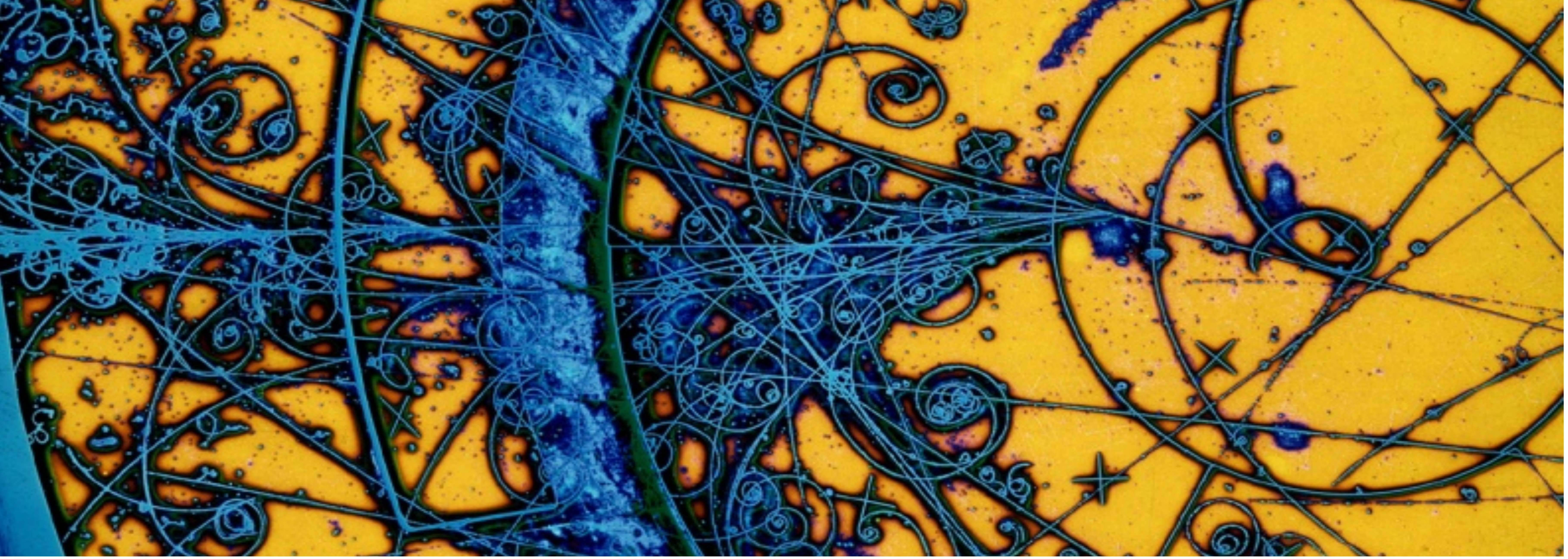


LHCspin simulations

Marco Santimaria [8]

in collaboration with

S.Bertelli[8], V.Carassiti[6], G.Ciullo[6][13], E.De Lucia[8], P. Di Nezza [8], N.Doshita[14], T.el Kordy[4], R.Engels[4], M.Ferro-Luzzi[1], C.Hadjidakis[2], T.Iwata[14], N.Koch[11], A.Kotzinian[9], P.Lenisa[6][13], C.Lucarelli[7], S.Mariani[1], M.Mirazita[8], A.Movsisyan[15], A.Nass[4], C.Oppedisano[9], L.Pappalardo[6][13], B.Parsamyan[1][9], C.Pecar[3], D.Reggiani[10], M.Rotondo[8], A.Saputi[6], E.Steffens[12], G.Tagliente[5]

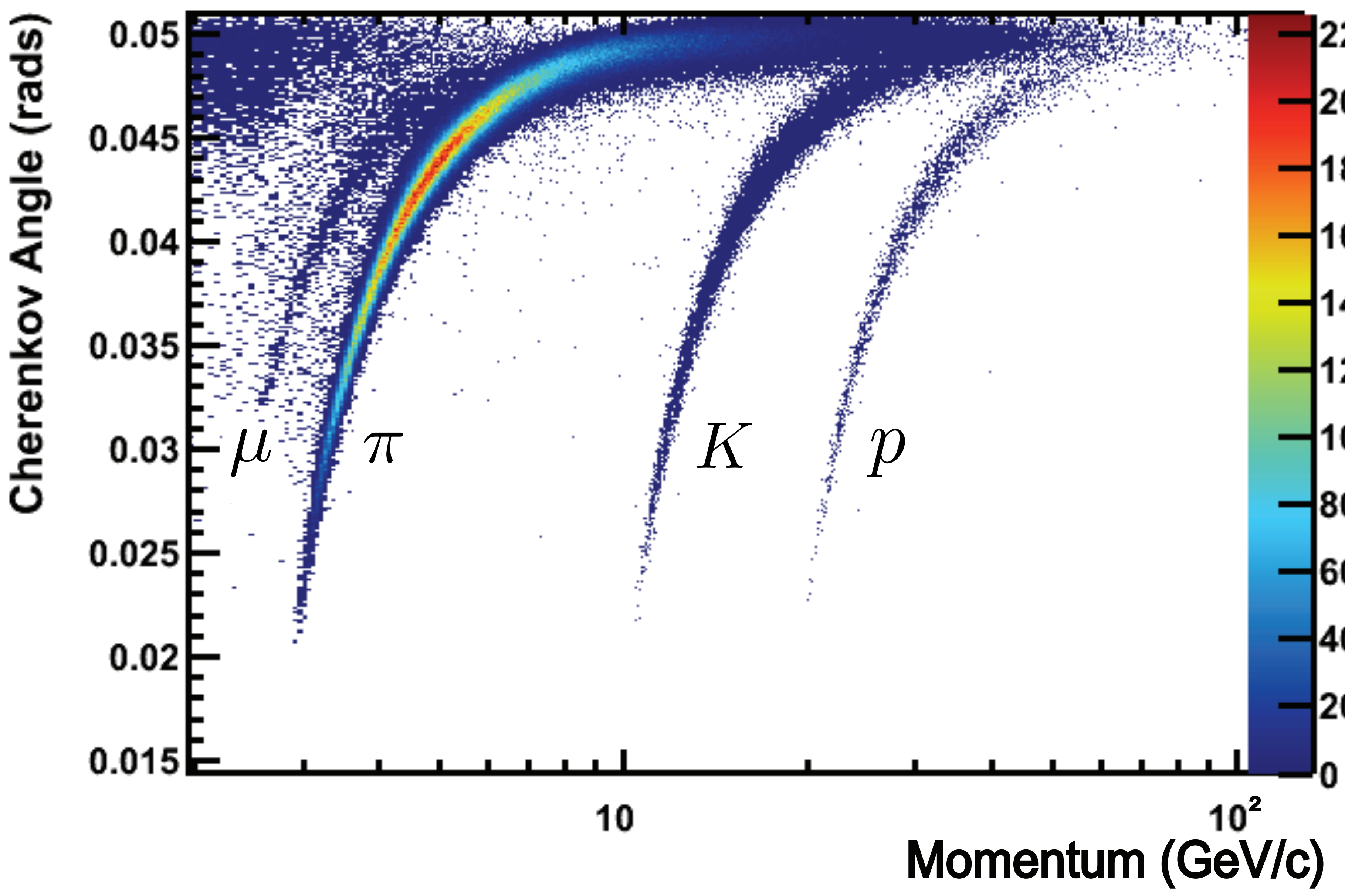
(1) CERN, (2) CNRS Saclay, (3) Duke University, (4) FZ Julich, (5) INFN Bari, (6) INFN Ferrara, (7) INFN Firenze, (8) INFN Frascati, (9) INFN Torino, (10) PSI Zurich, (11) TH Nuremberg, (12) University of Erlangen, (13) University of Ferrara, (14) University of Yamagata, (15) University of Yerevan

8th COMPASS Analysis Phase mini-workshop (COMAP-VIII); COMPASS - LHCspin - AMBER
CERN 22/05/2024

