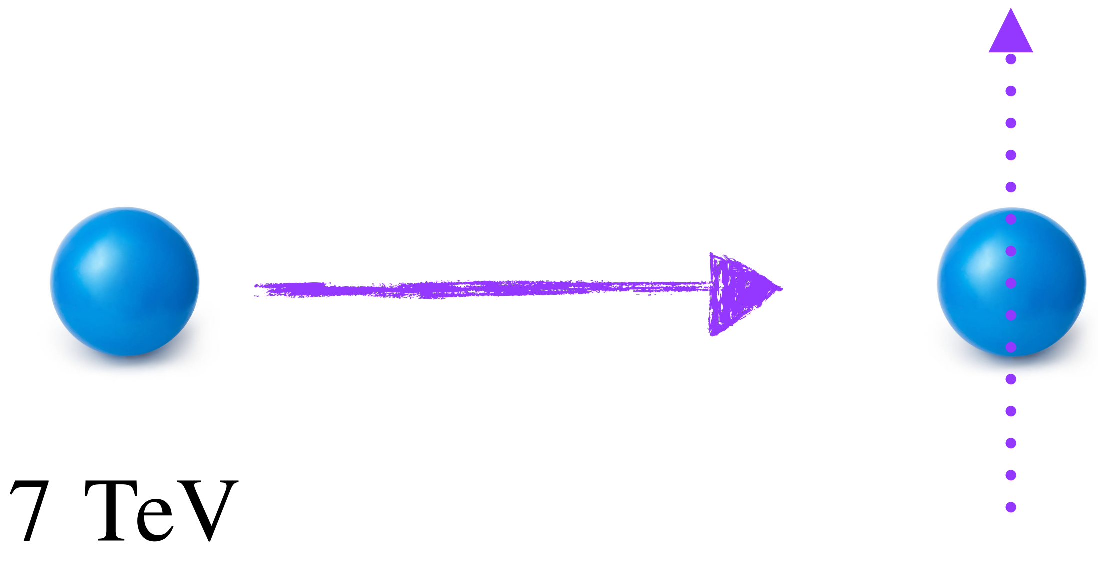
Introduction

In this talk:

1. Kinematic acceptance & reconstruction efficiency
2. Expected yields for selected channels
3. An example measurement: the gluon Sivers function



- The results are based on full LHCb simulations with p-H FT collisions
- Plenty of channels available, will focus on $J/\psi \to \mu^+\mu^-$ as a benchmark



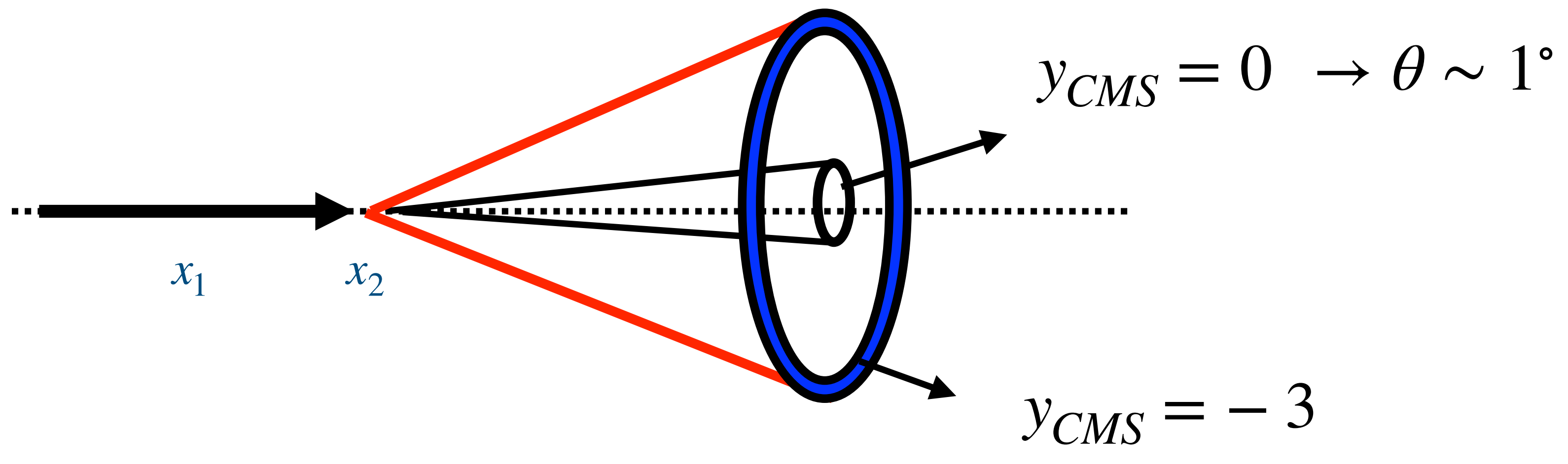
$$\sqrt{s} = \sqrt{2m_N E_p} = 115 \text{ GeV}$$

$$\gamma = \frac{\sqrt{s}}{2m_p} \sim 60$$

1: beam, 2: target

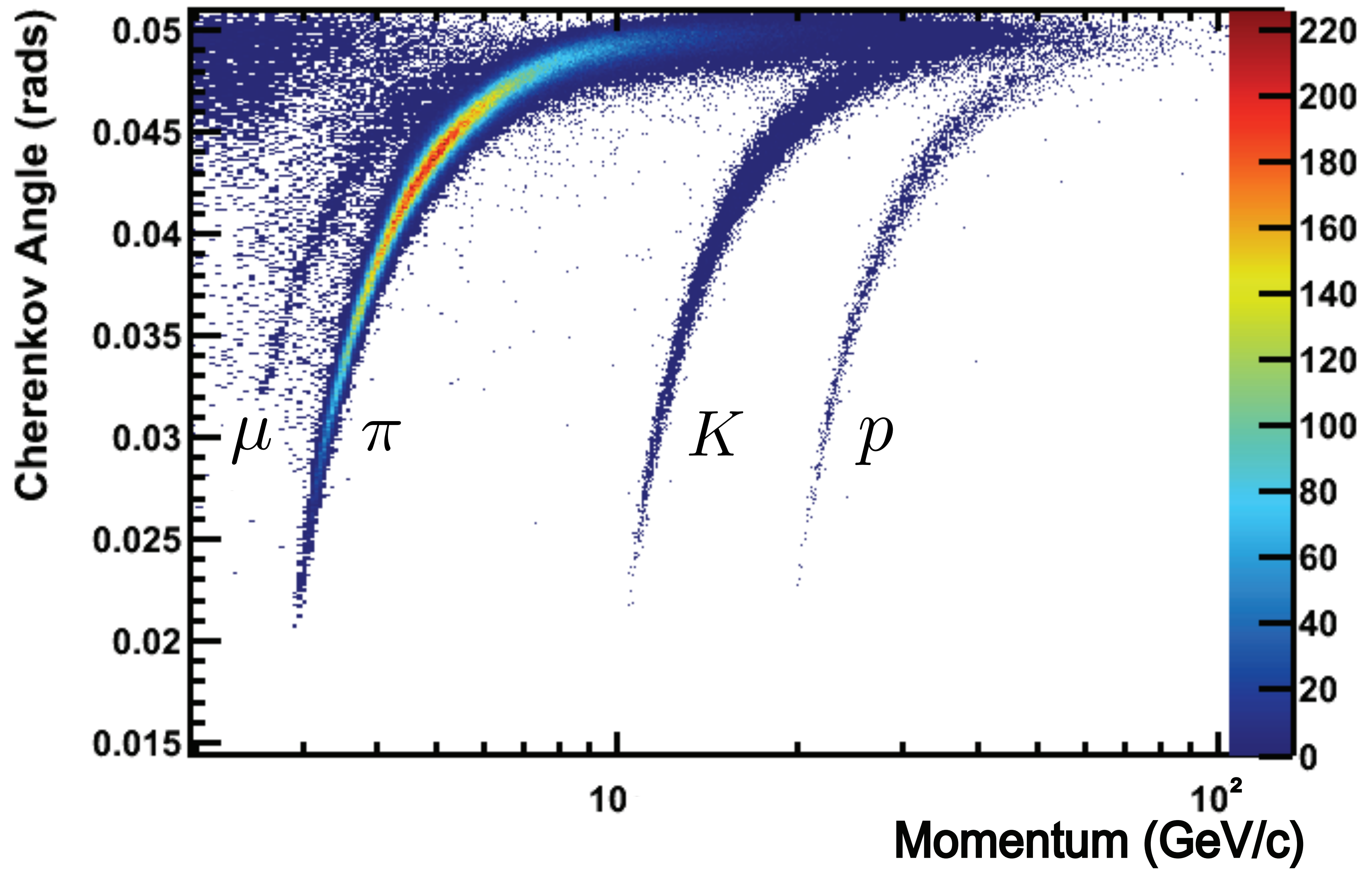
Large CM boost → large x_2 values

$2 \leq y_{lab} \leq 5 \ \rightarrow -3.0 \leq y_{CMS} \leq 0$

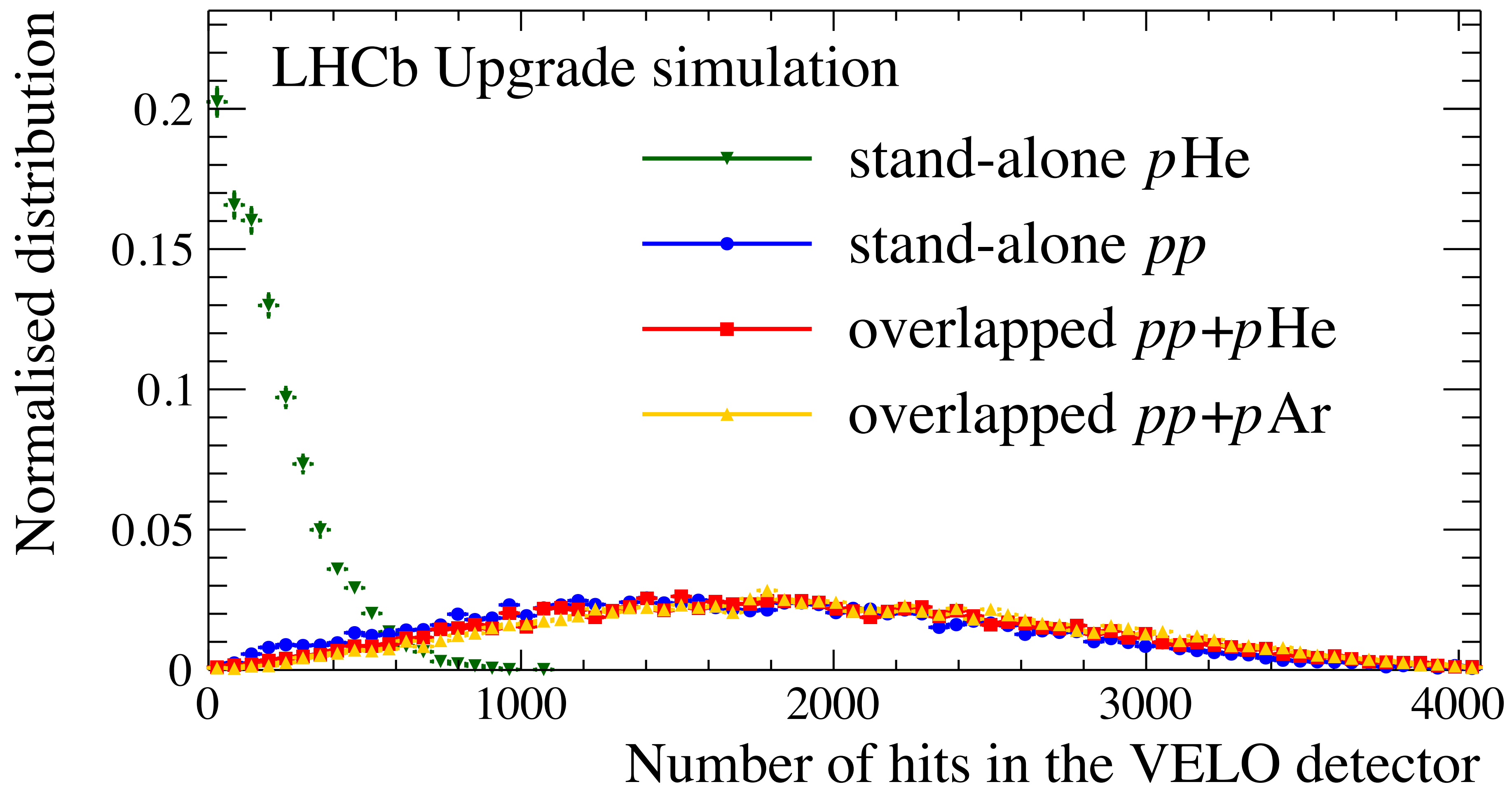


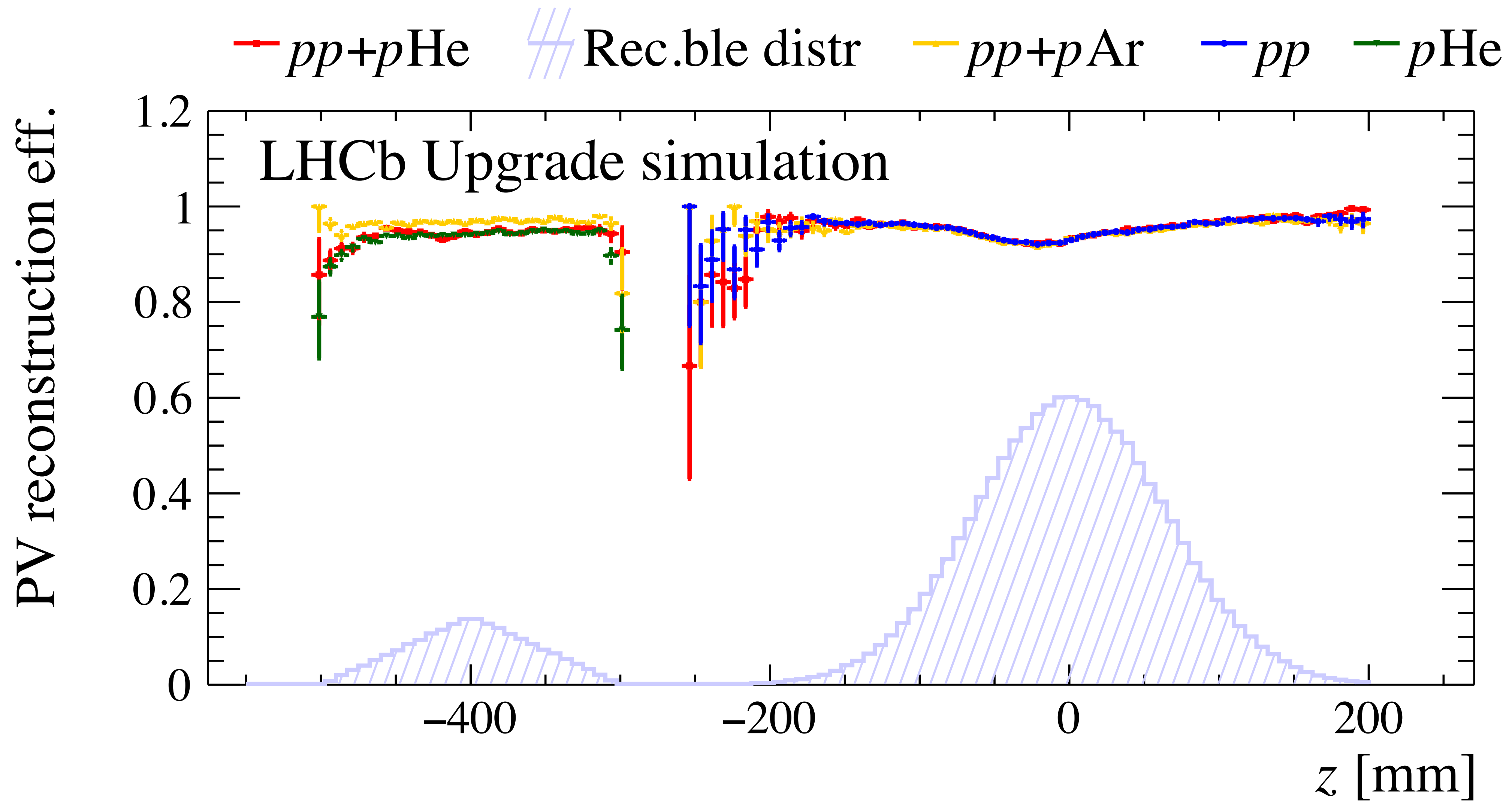
LHCb capabilities for FT

- Strength points of LHCb:
  - Fully instrumented in $2 < \eta < 5$ and optimised for b- and c-hadron detection
  - Excellent momentum resolution: $\sigma_p/p = 0.5 - 1.0\,\%$ $(p \in [2{,}200]$ GeV)
  - Excellent particle identification with RICH+CALO+MUON, e.g. $\epsilon_\mu \sim 98\,\%$ with $\epsilon_{\pi\to\mu} \lesssim 1\,\%$, hadron separation, γ/e
  - Light hadrons $(\pi, K\ldots)$ are also abundantly produced and well reconstructed, but will not be considered in the following since are not unique to LHCspin
  - Can do simultaneous p-p and p-gas data-taking



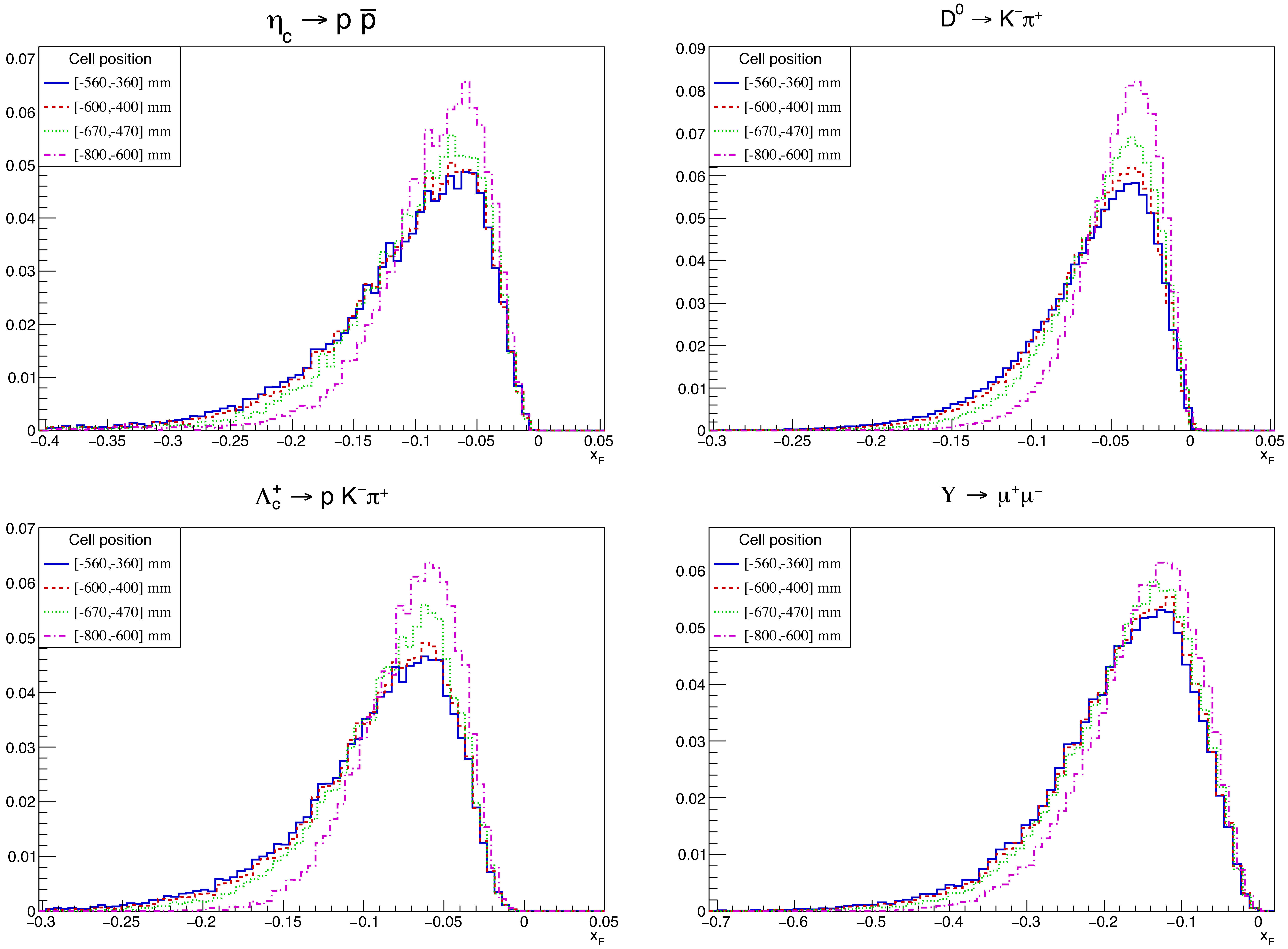
[EPJC 73 (2013) 2431]





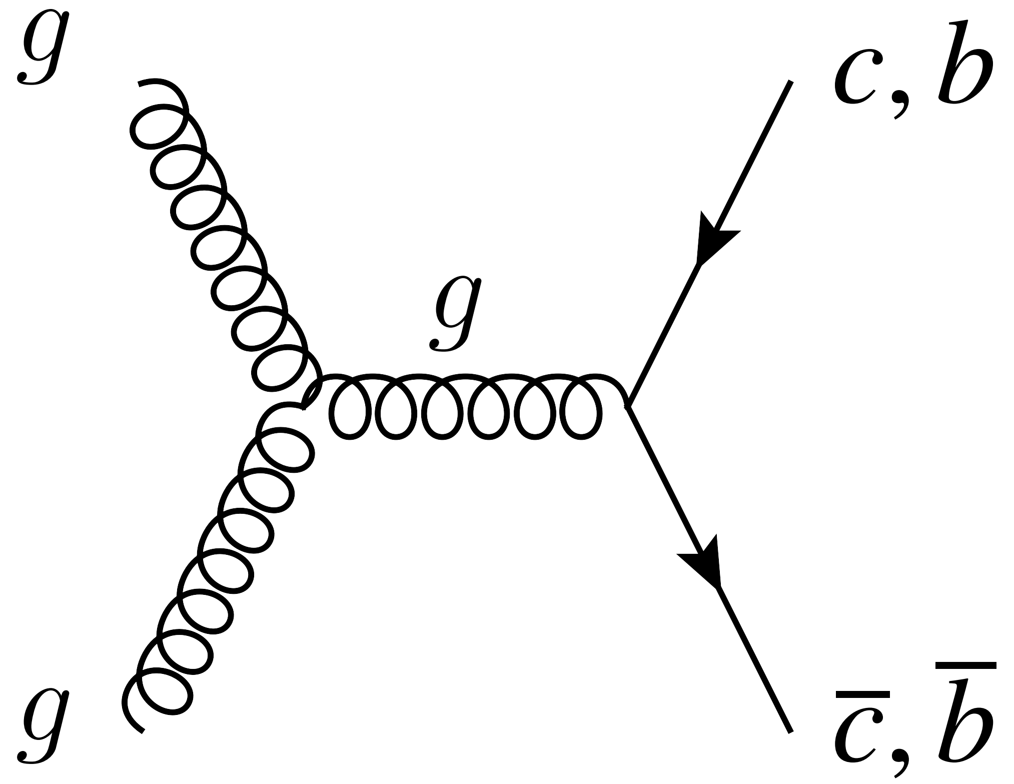
[LHCB-FIGURE-2022-002]

Heavy flavour channels: examples



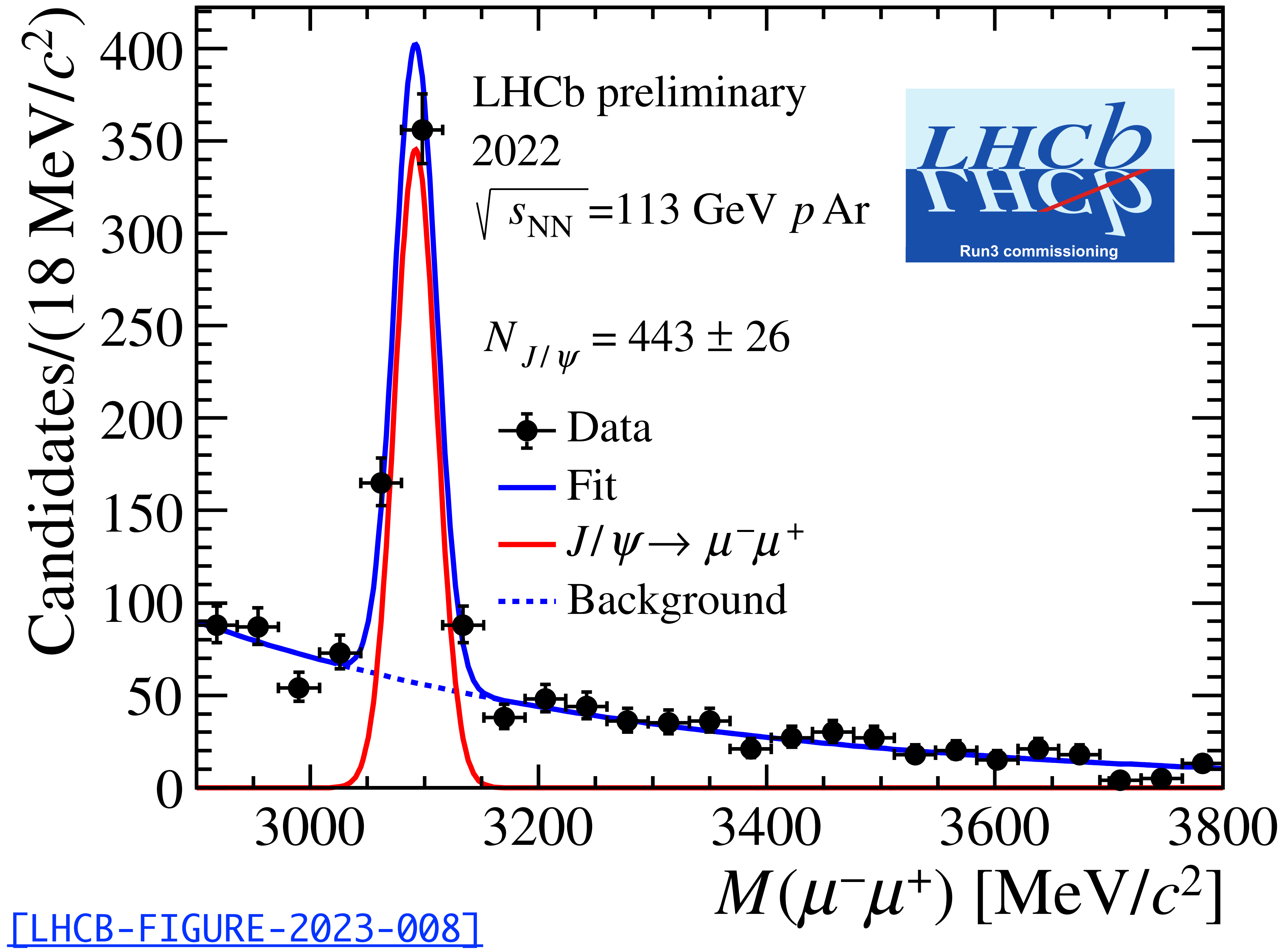
- c-hadrons will have the largest product of cross section and reconstruction efficiency
- Exotic probes and b-hadrons are also possible
- This is just a portion of the expected data (see later)

→ unique opportunity to probe gluon TMDs over a broad x range!