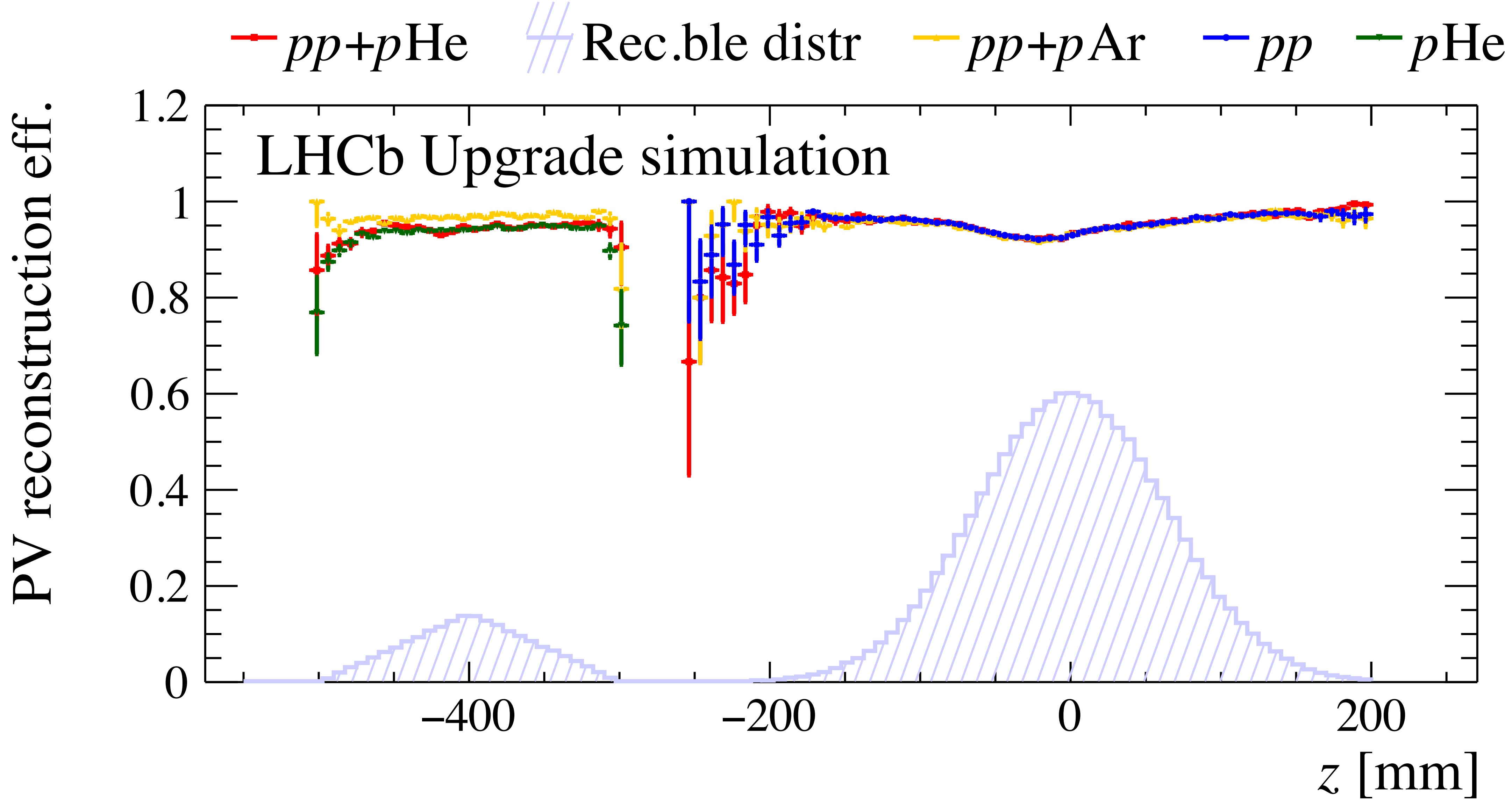
marco.santimaria@lnf.infn.it

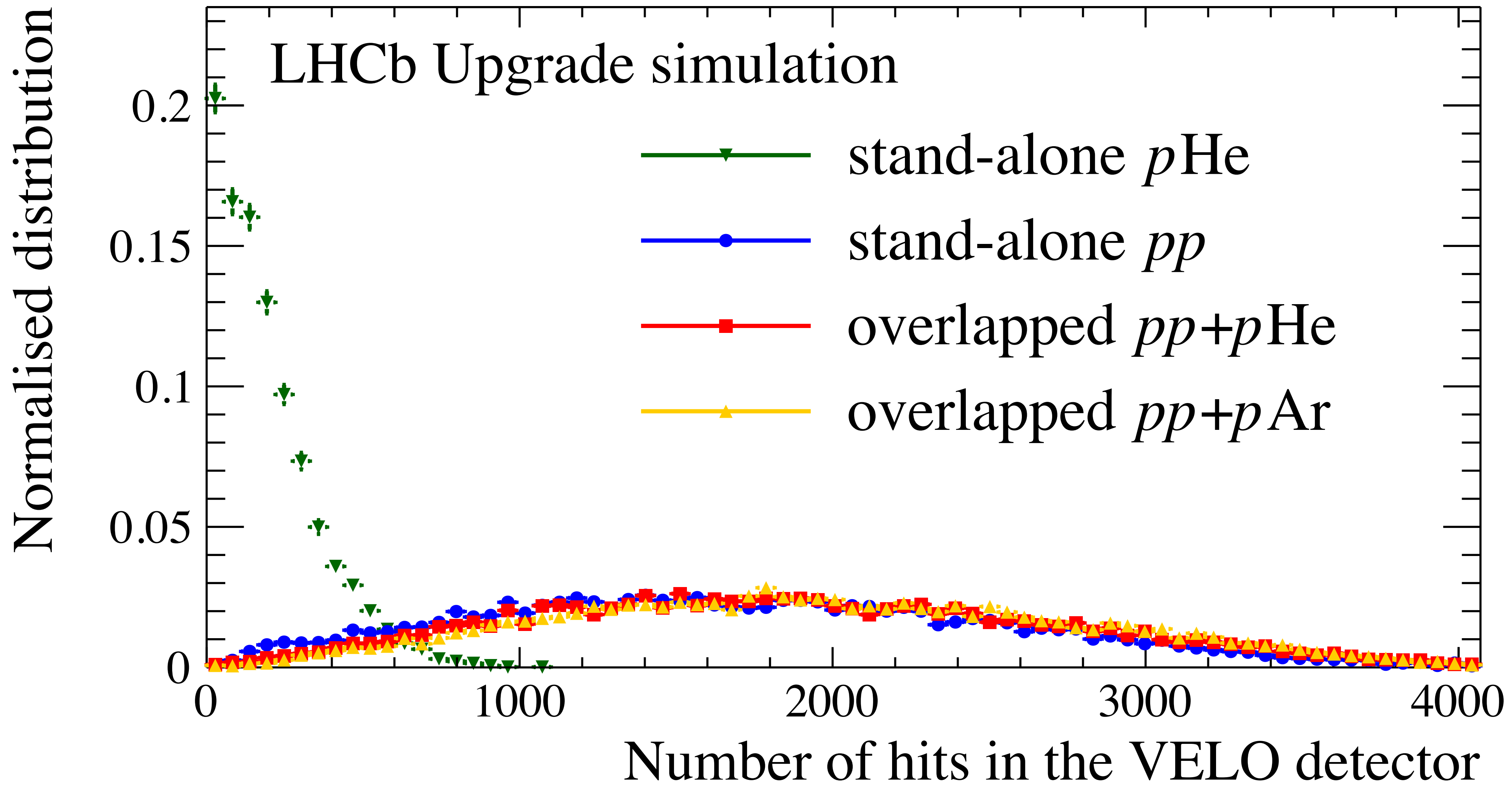
Fixed-target physics at LHCb

- Strength points of FT @ LHCb:
  - Fully instrumented detector in $2 < \eta < 5$
  - Optimised for b- and c-hadron detection, but s-hadrons are also well reconstructed and abundantly produced
  - 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
  - Can do simultaneous p-p and p-gas data-taking with nominal efficiency and negligible impact on the trigger load



[EPJC 73 (2013) 2431]