Expected yields

- SMOG2 is performing above the expectation despite detectors are still under commissioning:



[LHCB-FIGURE-2023-008]

- Assuming 84 hours of data-taking per week and 120-week Run… we can collect a huge amount of data!

Channel	Events / week	Total yield
$J/\psi \to \mu^+\mu^-$	1.3×10^7 !!	1.5×10^9
$D^0 \to K^-\pi^+$	6.5×10^7	7.8×10^9
$\psi(2S) \to \mu^+\mu^-$	2.3×10^5	2.8×10^7
$J/\psi J/\psi \to \mu^+\mu^-\mu^+\mu^-$ (DPS)	8.5	1.0×10^3
$J/\psi J/\psi \to \mu^+\mu^-\mu^+\mu^-$ (SPS)	2.5×10^1	3.1×10^3
Drell Yan ($5 < M_{\mu\mu} < 9$ GeV)	7.4×10^3	8.8×10^5
$\Upsilon \to \mu^+\mu^-$	5.6×10^3	6.7×10^5
$\Lambda_c^+ \to pK^-\pi^+$	1.3×10^6	1.5×10^8

- Based on this milestone, we can project to $\phi = 6.5 \times 10^{16}$ atoms/s (HERMES ABS) and SMOG2-like cell conductance
  → $\theta = 3.7 \times 10^{13}/\mathrm{cm}^2$ for polarised hydrogen

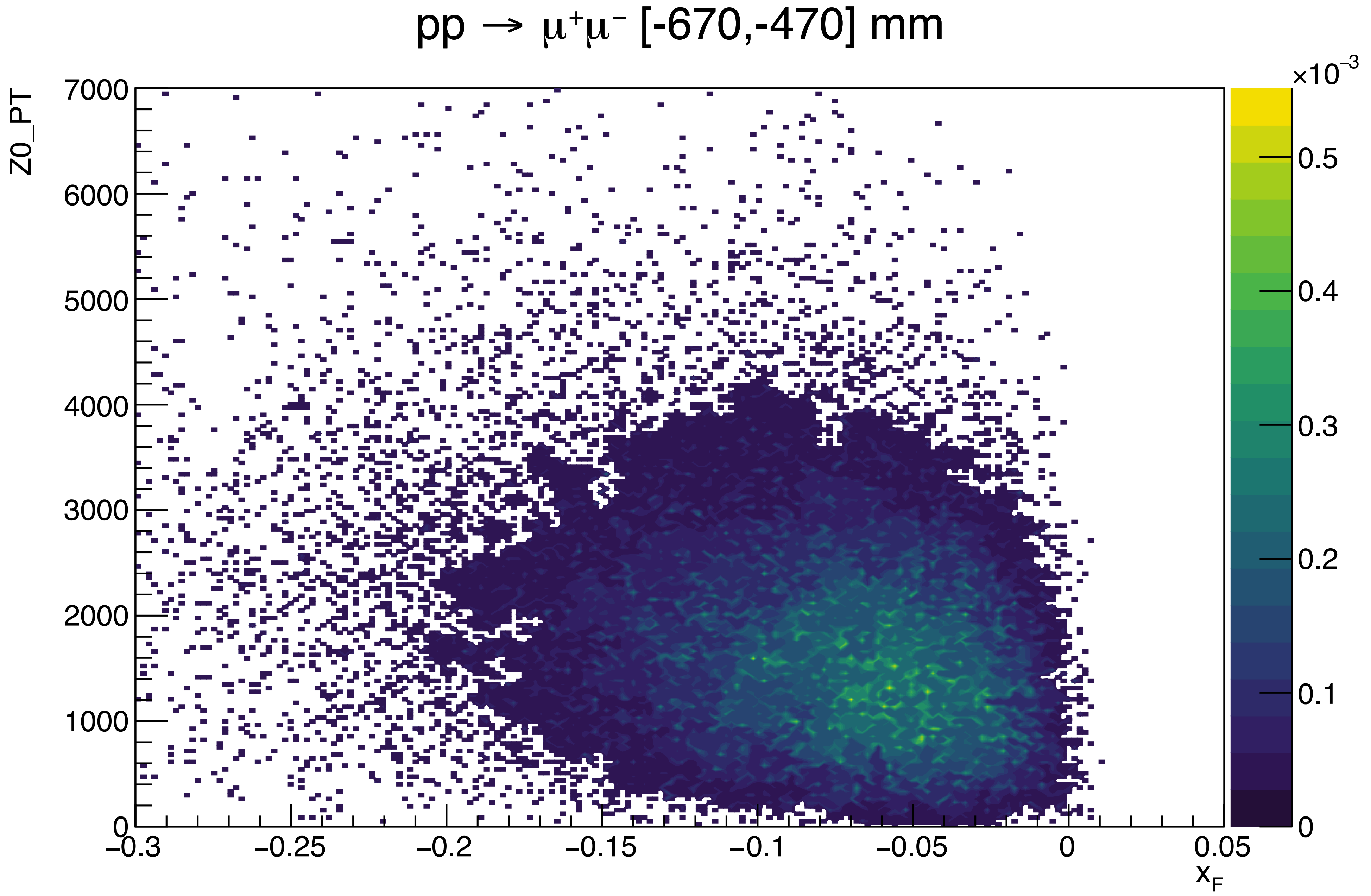
- This is the number of fully-reconstructed and selected events based on our current capabilities
  - Event rate enhanced during HL-LHC (Upgrade II)
  - Fully-software trigger allows further improvements

Polarised Drell-Yan

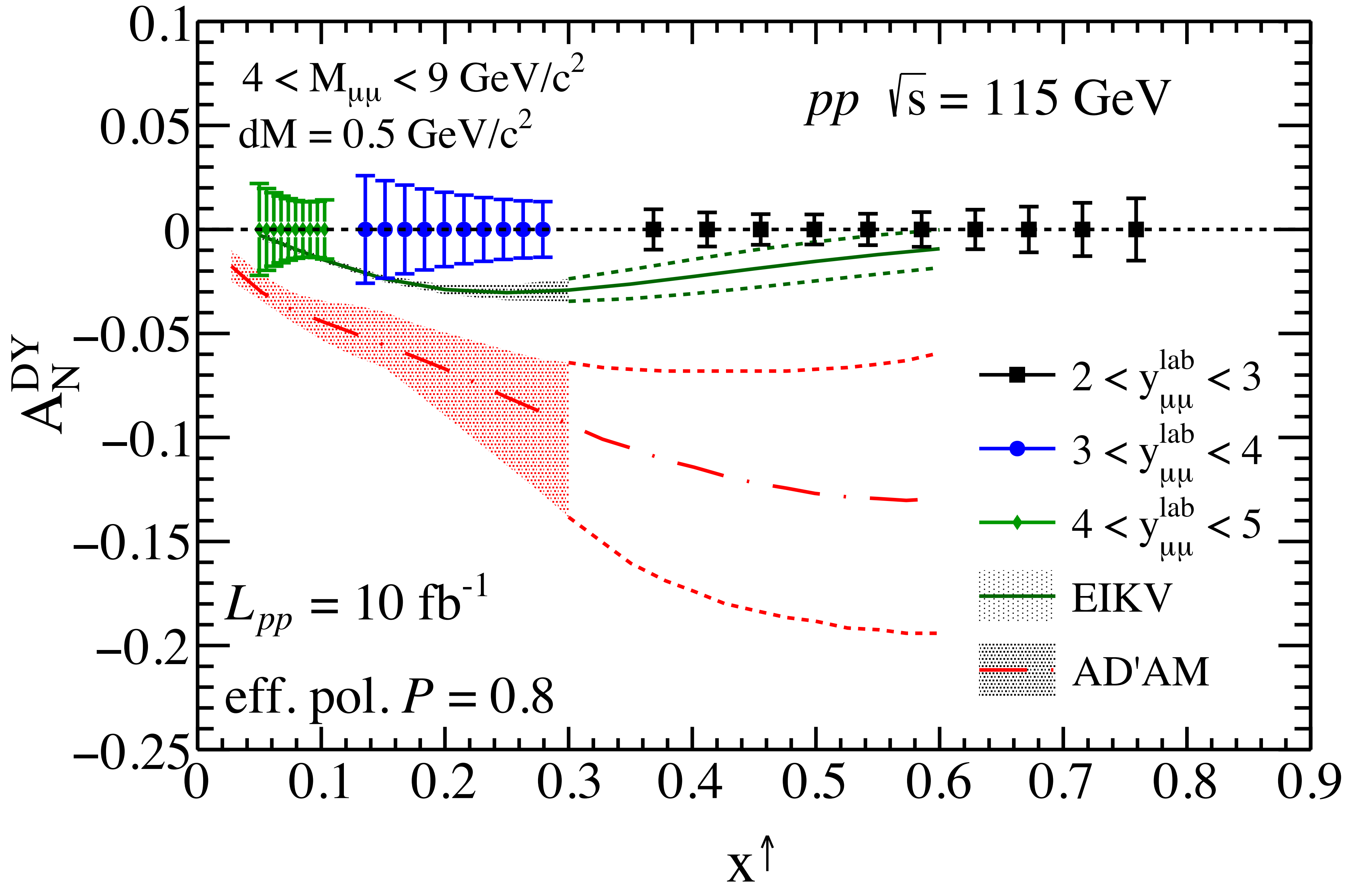
- To access the transverse motion of partons inside a polarised nucleon: measure TMDs via TSSAs at high $x_2^\uparrow$ (and low x_1)

$$A_N = \frac{1}{P}\frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow} \longrightarrow A_N \sim \frac{f_1^q(x_1, k_{T1}^2) \otimes f_{1T}^{\perp\bar{q}}(x_2, k_{T2}^2)}{f_1^q(x_1, k_{T1}^2) \otimes f_1^q(x_2, k_{T2}^2)}$$

- Kinematics (~30k events):



- Projections of polarised DY with $10\ \text{fb}^{-1}$ of data from [ArXiv:1807.00603] :



- Precise measurements but also unique features:
  - Verify the sign change of the Sivers TMD in DY wrt SIDIS:

$$f_{1T}^{\perp q}(x, k_T^2)_{\text{DY}} = -f_{1T}^{\perp q}(x, k_T^2)_{\text{SIDIS}}$$

  - + isospin effect with polarised deuterium

More TMDs

- Can probe TMDs via azimuthal asymmetries of the dilepton pair:
- h_q^1 : transversity → difference in densities of quarks having T pol. ↑↑ or ↑↓ in T pol. nucleon
- $f_{1T}^{\perp q}$: Sivers → dependence on p_T orientation wrt T pol. nucleon
- $h_1^{\perp q}$: Boer-Mulders → dependence on p_T orientation wrt T pol. quark in unp. nucleon
- $h_{1T}^{\perp q}$: pretzelosity → dependence on p_T and T. pol of both T pol. quark and nucleon
- f_1^q : unpolarised TMD, always present at the denominator

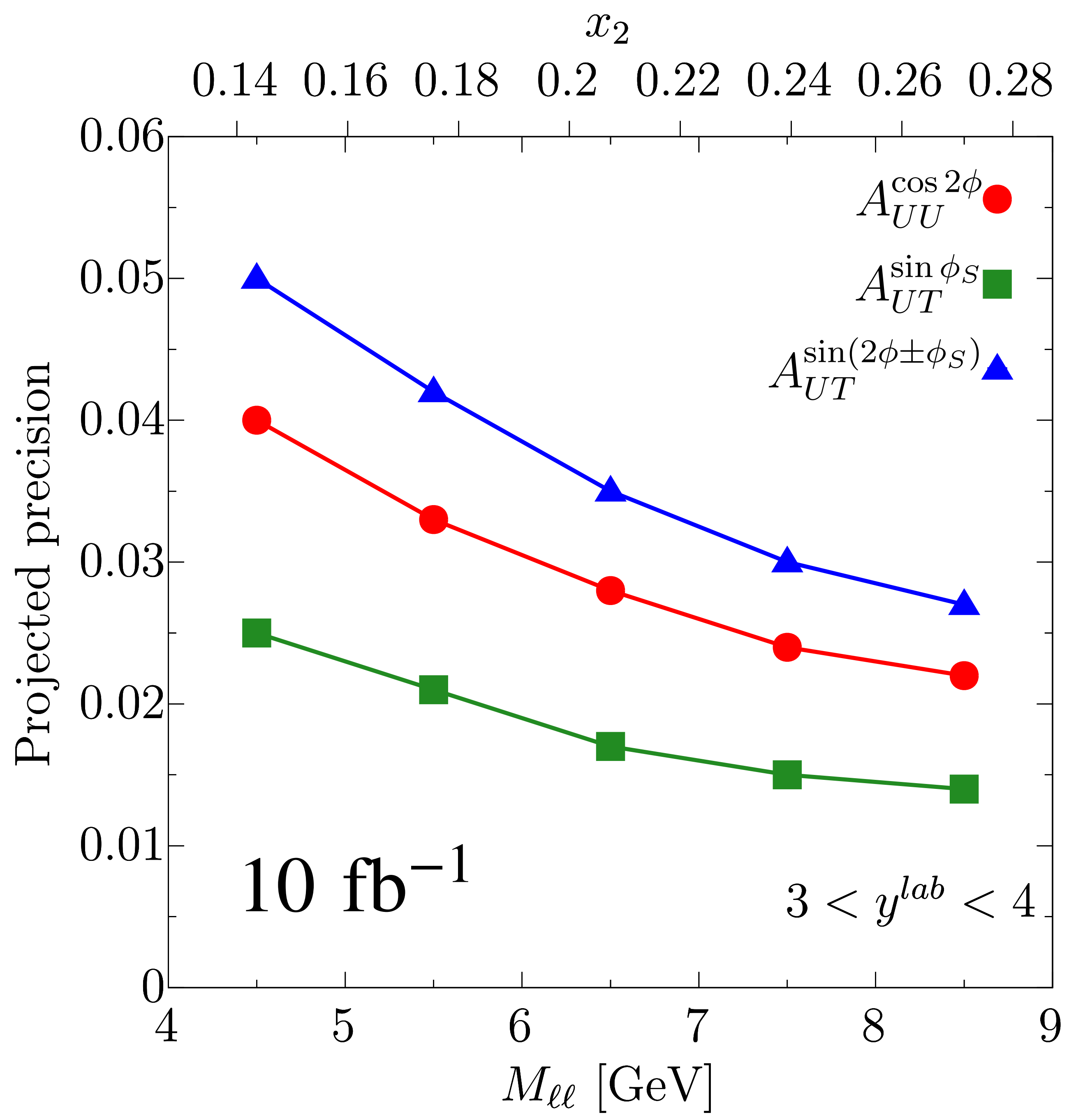
$$A_{UU}^{cos2\phi} \sim \frac{h_1^{\perp q}(x_1,k_{1T}^2)\otimes h_1^{\perp \bar{q}}(x_2,k_{2T}^2)}{f_1^q(x_1,k_{1T}^2)\otimes f_1^{\bar{q}}(x_2,k_{2T}^2)}$$

$$A_{UT}^{sin\phi_S} \sim \frac{f_1^q(x_1,k_{1T}^2)\otimes f_{1T}^{\perp \bar{q}}(x_2,k_{2T}^2)}{f_1^q(x_1,k_{1T}^2)\otimes f_1^{\bar{q}}(x_2,k_{2T}^2)}$$

$$A_{UT}^{sin(2\phi+\phi_S)} \sim \frac{h_1^{\perp q}(x_1,k_{1T}^2)\otimes h_{1T}^{\perp \bar{q}}(x_2,k_{2T}^2)}{f_1^q(x_1,k_{1T}^2)\otimes f_1^{\bar{q}}(x_2,k_{2T}^2)}$$

$$A_{UT}^{sin(2\phi-\phi_S)} \sim \frac{h_1^{\perp q}(x_1,k_{1T}^2)\otimes h_1^{\bar{q}}(x_2,k_{2T}^2)}{f_1^q(x_1,k_{1T}^2)\otimes f_1^{\bar{q}}(x_2,k_{2T}^2)}$$

- Polarised Drell-Yan to access unpolarised TMDs of sea quarks and polarised TMDs in the valence region
- A good precision can be attained with ~1M events and 20-40 MeV mass resolution
- Also, dedicated trigger lines can be implemented e.g. tight muonID and relaxed p cuts, electron lines…



[ArXiv:1807.00603]

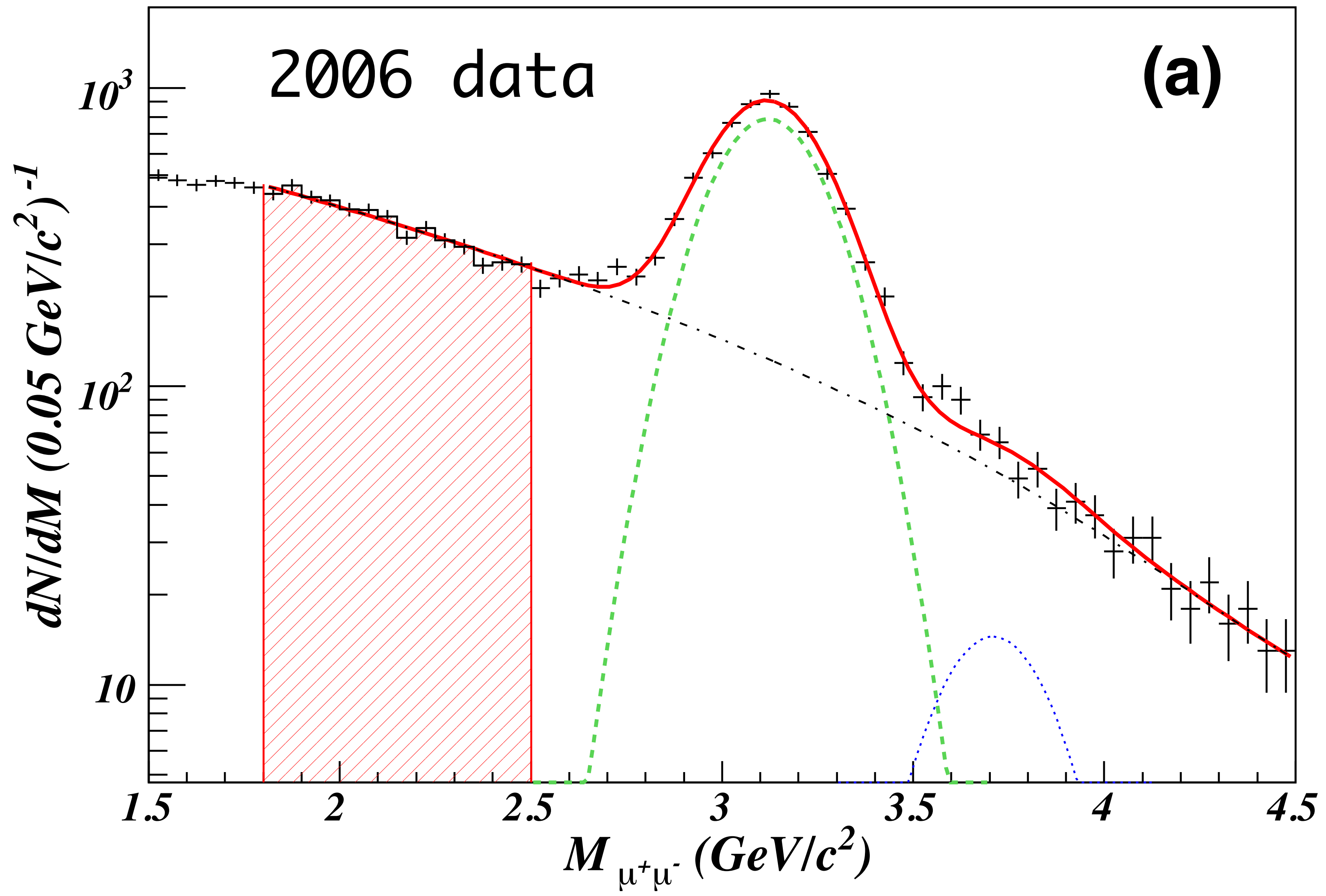
Heavy-flavour and comparison with PHENIX

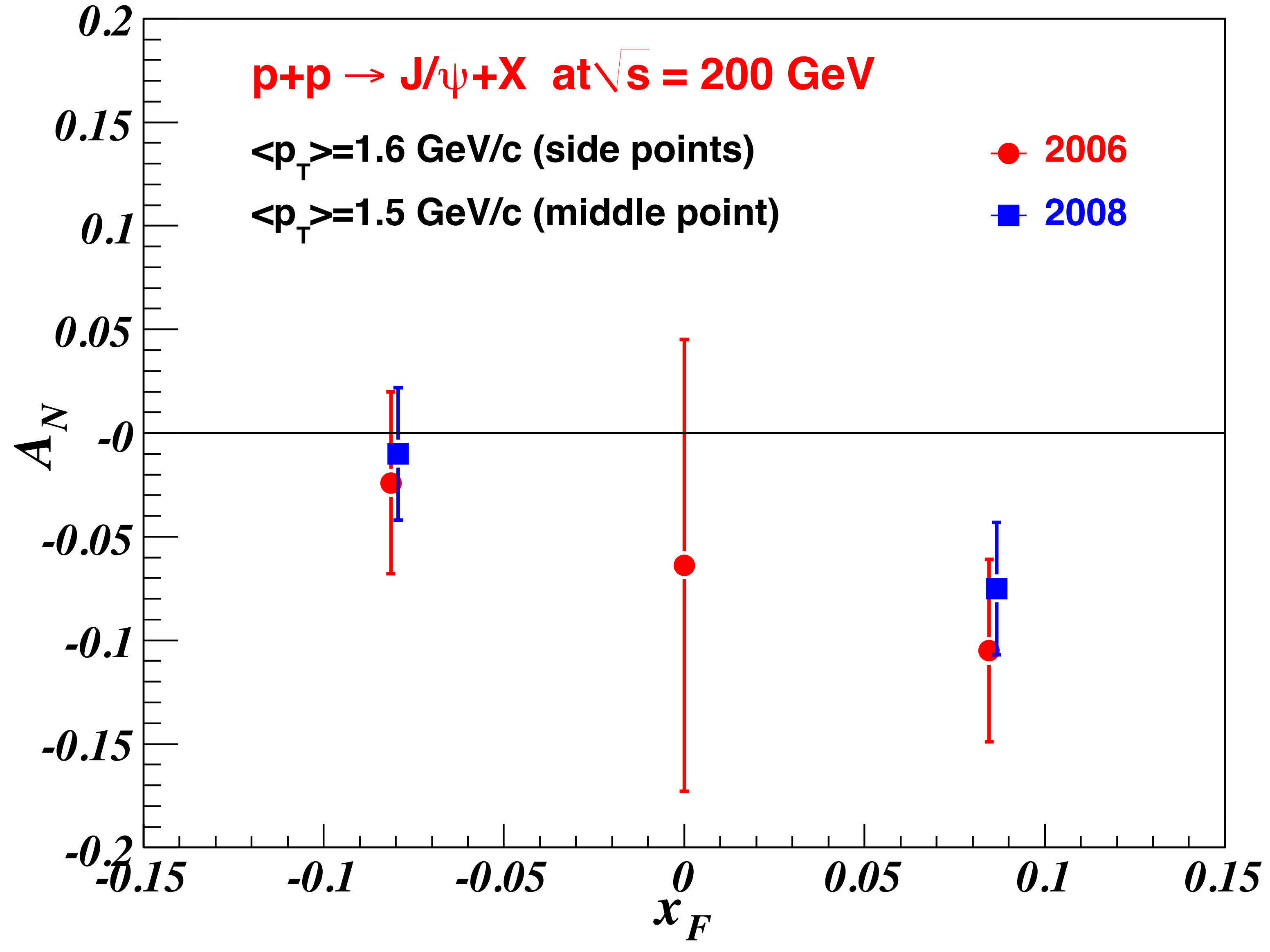
- LHCspin strength point and uniqueness will be heavy flavours, mostly unexplored by existing facilities
- The (only?) exception is J/ψ, for which measurements have been performed at PHENIX in polarised pp at $\sqrt{s} = 200$ GeV. However, compared to LHCspin:
  - ~ 21k signal candidates (2006 + 2008 data) → can be collected in ~10 minutes (cell) or ~7 hours (jet)
  - Mass resolution ~ 150 MeV → $\sigma_{\mu\mu} \approx 13$ MeV at the J/ψ mass and $\sigma_{\mu\mu} \approx 42$ MeV at the Υ mass
  - $\psi(2S)$ barely visible → can measure excited states

→ we can greatly enrich these results with high precision measurements and much larger kinematic coverage!