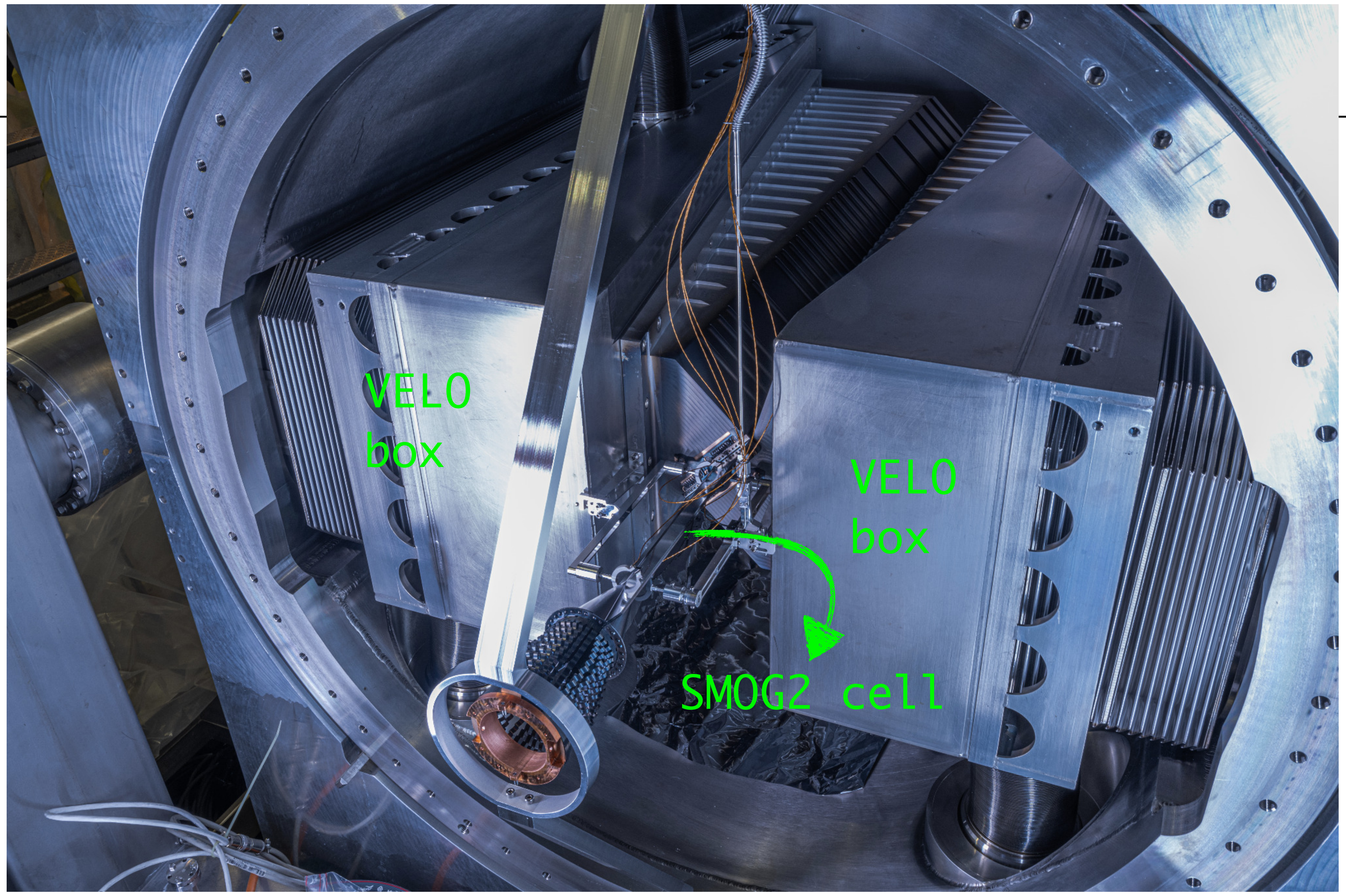


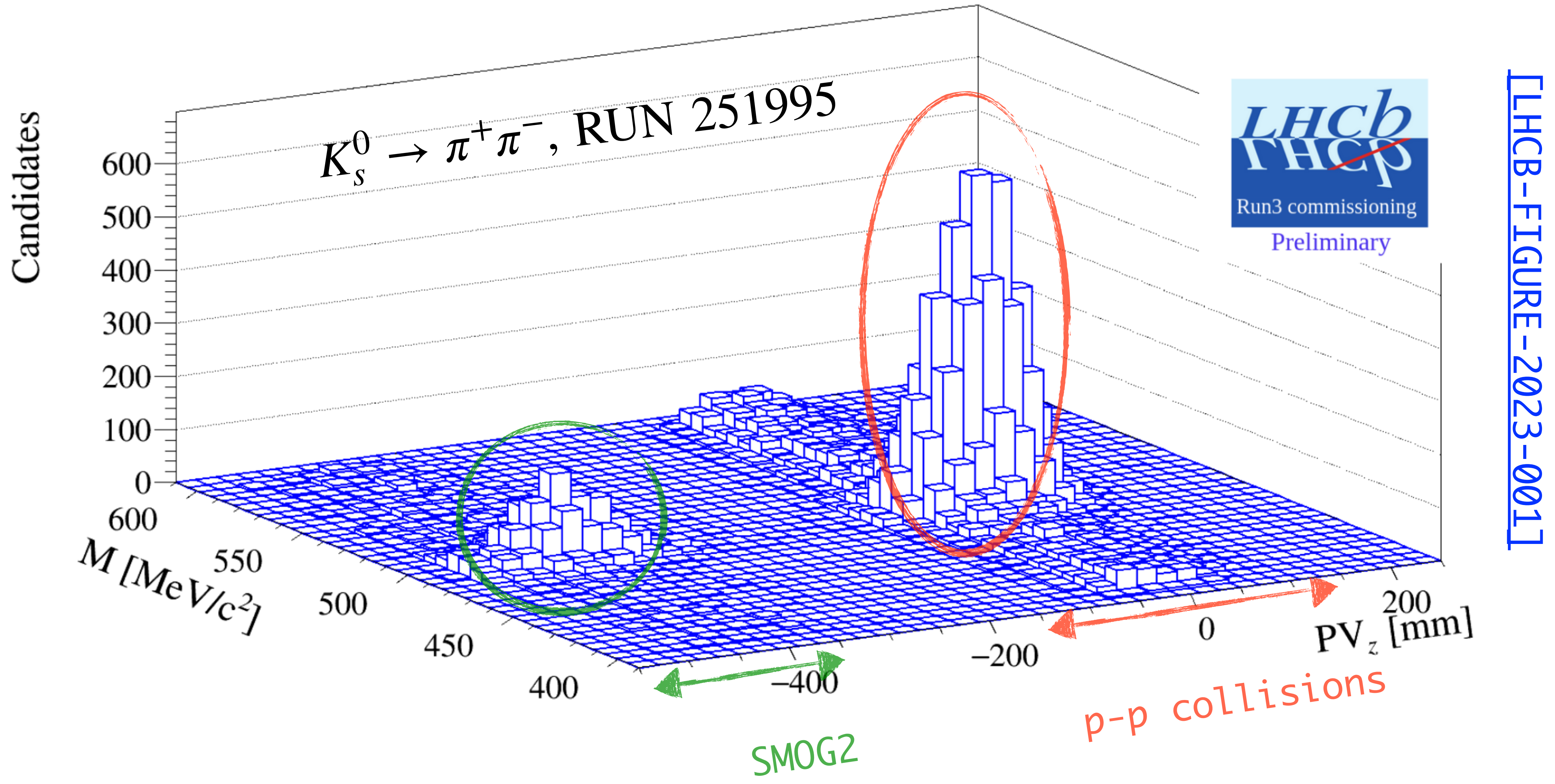


[LHCB-FIGURE-2022-002]

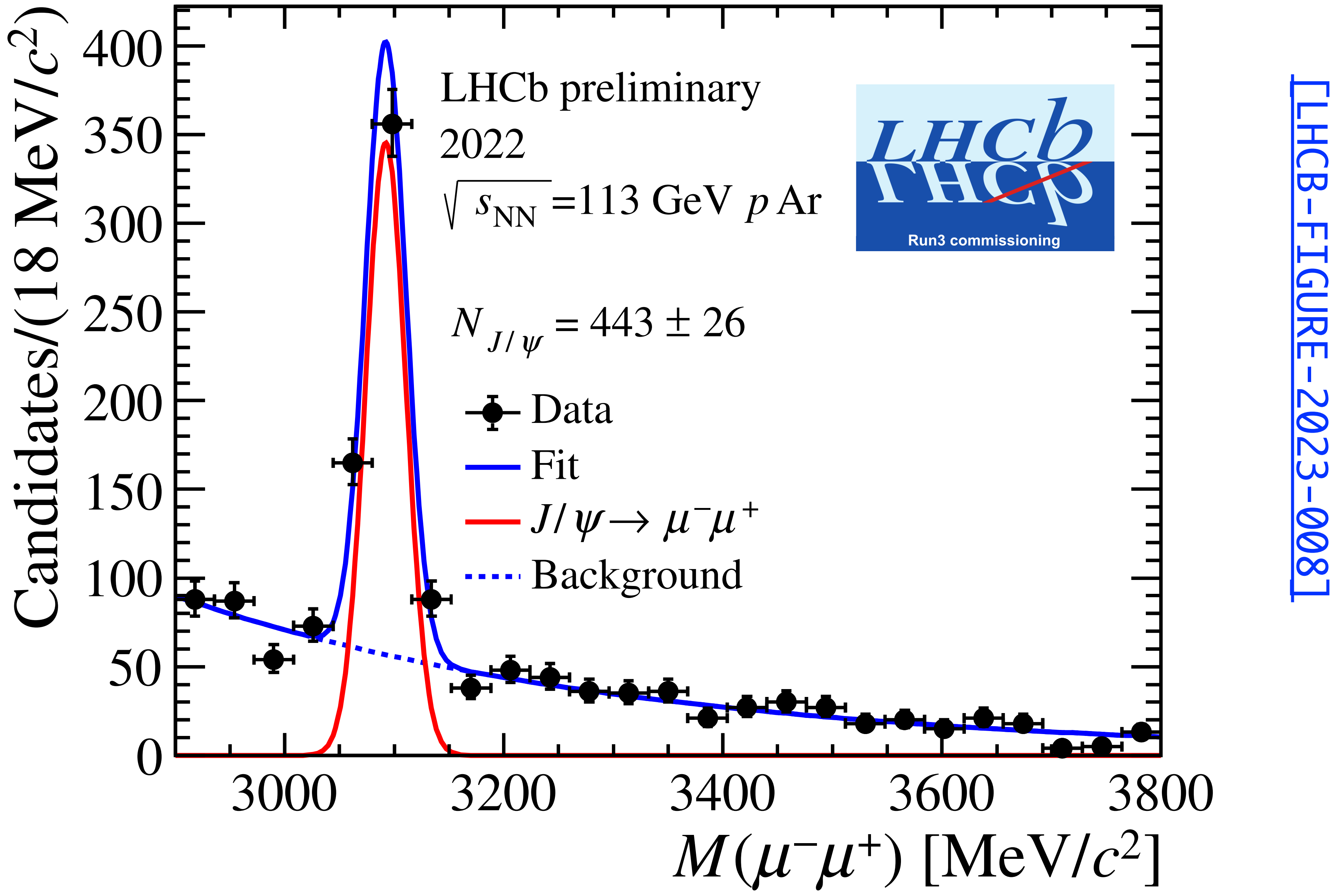
The SMOG2 gas storage cell

- SMOG2: High density gas storage cell installed for Run 3
- Injected gas has a negligible impact on the beam lifetime: $\tau^{p-H_2}_{beam-gas} \sim 2000$ days , $\tau^{Pb-Ar}_{beam-gas} \sim 500$ h
- Luminosity precision at the percent level thanks to new Gas Feed System and temperature probes
- Took data with He, Ne, Ar, H_2 , to be tested: D_2, N_2, O_2, Kr, Xe
- Demonstrated simultaneous and efficient data-taking! (2022 data shown below)