- Also, with a few thousands of di-J/ψ events we could measure the gluon Sivers $f_{1T}^{\perp g}$, transversity h_{1T}^{g} and pretzelosity $h_{1T}^{\perp g}$
- Unique in FT! Challenging, but specific lines can be developed already in the Run 3

[PLB 784 (2018) 217-222] [J. Bor @ DESY 2023]





[PRD 82 (2010) 112008]

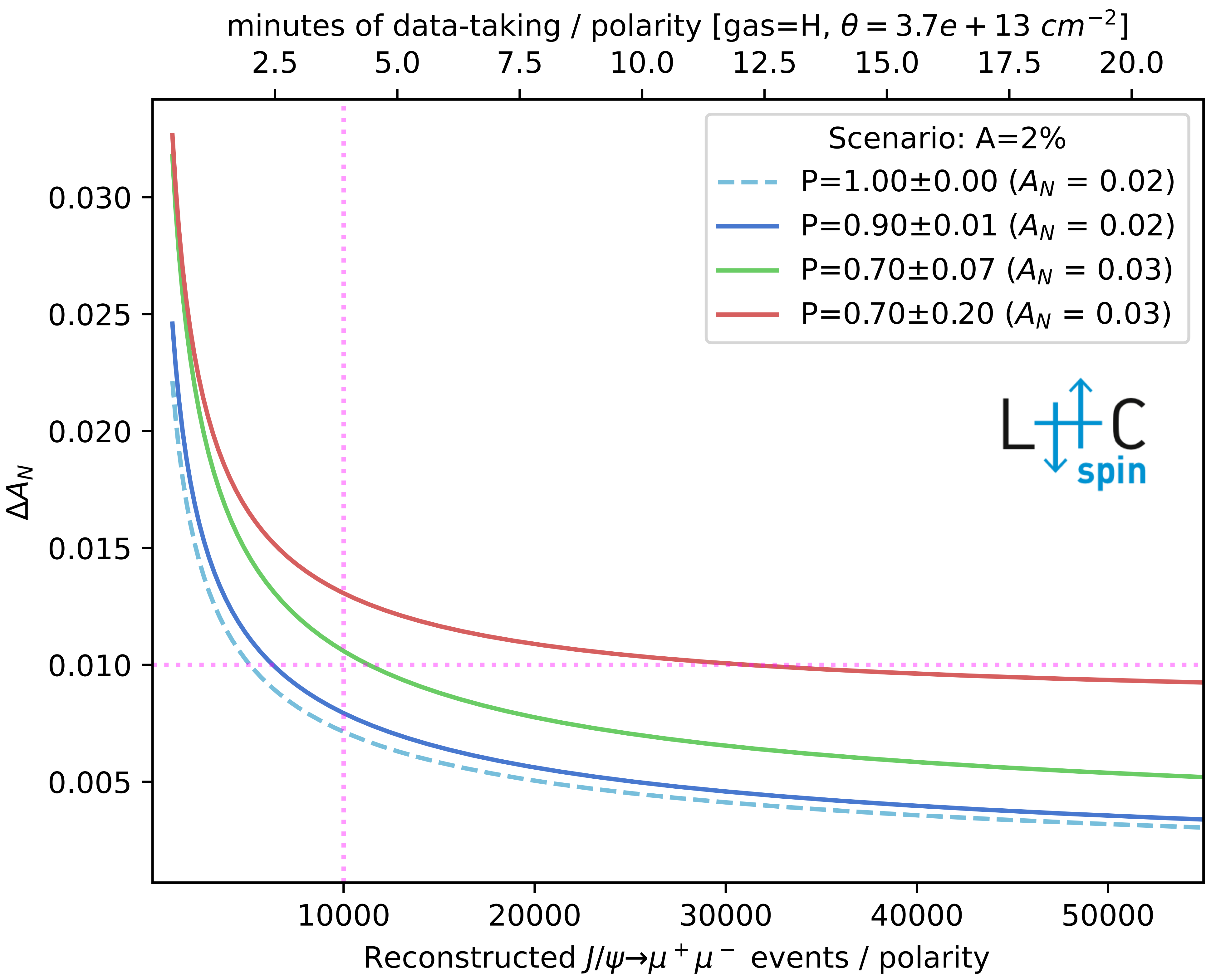
Expected precision on A_N

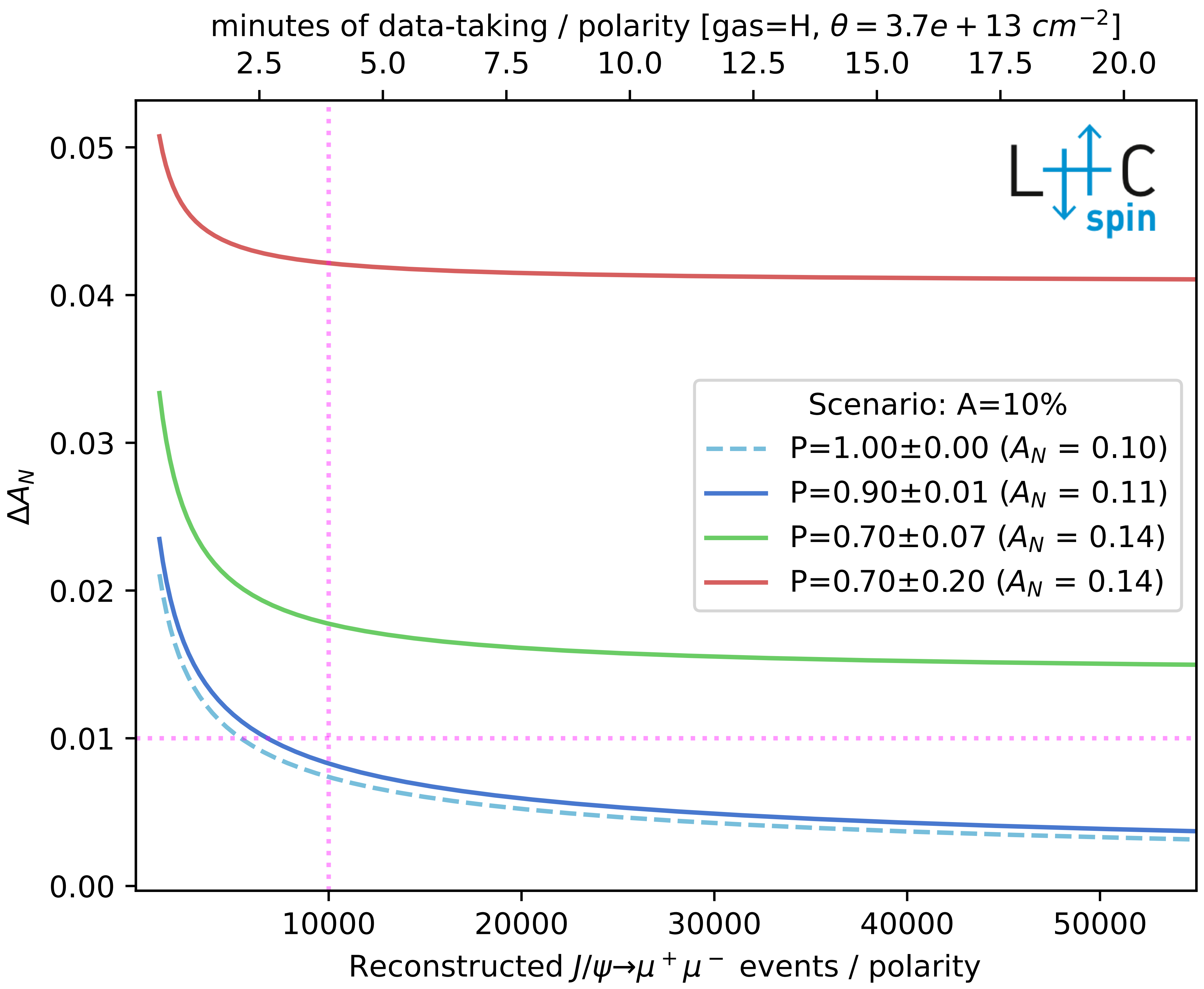
- Expected uncertainty on a TSSA at LHCspin:

$$A_N = \frac{1}{P}\frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}} \quad \rightarrow \quad \Delta A \approx \frac{1}{\sqrt{2N^{\uparrow}}}$$

- ΔA_N showed for different polarisation degrees on two scenarios: small asymmetry $A = 2\,\%$ (left) and large asymmetry $A = 10\,\%$ (right)

- Systematic limit from P reached after few minutes for $J/\psi \rightarrow \mu^+\mu^-$: precision TSSA measurements possible with very short $pH^{\uparrow}$ runs!
  - Cell target example: $P = 0.70 \pm 0.07$, $\theta = 3.7 \times 10^{13}/\mathrm{cm}^2$ (used in the plots)
  - Jet target example: $P = 0.90 \pm 0.01$, $\theta \approx 10^{12}/\mathrm{cm}^2$