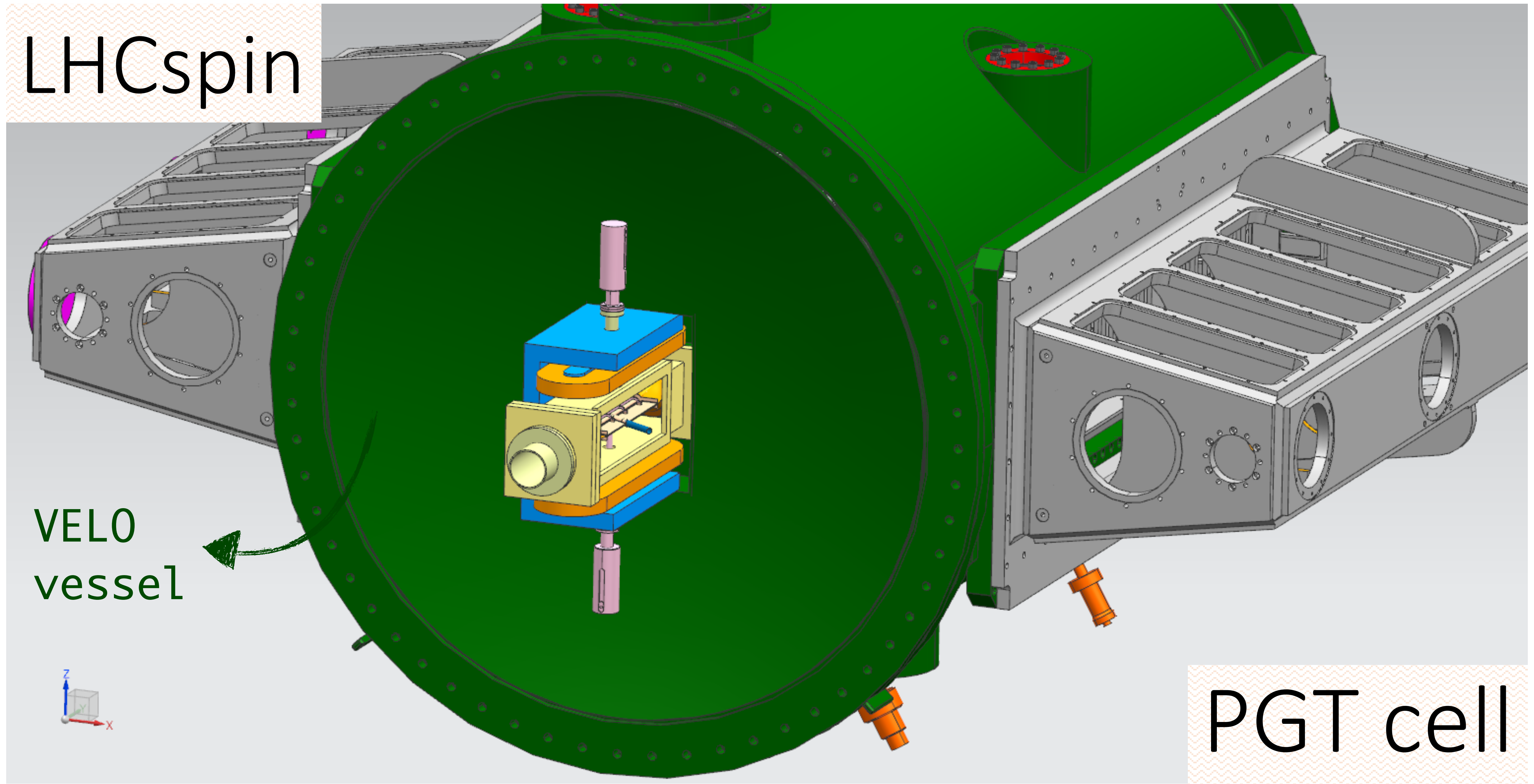


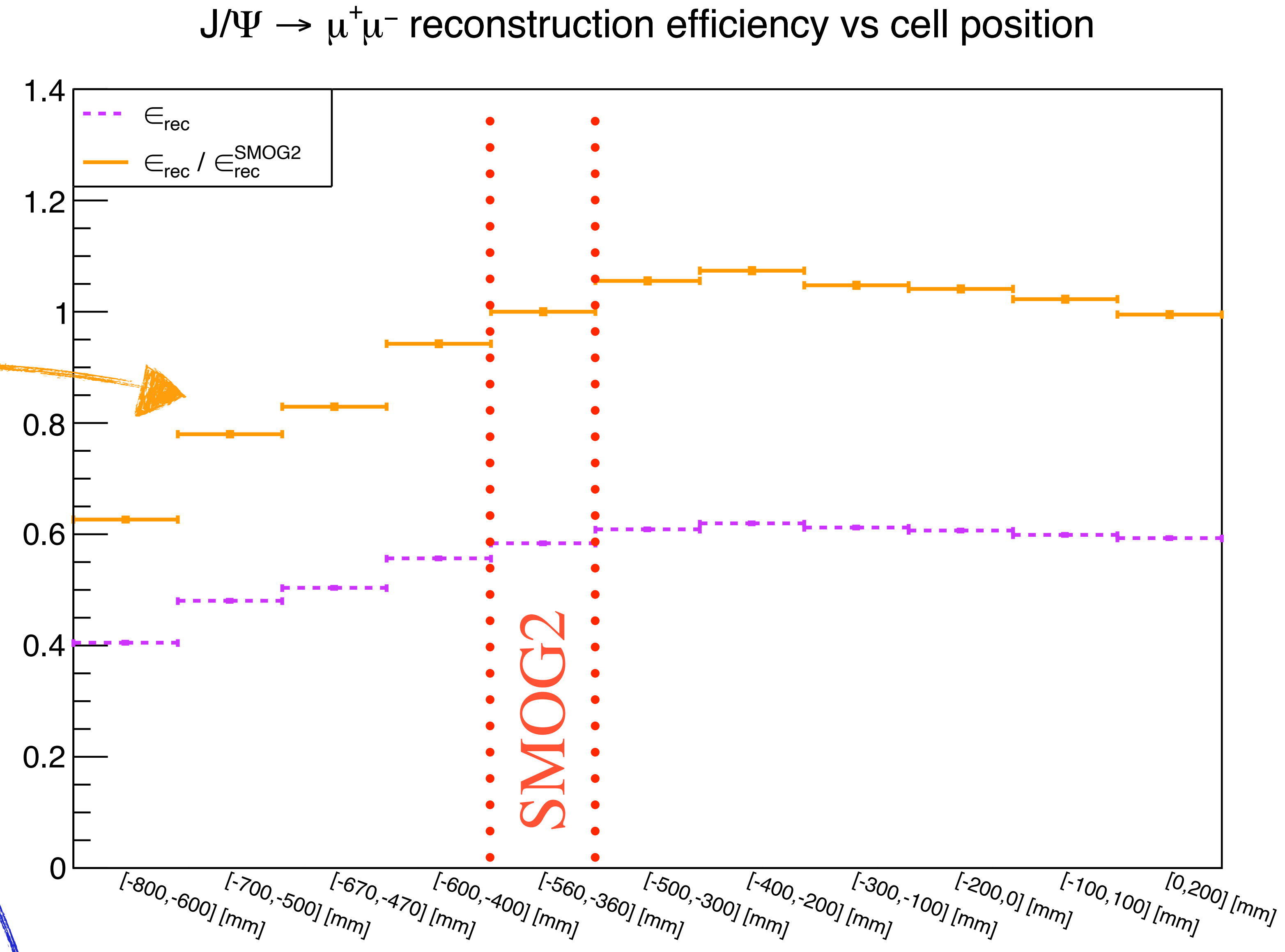
- 18 minutes of injection test

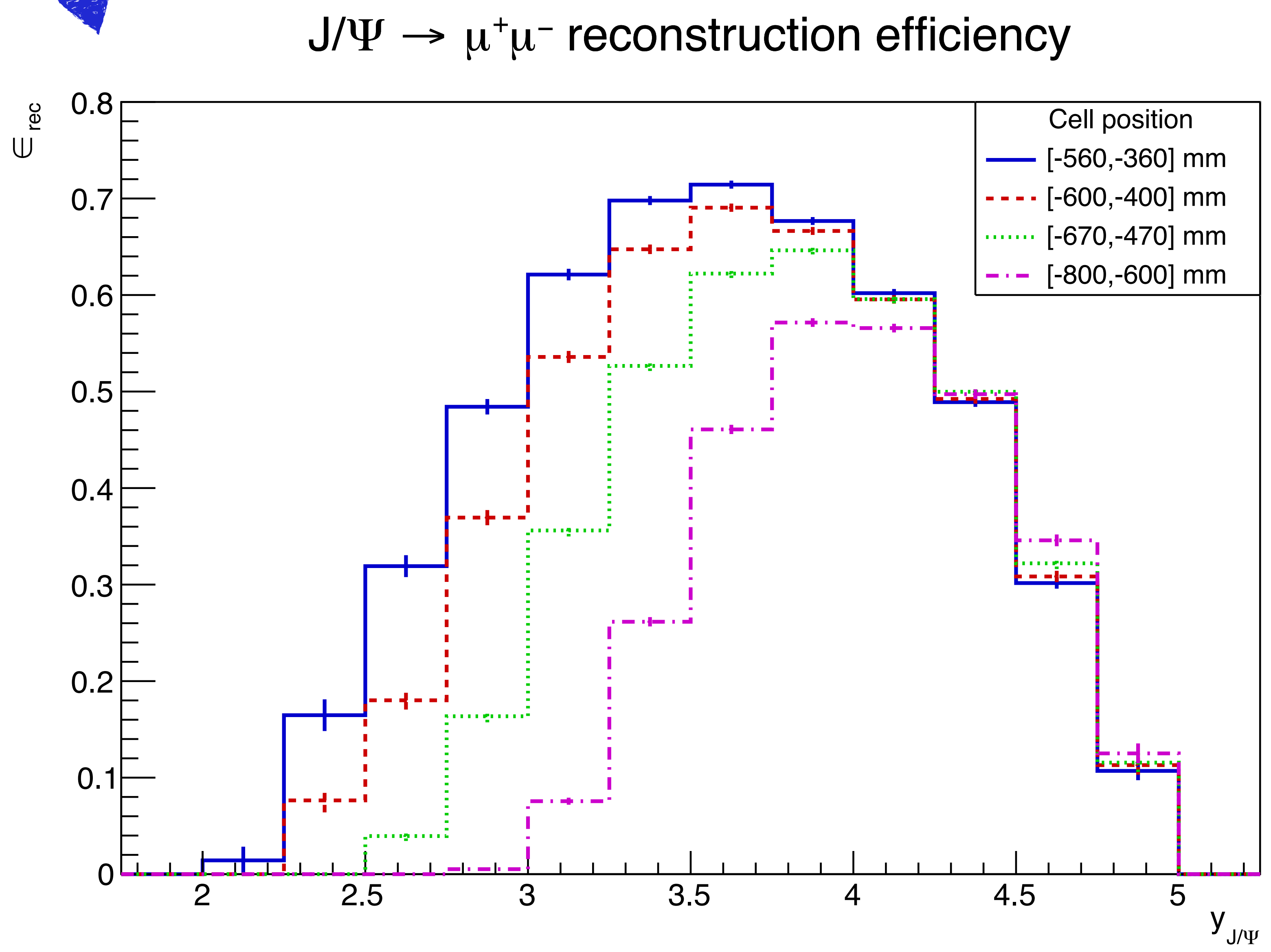


LHCspin: the Polarised Gas Target

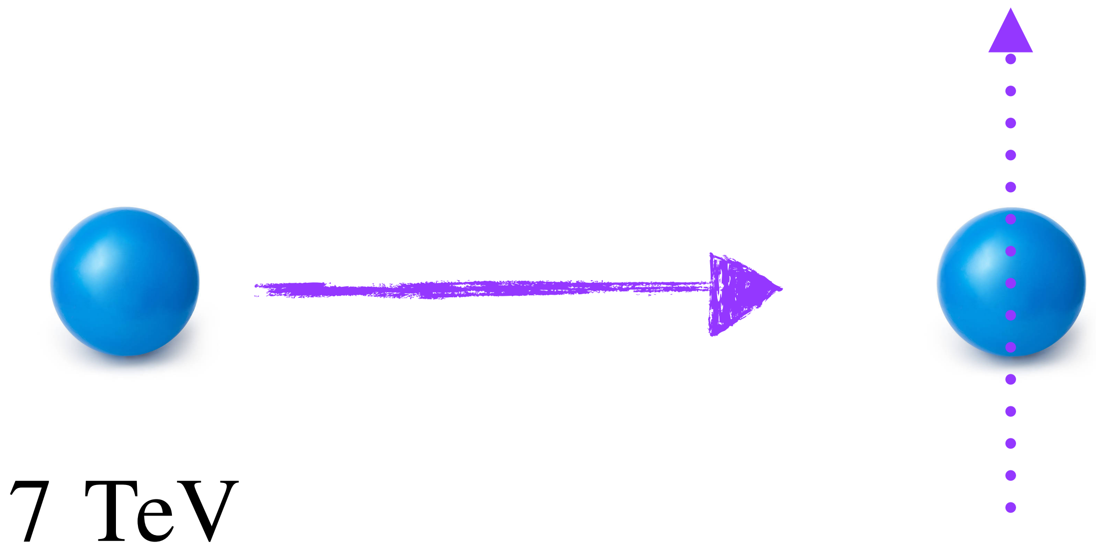
- LHCspin is the natural evolution of our FT program towards spin physics
- Drawing: cylindrical target cell with $L = 20$ cm and $D = 1$ cm (SMOG2 dimensions) and modified VELO flange
- LHCb simulations show broader kinematic acceptance & better reconstruction efficiency when the cell is close to the VELO
- Our new fully-software trigger gives flexibility & room for improvement e.g. better reconstruction algorithms, dedicated trigger lines… this is already ongoing for the Run 3







Kinematic coverage



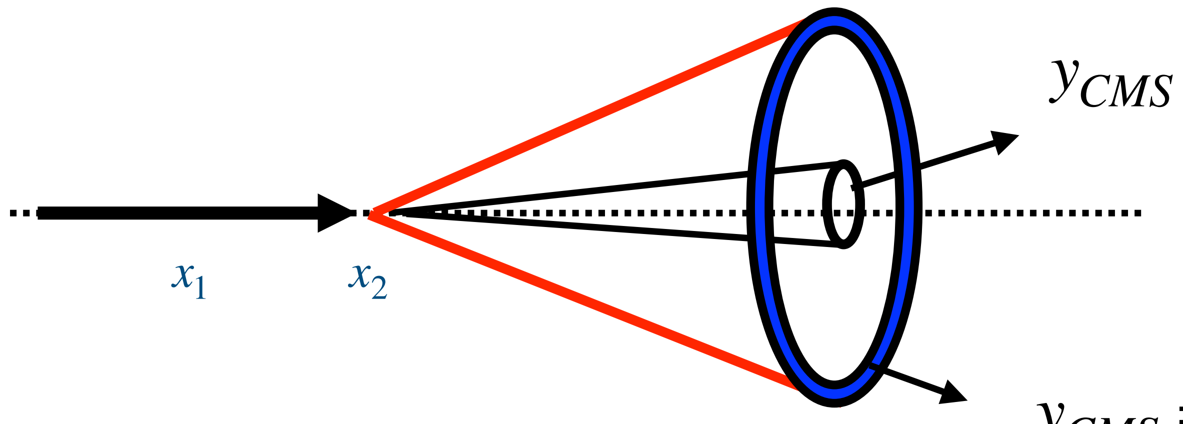
7 TeV

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

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

Large CM boost → large x_2 values

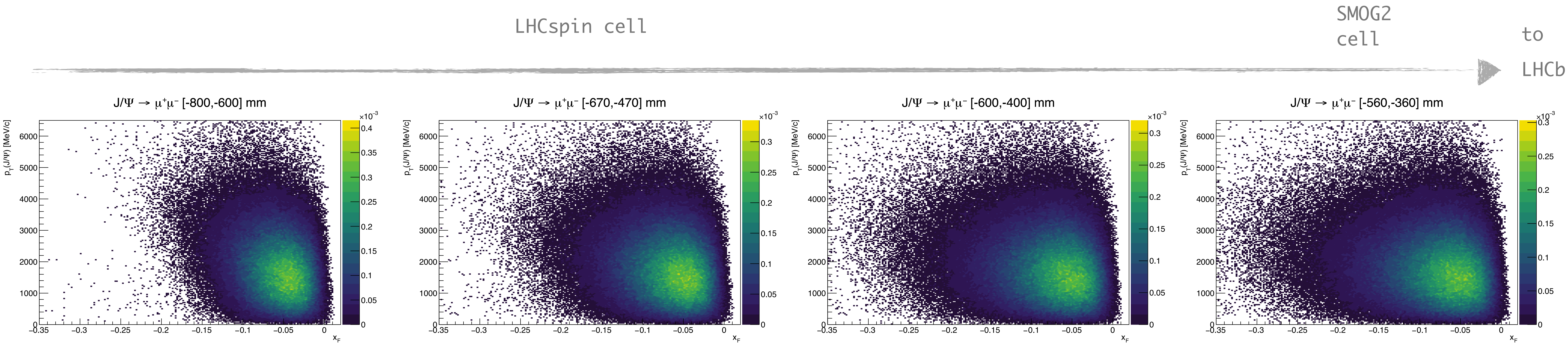
$2 \leq y_{lab} \leq 5 \ \rightarrow -3.0 \leq y_{CMS} \leq 0$



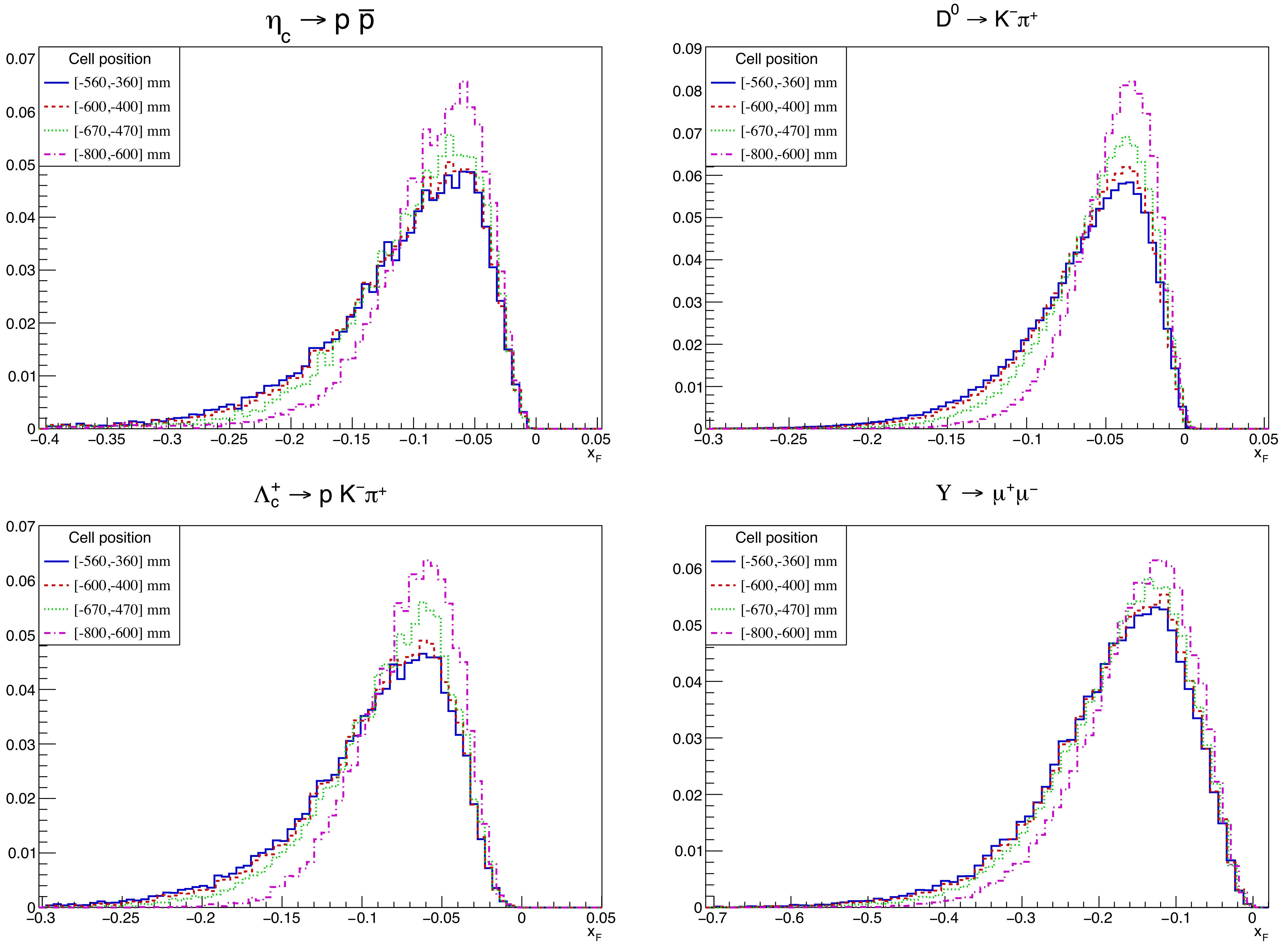
$y_{CMS} = 0 \ \rightarrow \theta \sim 1^{\circ}$

$y_{CMS} = -3$

- Full LHCb simulations for pH collisions at $\sqrt{s} = 115$ GeV. 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



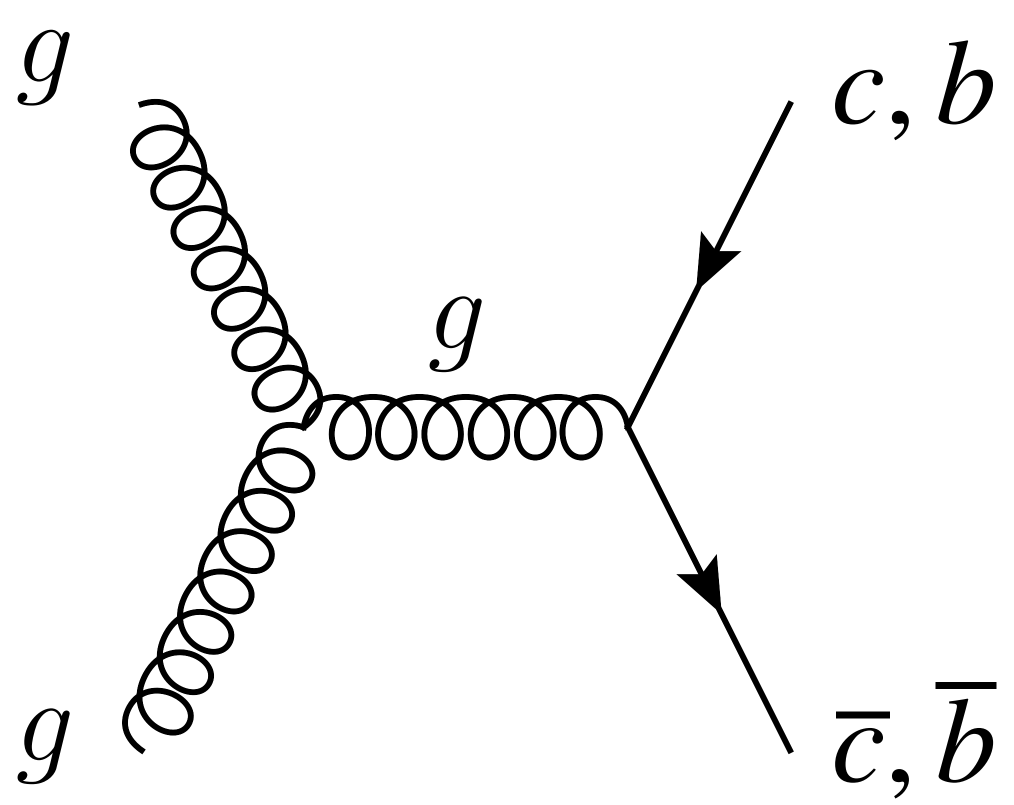
x_F ranges for various channels



- c-hadrons will have the largest product of cross section and reconstruction efficiency
- Only a small portion of the expected statistics is shown: can well cover high-x values (see next slide)

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

  More on the physics case in the → talk by Luciano



Expected yields

- Using early SMOG2 performance, we can estimate the expected yield at LHCspin for p-H collisions with $\phi = 6.5 \times 10^{16}\ \mathrm{s}^{-1} \rightarrow \theta = 3.7 \times 10^{13}/\mathrm{cm}^2$
- 120-week Run with 84 h / week of data-taking
- This is the number of fully-reconstructed and selected events based on 2022 detector performance (commissioning)
- Here considering Run 3 beam : rates are further enhanced during HL-LHC

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

- Extremely large data sample for heavy flavours
- 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 (unpolarised gas)

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

What about a jet target?