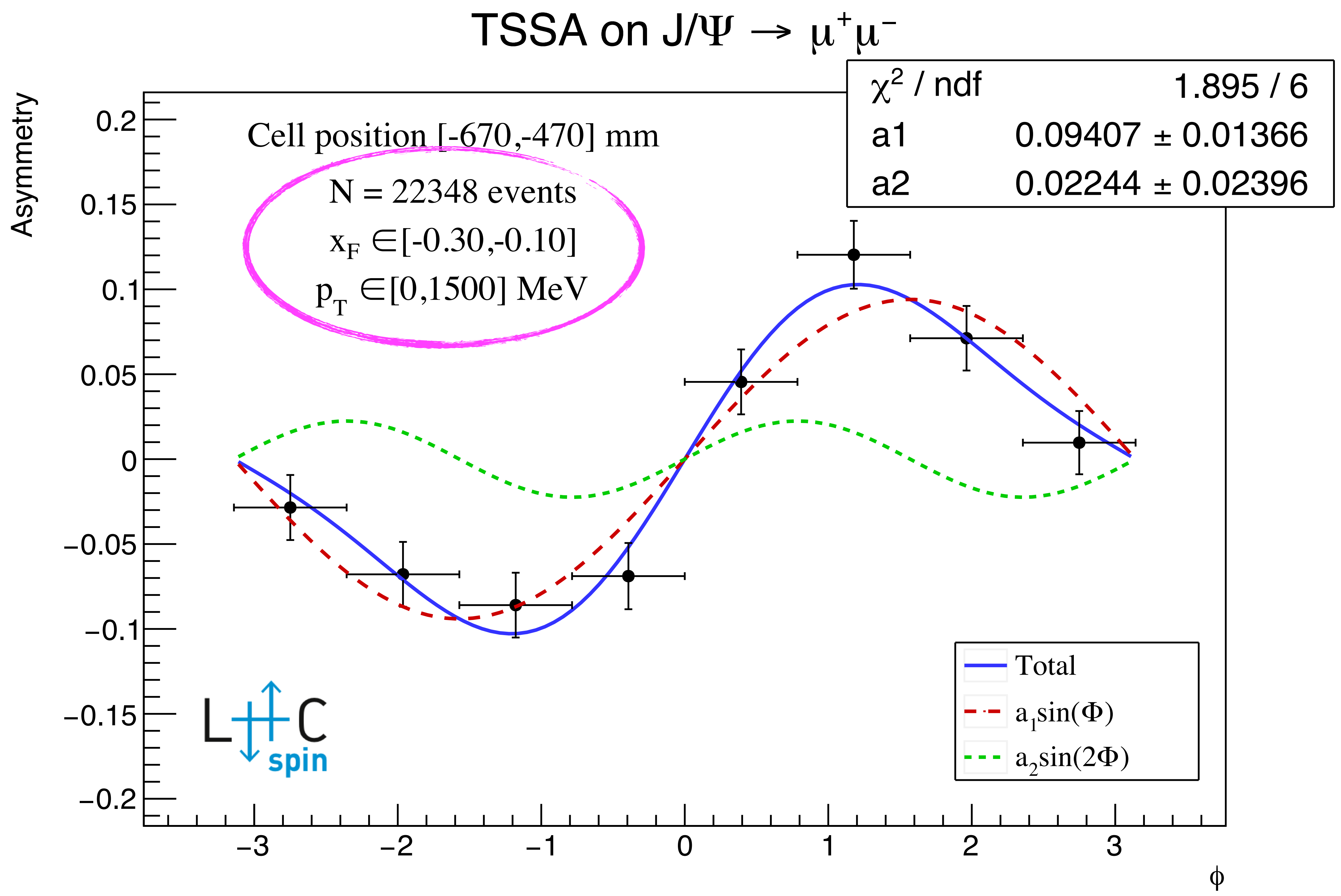
Polarised data

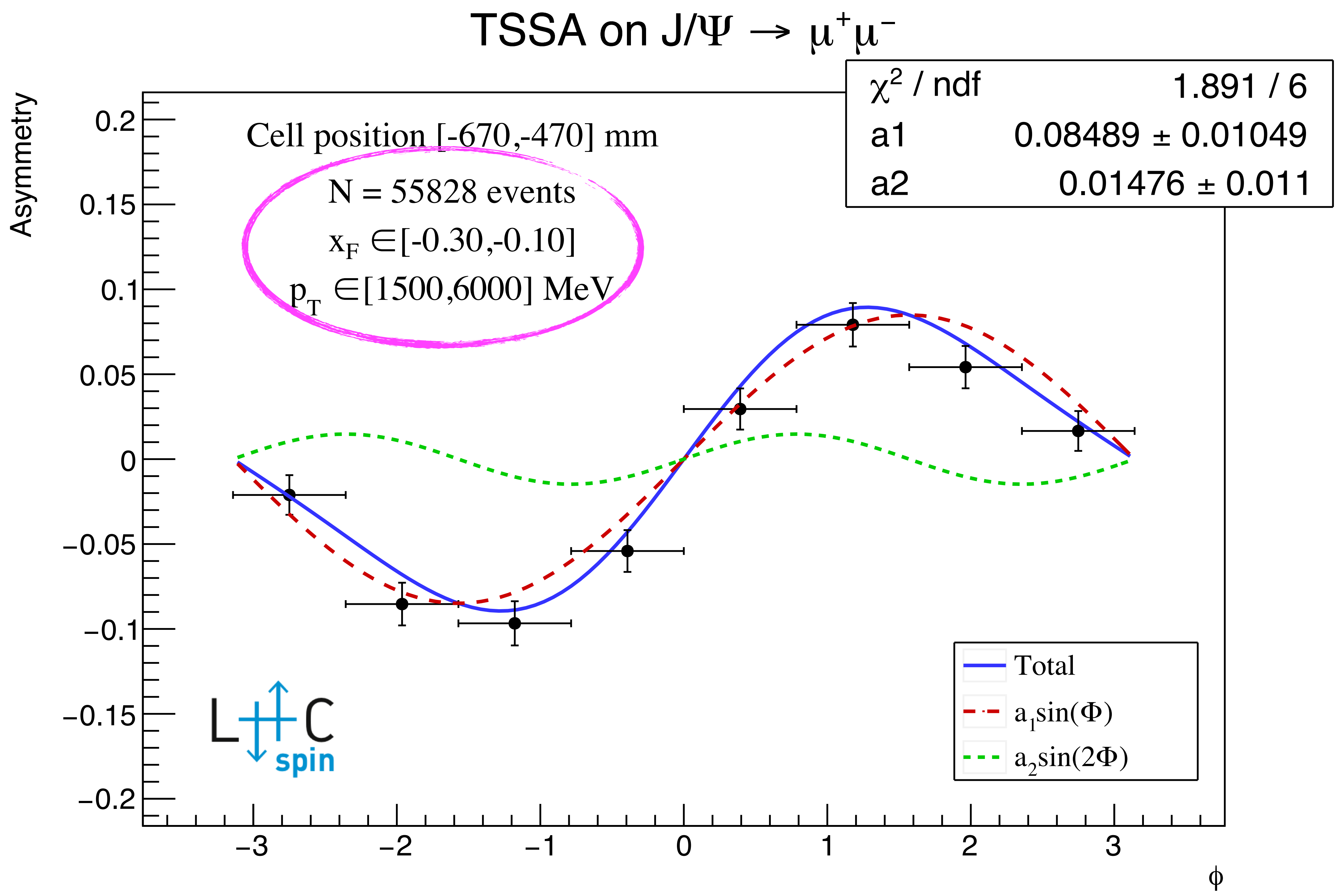
[JHEP 12 (2020) 010]

- Our MC is unpolarised. The polarisation can be emulated by assigning +-1 state according to

$$\rho = \frac{1}{2}\left[1 + \left(a_1 + a_2\frac{x-\overline{x}}{x_{max}} + a_3\frac{p_T - \overline{p_T}}{p_{T\ max}}\right)\sin\phi + \left(b_1 + b_2\frac{x-\overline{x}}{x_{max}} + b_3\frac{p_T - \overline{p_T}}{p_{T\ max}}\right)\sin 2\phi\right]$$

- The resulting pseudo-data are fitted, in this examples with two amplitudes in $4\ x_F \times 2\ p_T \times 8\ \phi$ bins using $A_N \sim 0.1 \pm 0.01$ and $\Delta P = 5\,\%$:

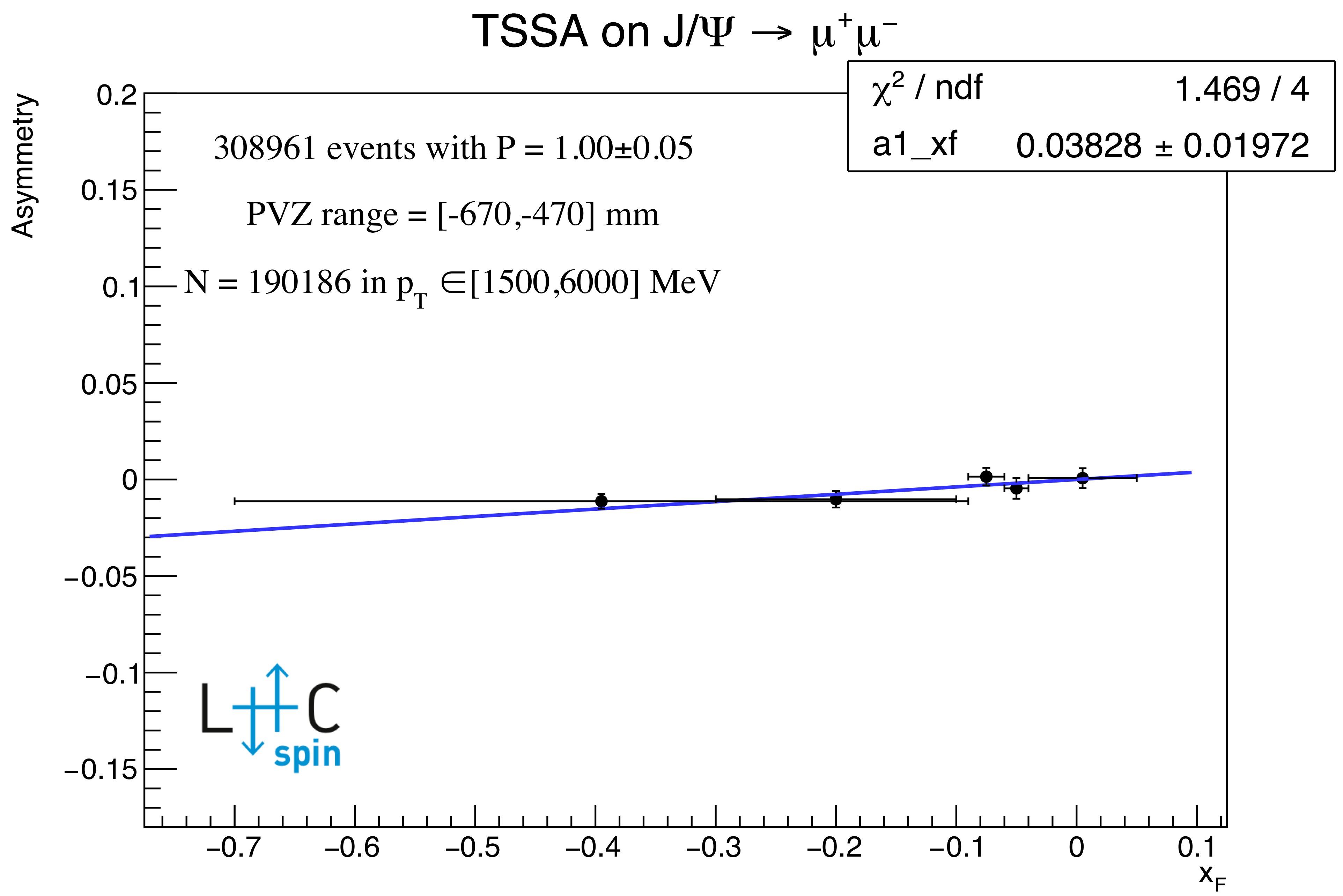


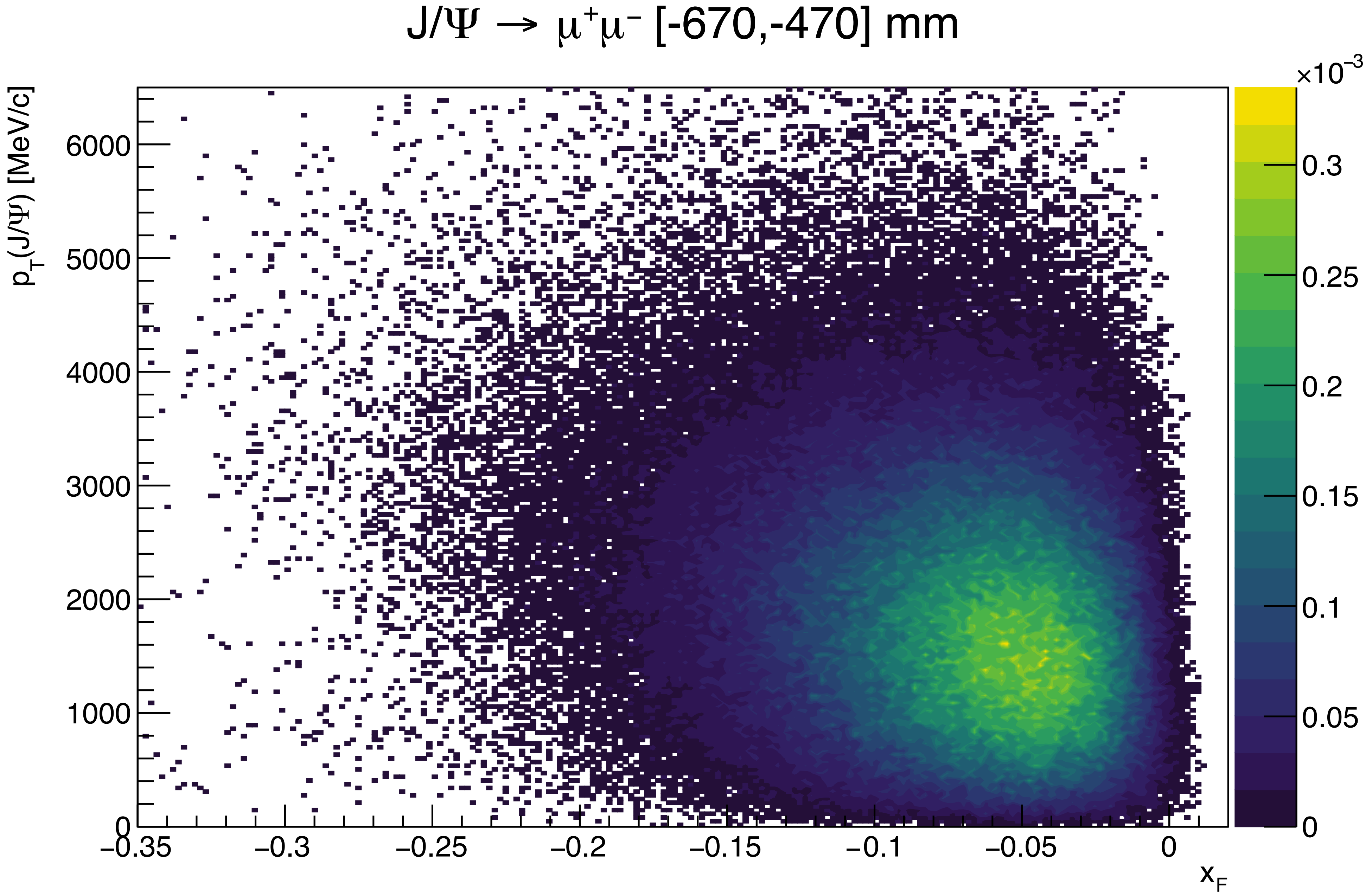


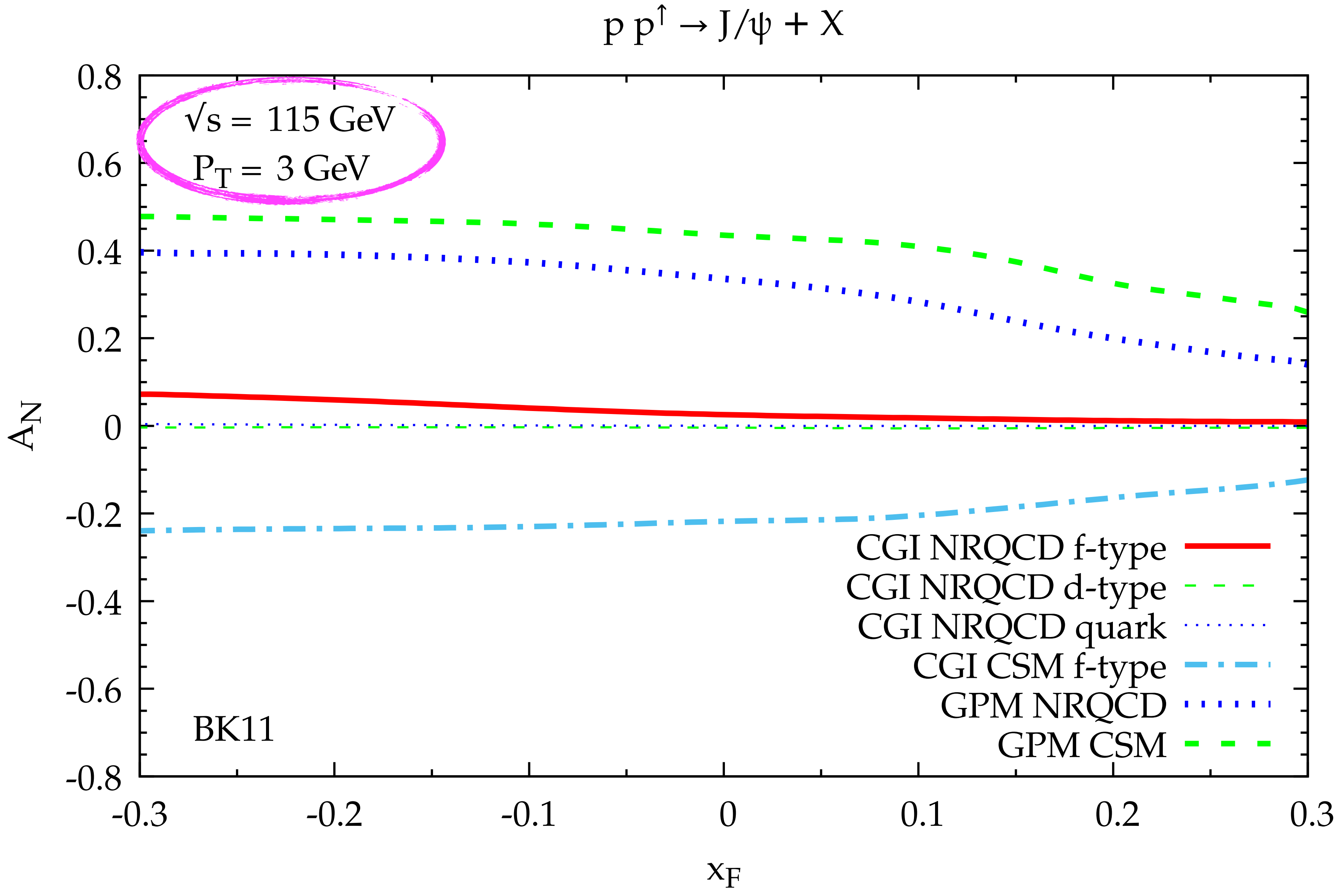
- Just a starting point: can refine & test any model of choice!