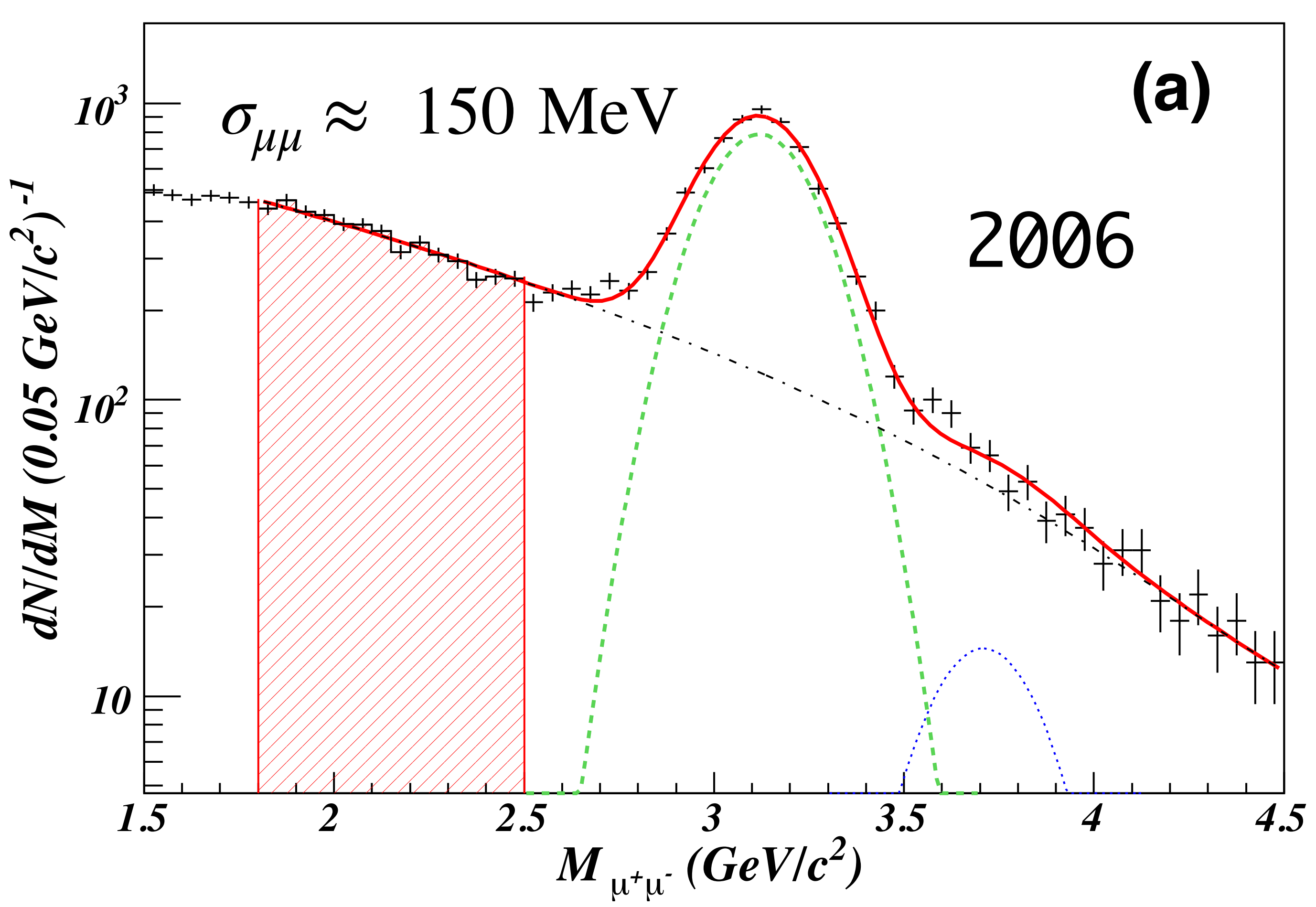
- The alternative to the cell is a jet target which would provide lower density ($\approx 1/40$) but higher polarisation degree
- $\theta_{jet} \approx 10^{12}\ \mathrm{cm}^{-2}$ but $P \approx 90\,\%$ with very small systematic error
- PRO: precision measurements on high-statistics channels
- CON: Makes kinematic binning and rare channels harder

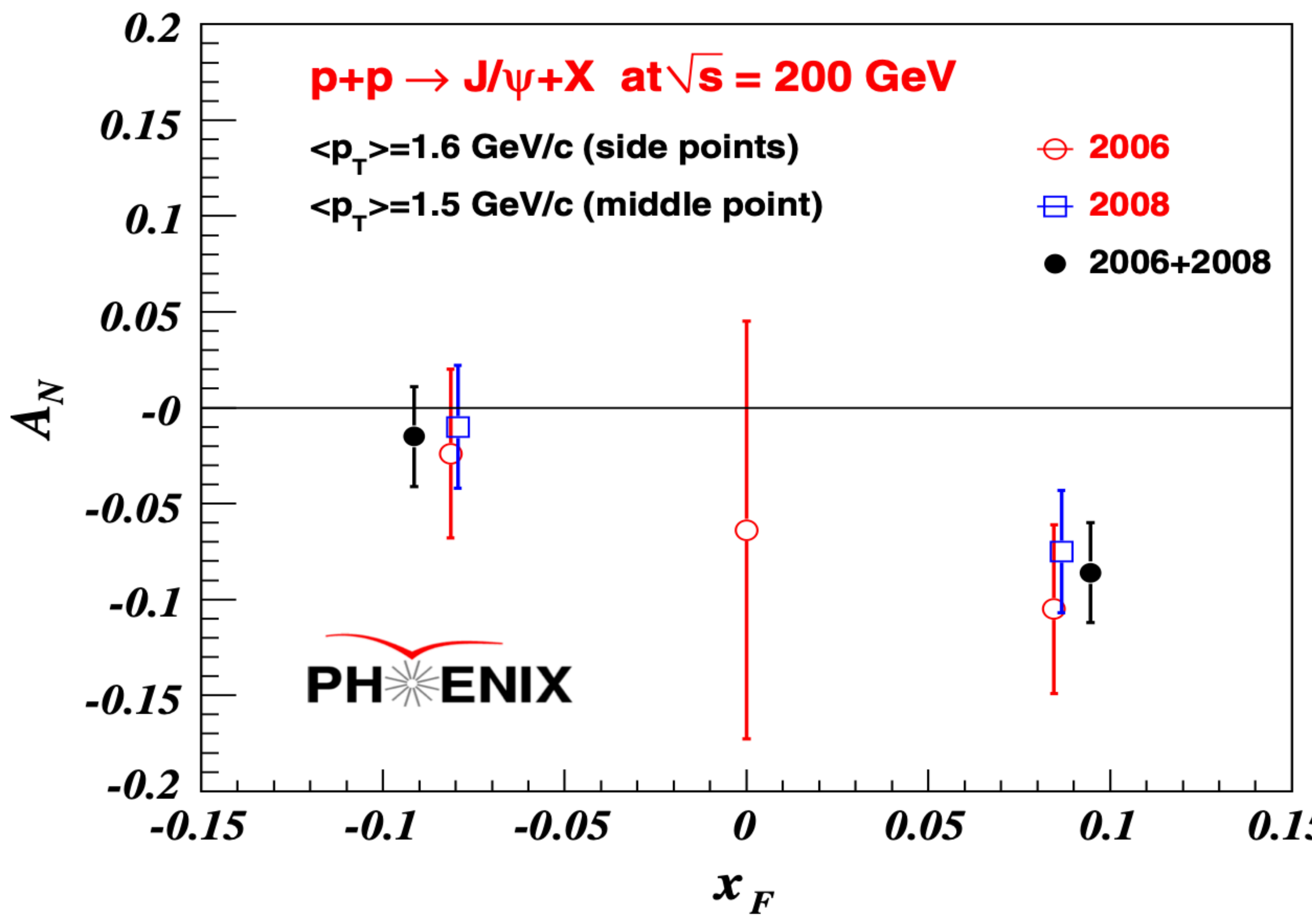
Comparing $J/\psi \to \mu^+\mu^-$

- LHCspin strength point and uniqueness will be heavy flavours, mostly unexplored by existing facilities with the exception of the J/ψ, for which measurements have been performed at PHENIX and COMPASS:
  - PHENIX: ~ 21k signal candidates (2006 + 2008 data) → at LHCspin they can be collected in ~10 minutes (cell) or ~7 hours (jet)
  - Mass resolution: LHCb nominal $\sigma_{\mu\mu} \approx$ 13 MeV at the J/ψ mass and $\sigma_{\mu\mu} \approx$ 42 MeV at the Υ mass
  - Can also measure excited states & heavier mesons

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

PHENIX: 2006 and 2008 data

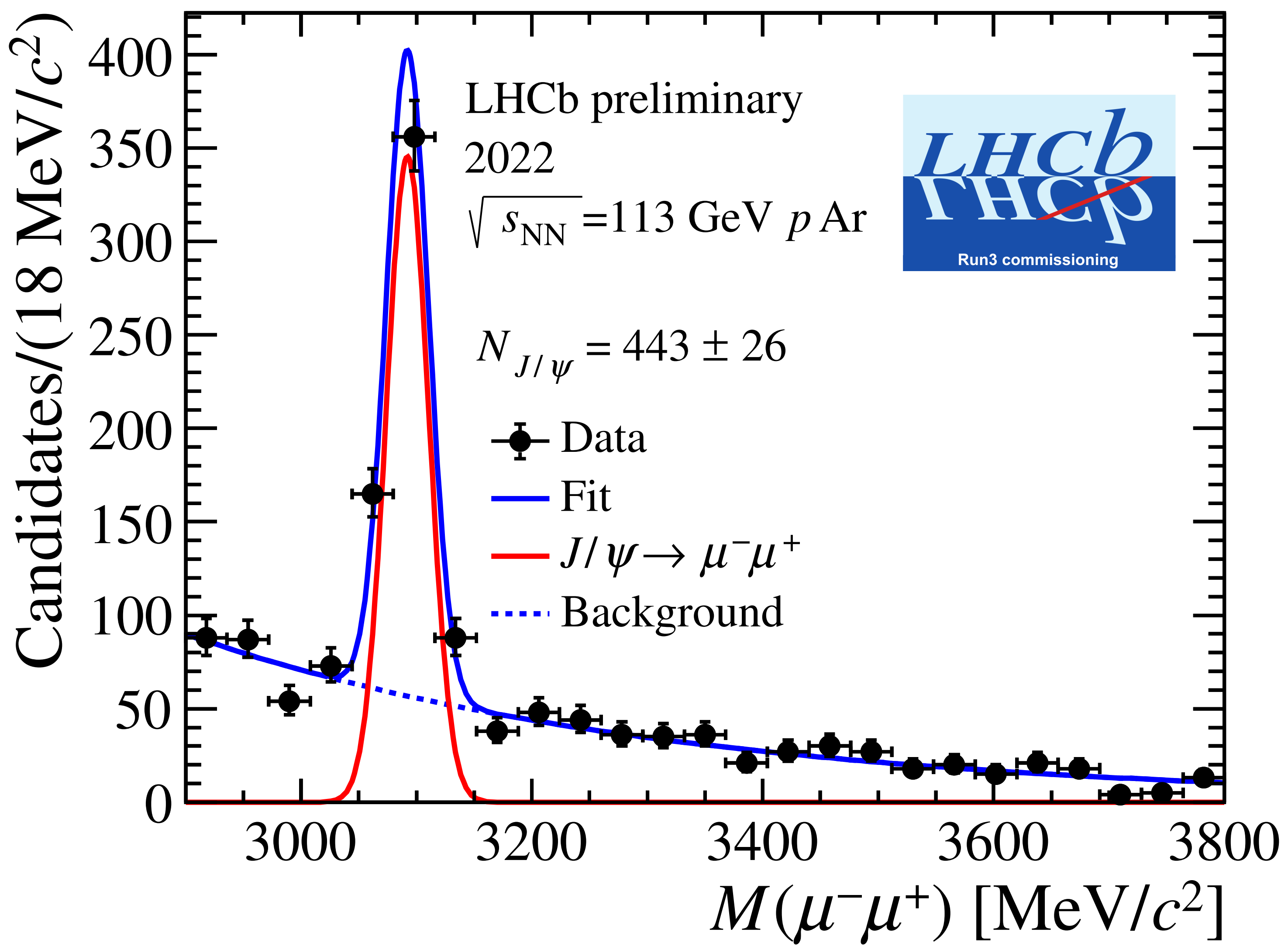




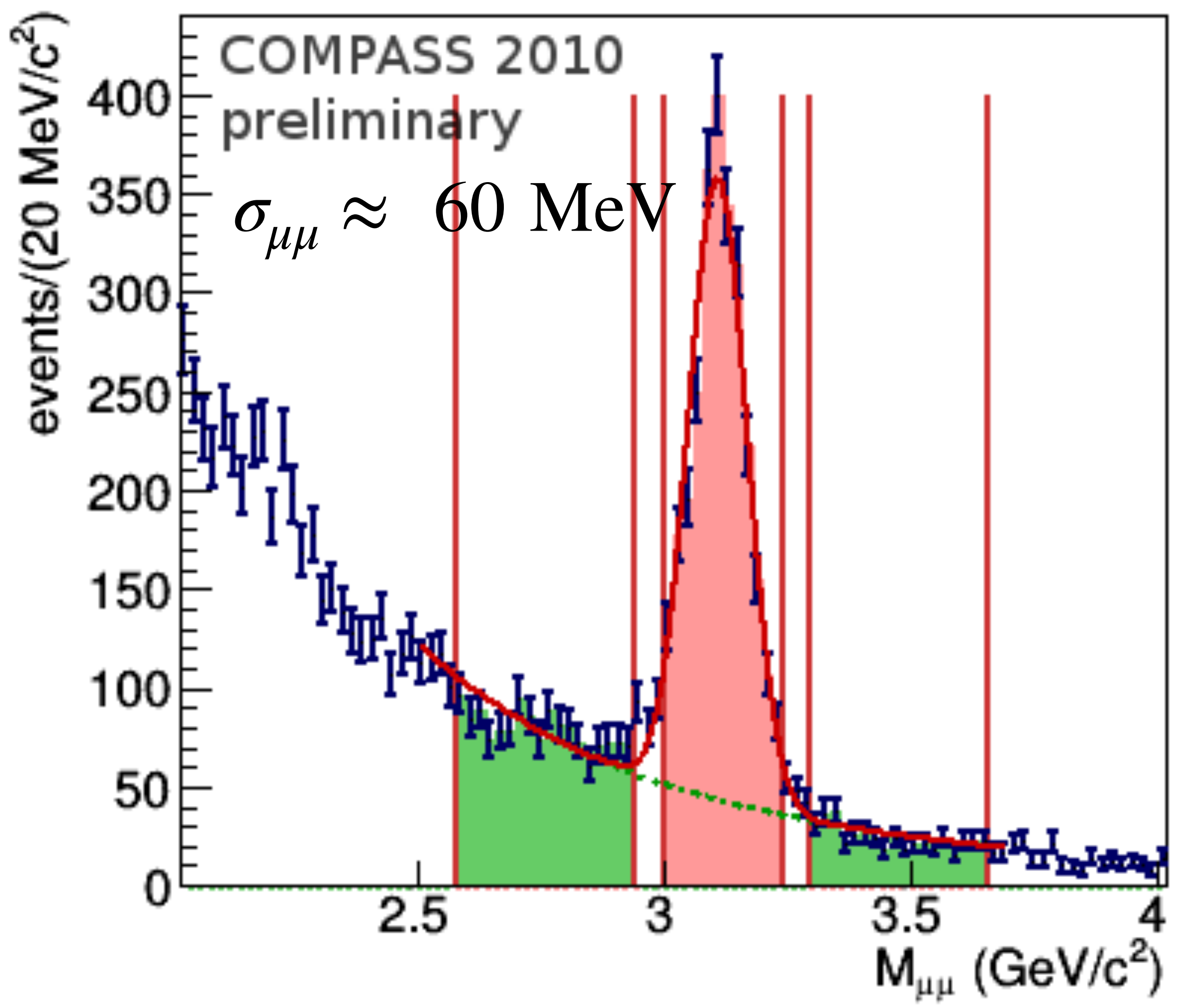
[arXiv:1009.4864]

SMOG2: 18 minutes test

[LHCB-FIGURE-2023-008]