An example measurement: the Gluon Sivers function

- A simpler approach for large asymmetry: x_F and p_T dependence of A_N (here ~0) → this precision can be achieved with just few hours of data-taking!
- We can provide precision measurements well able to distinguish among theoretical predictions of the GSF
- Kinematic coverage given below for ~300k events (small sample)
- Simulations with the full LHCb detector shown
  → to be performed also for the IR4 setup





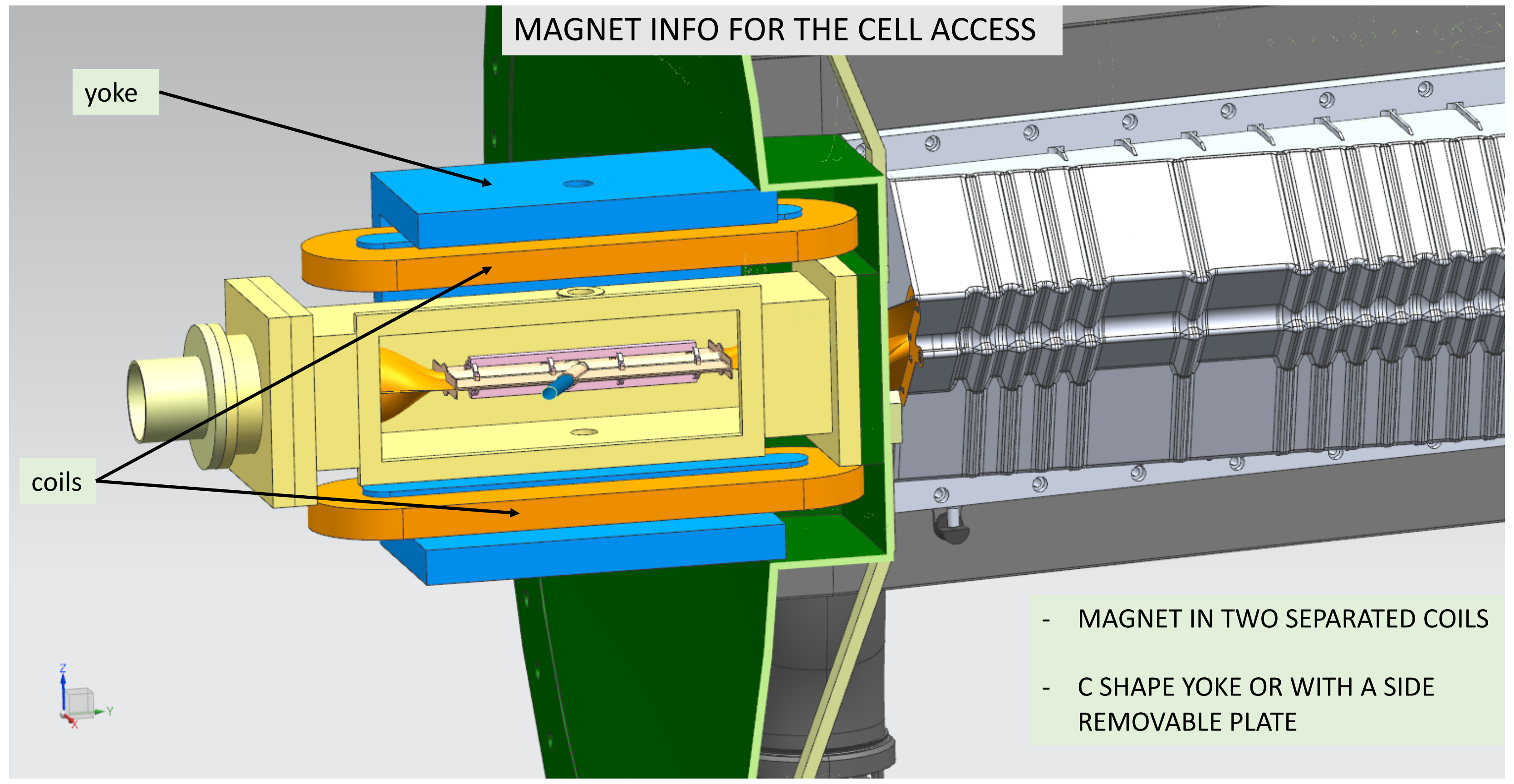


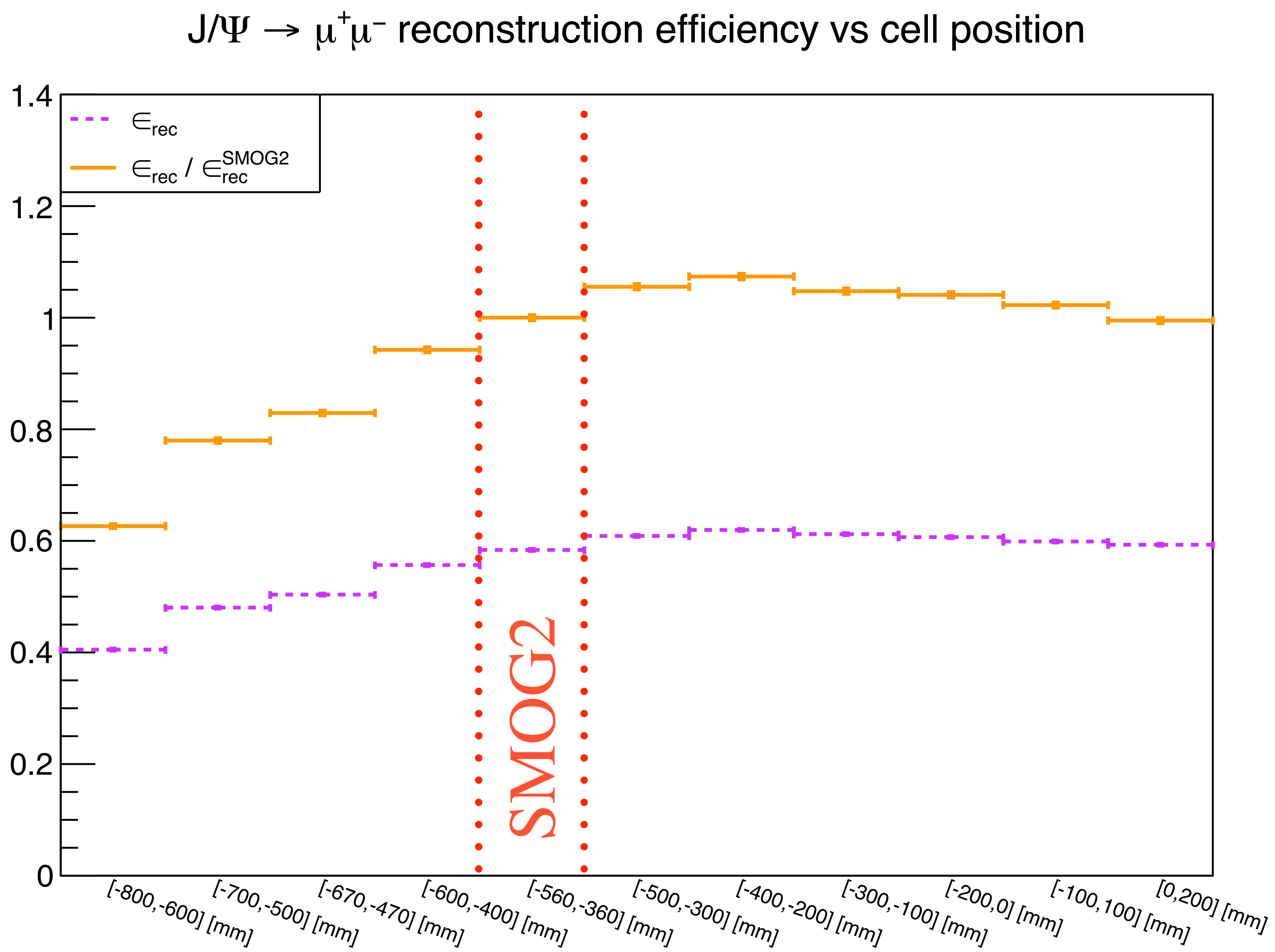
[PRD 102 (2020) 094011]

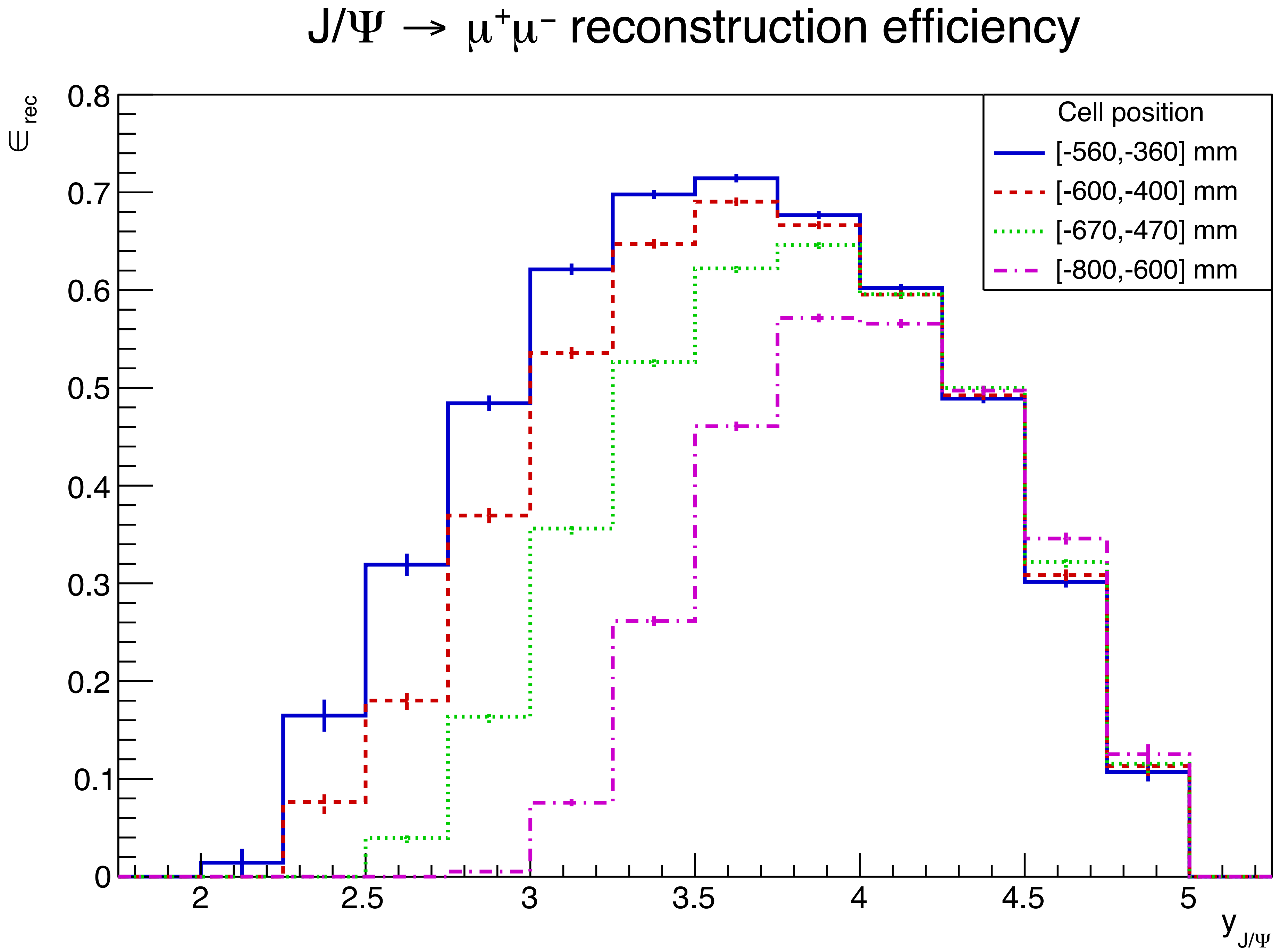
backup

Reconstruction efficiency

- LHCb simulations show broader kinematic acceptance & better reconstruction efficiency when the cell is close to the VELO, however:
  - Several reconstruction & trigger improvements have already been deployed for the Run 3
  - More reliable number will come with data next year, so here the focus is on ratios of efficiencies



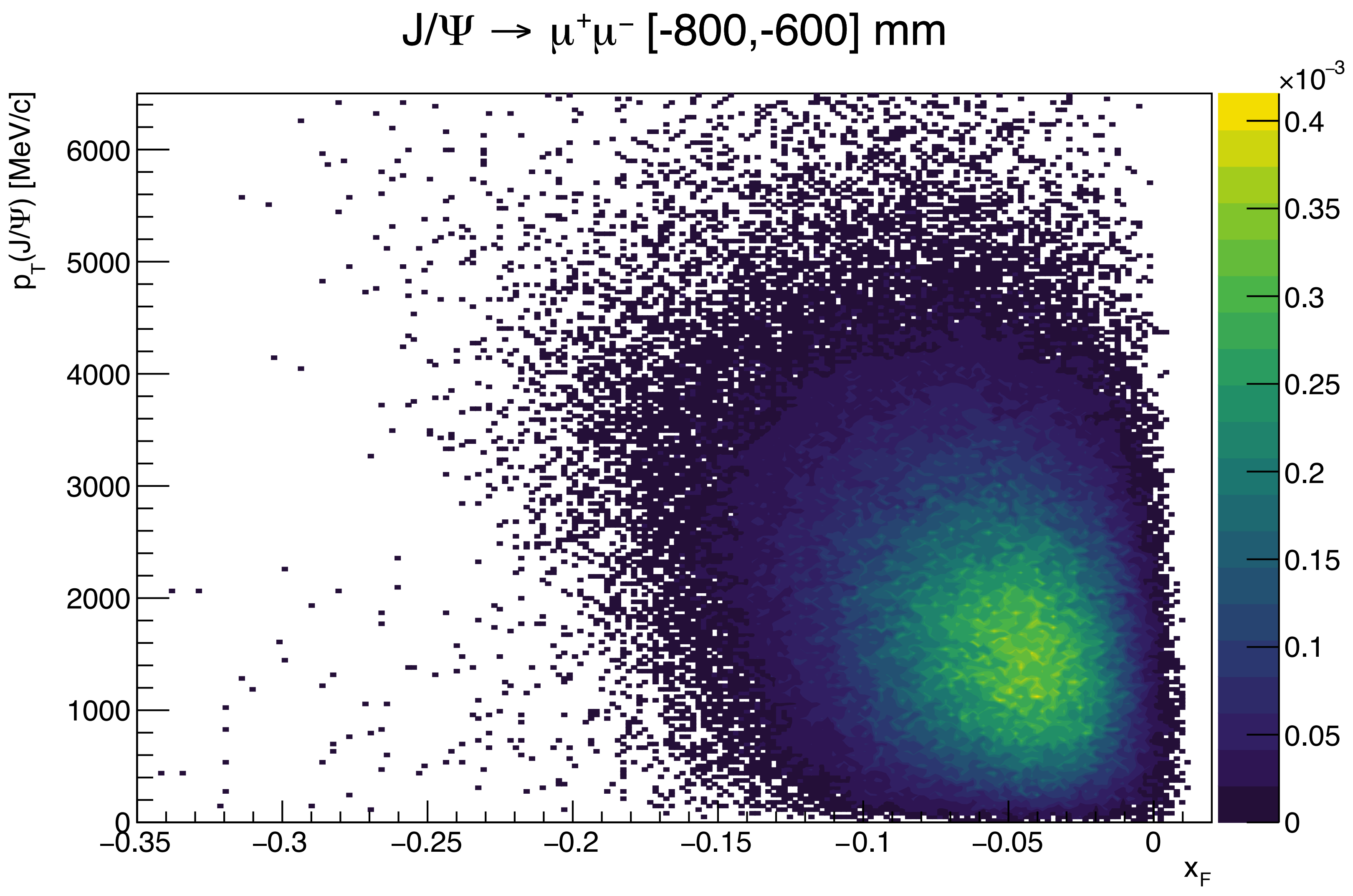

$J/\Psi \rightarrow \mu^+\mu^-$ reconstruction efficiency vs cell position


$J/\Psi \rightarrow \mu^+\mu^-$ reconstruction efficiency

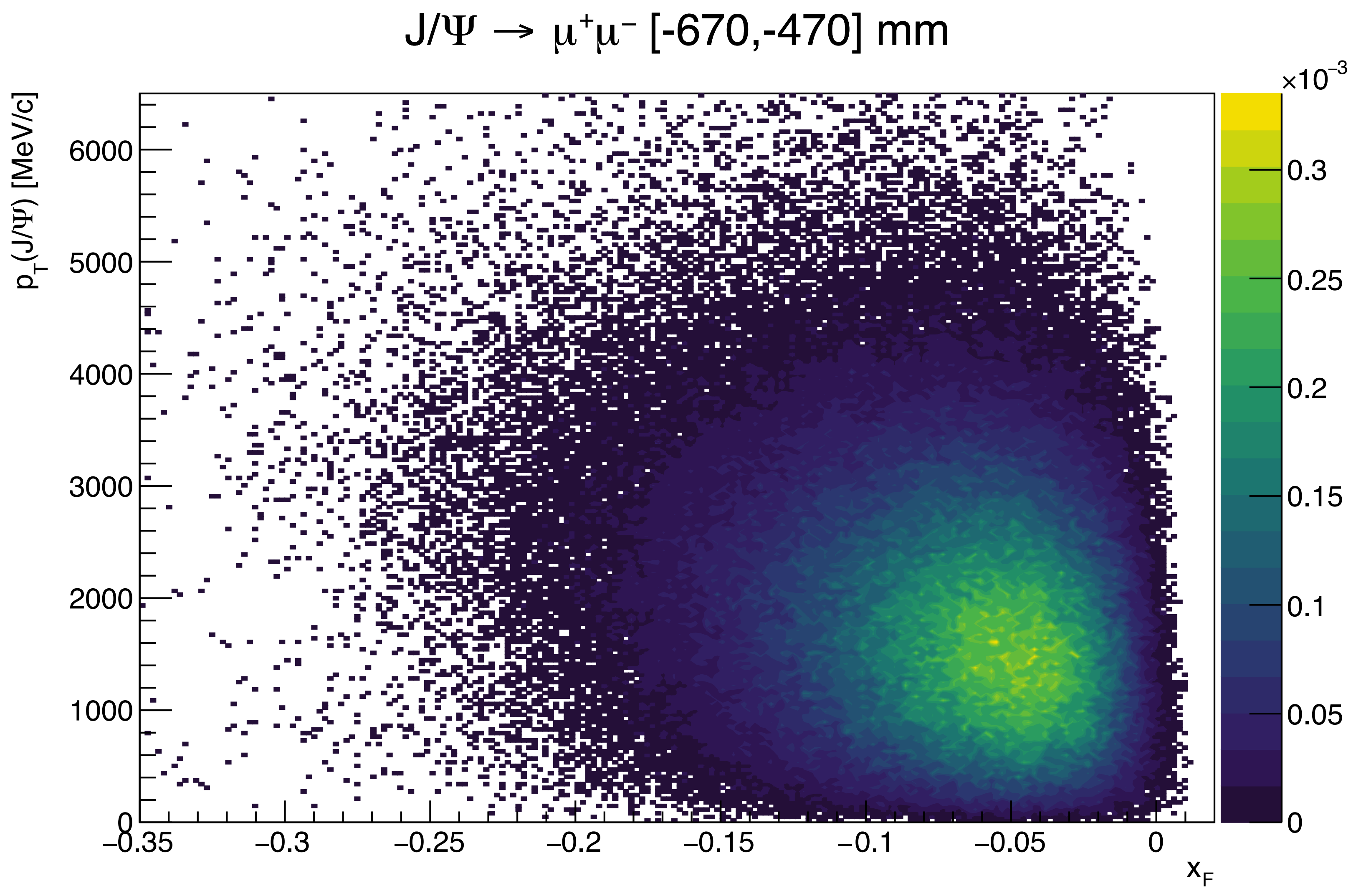
$J/\psi \to \mu^+\mu^-$ kinematics vs cell position

- Using $x_F = 2E_T/\sqrt{s_{NN}}\ \sinh(y^*)$ with $E_T^2 = M^2 + P_T^2$
- Actual SMOG2 region $[-560,-360]$ mm as a reference, $[-670,-470]$ mm a possible solution to fit the LHCspin setup
- The kinematic coverage depends on the cell position → p_T slightly affected, x range shrinks when moving upstream:

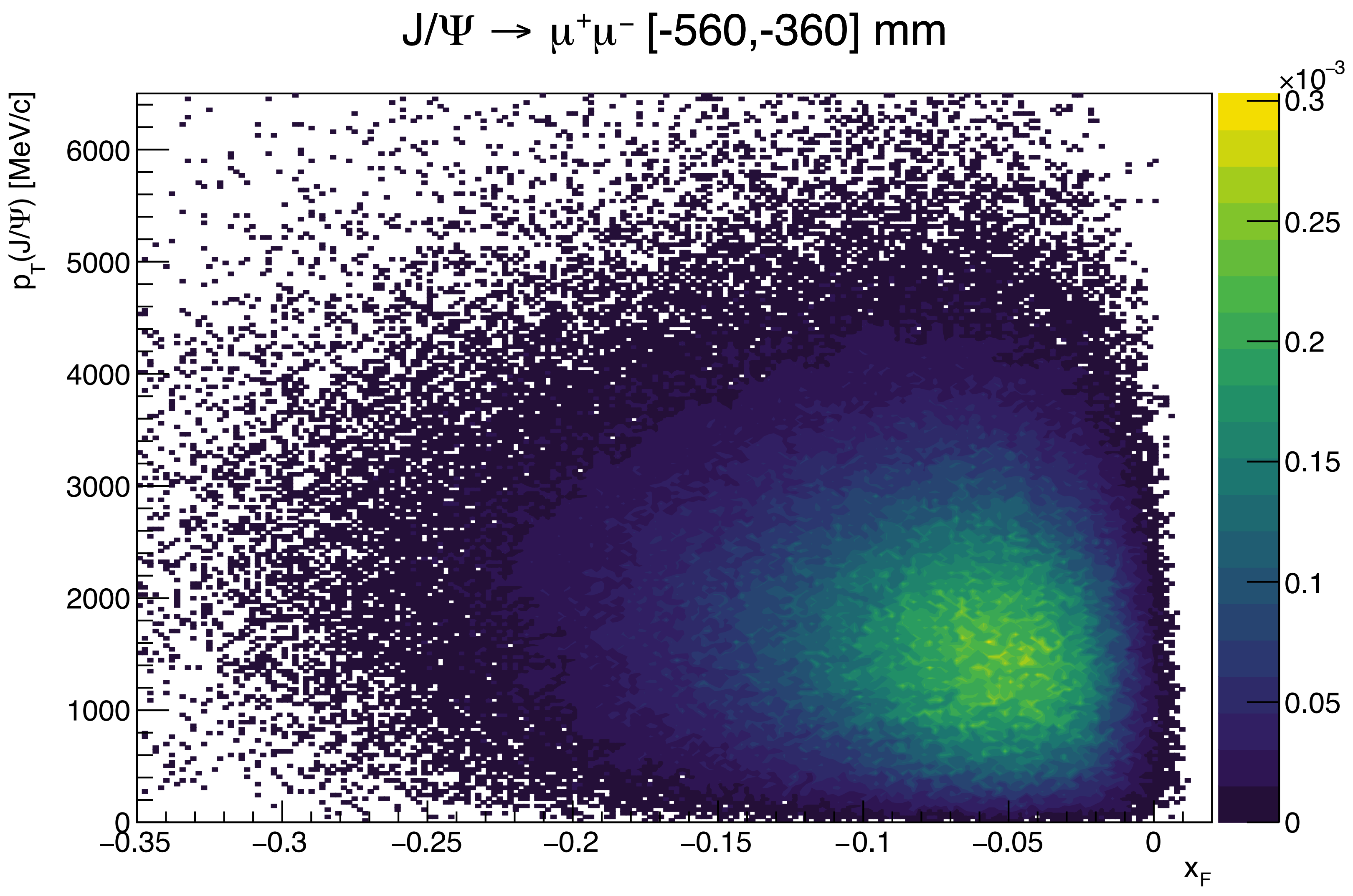
VELO



upstream
position



a possible
LHCspin
position



SMOG2
position

- Here are ~300k events per plot, just a small fraction of the expected data