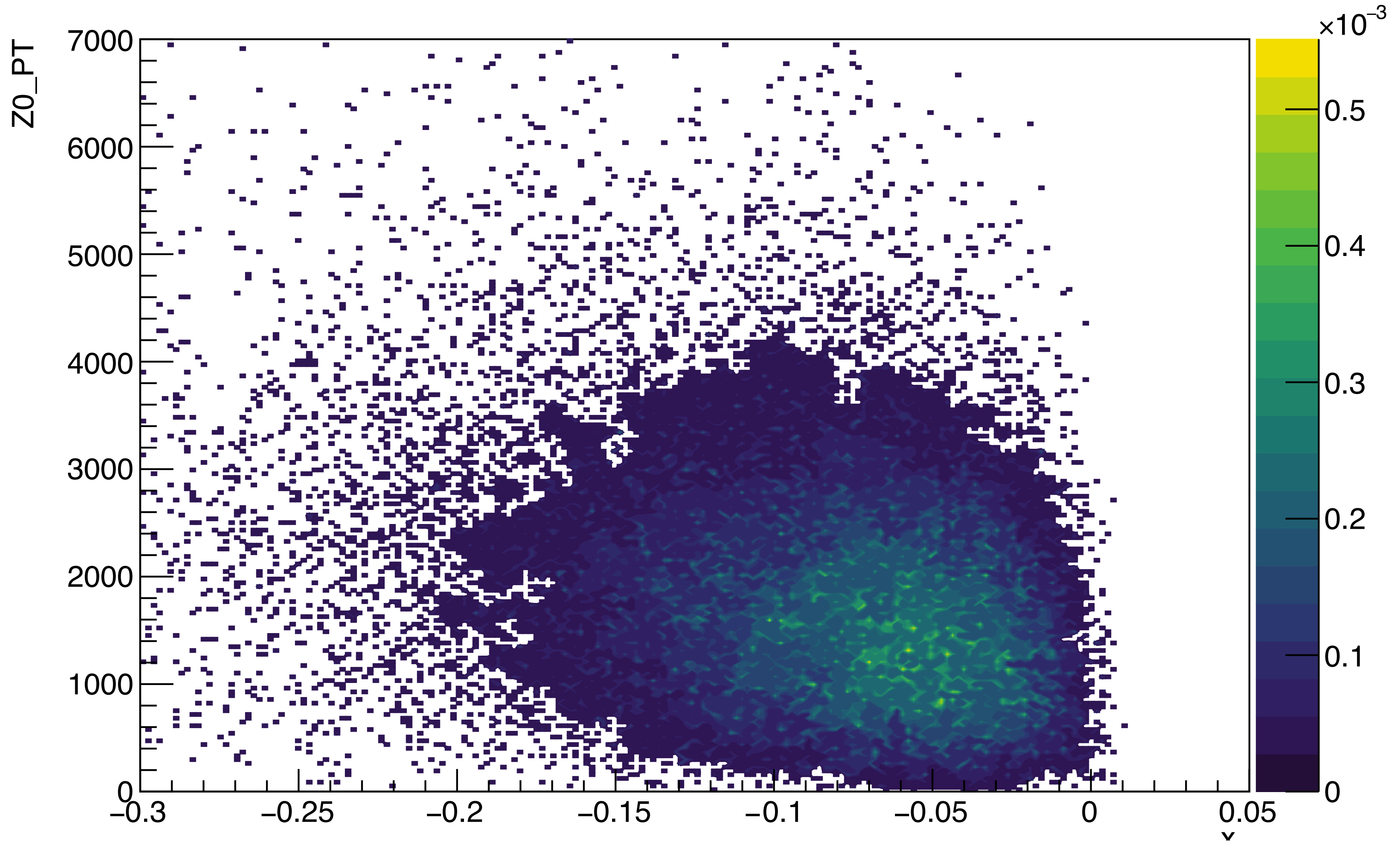
COMPASS: 2010 data

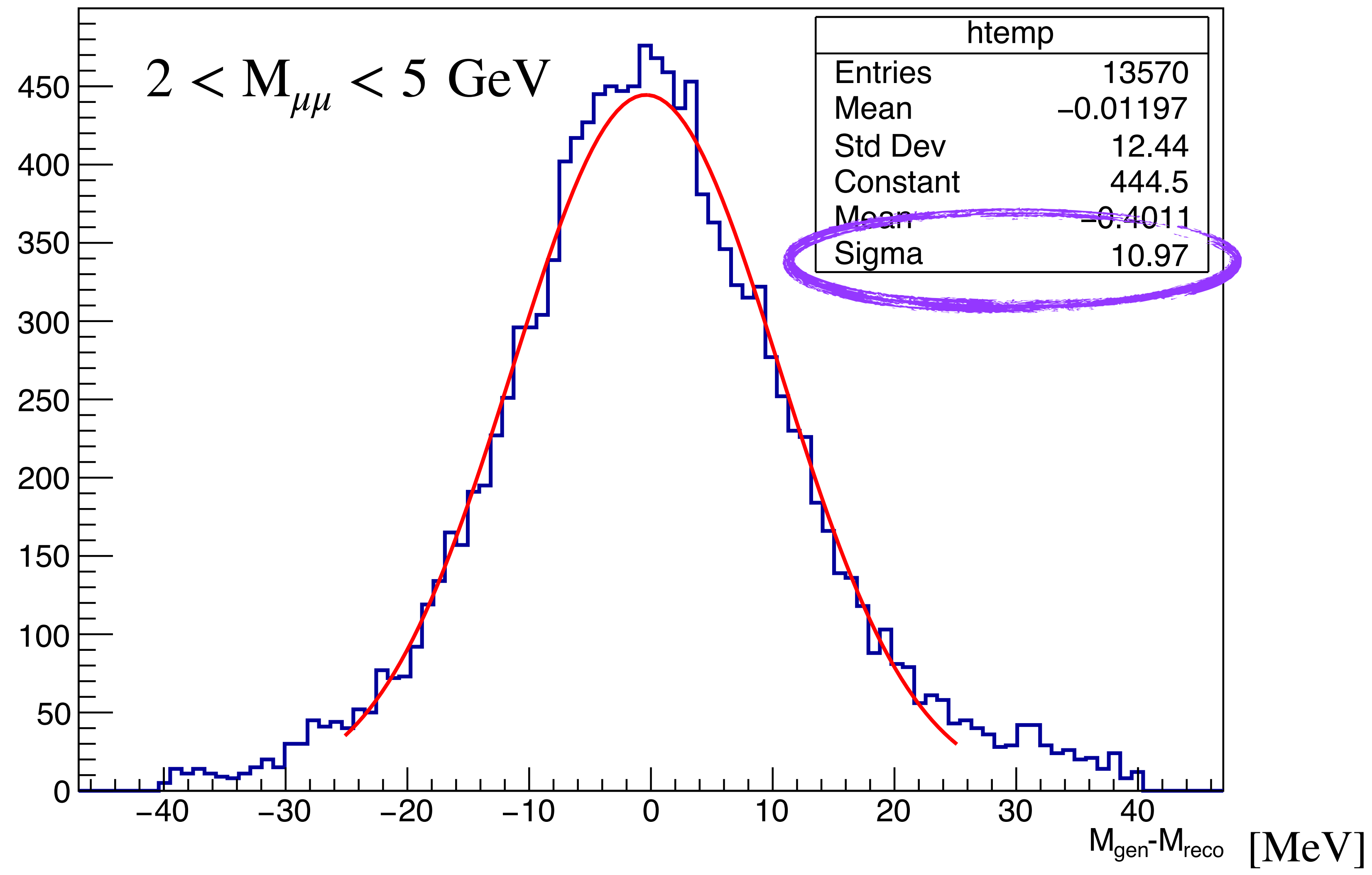


[2016 J. Phys.: Conf. Ser. 678 012050]

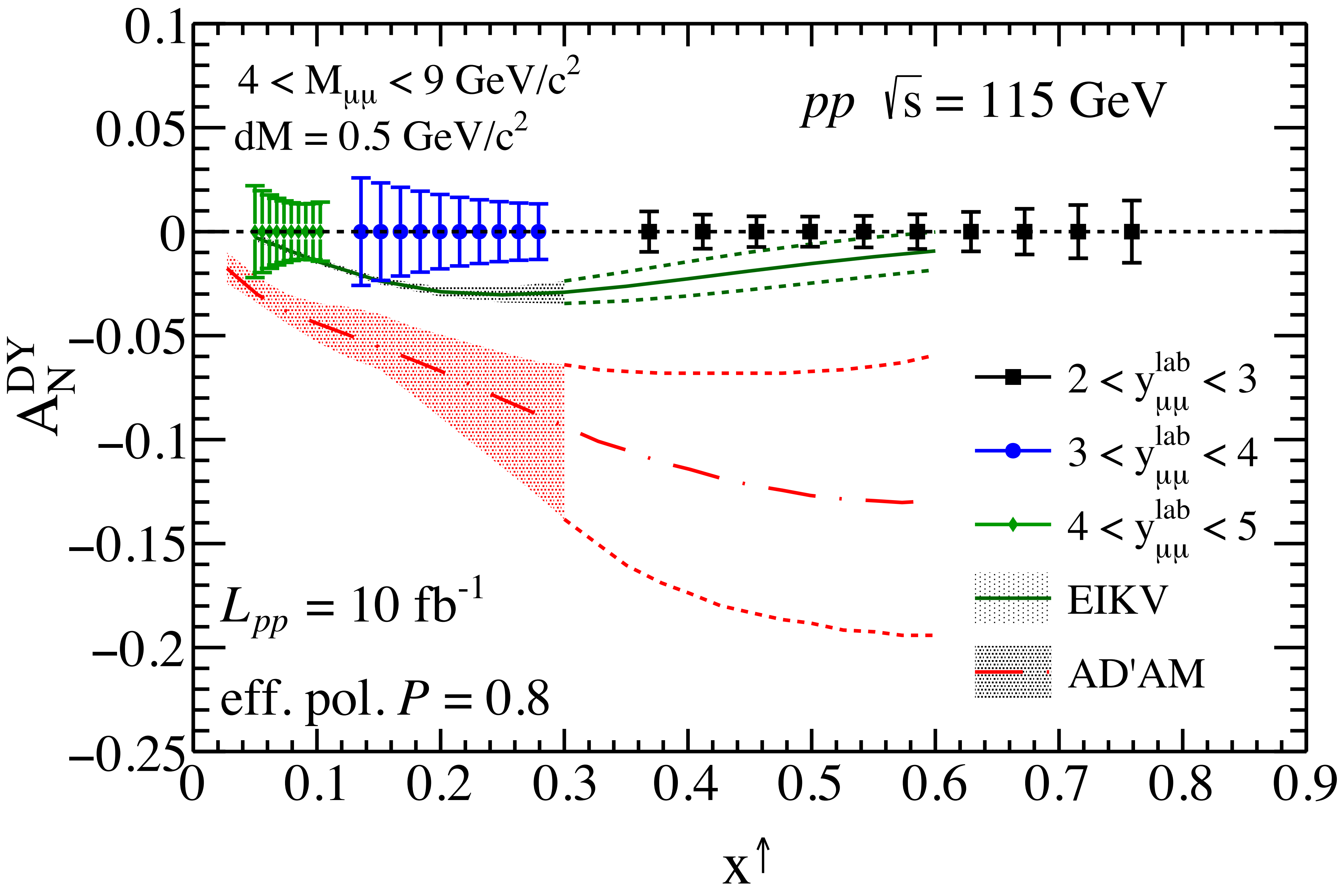
Polarised Drell-Yan

- Kinematics @ LHCspin (~30k events) and mass resolution:





- 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

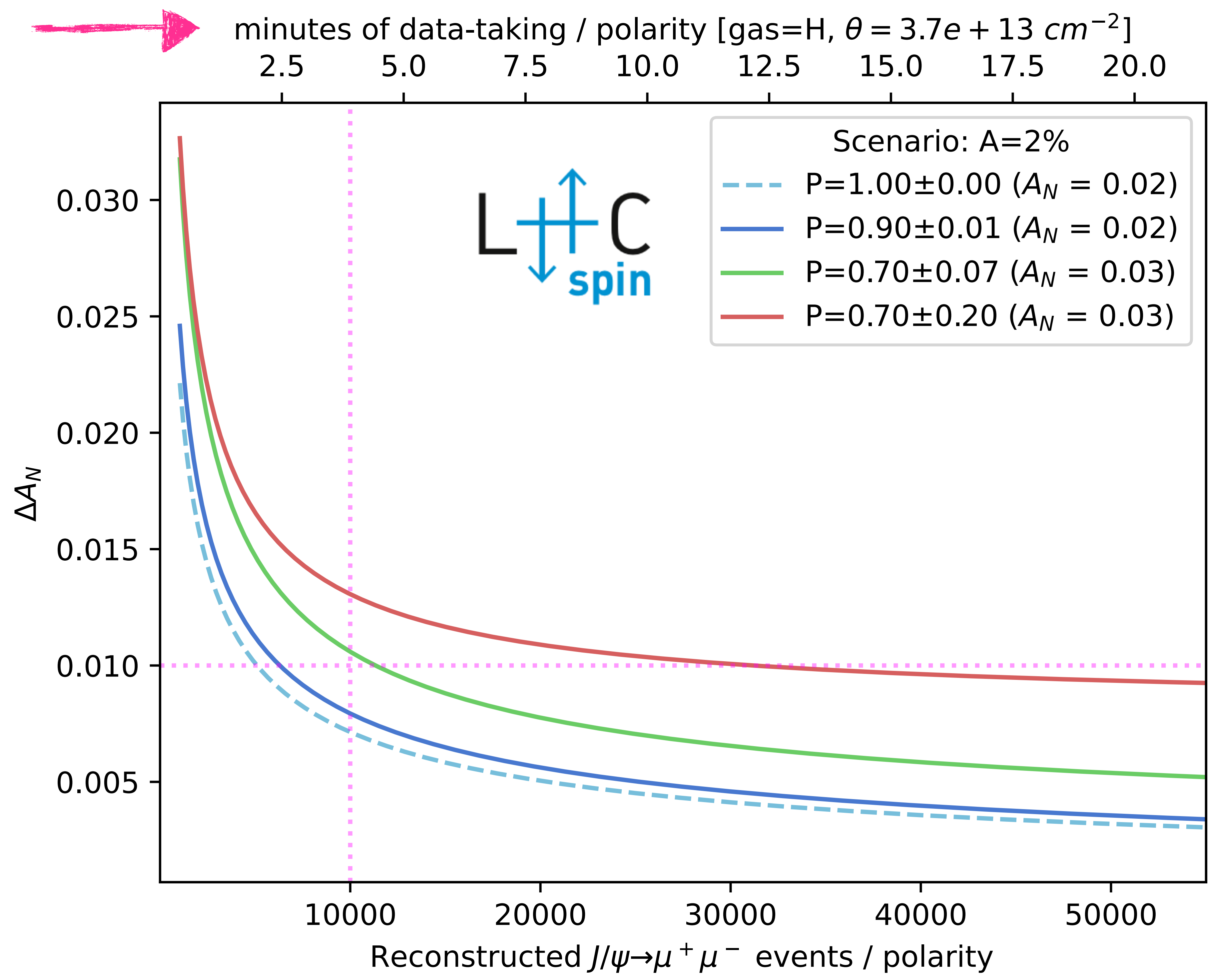
Expected precision on A_N

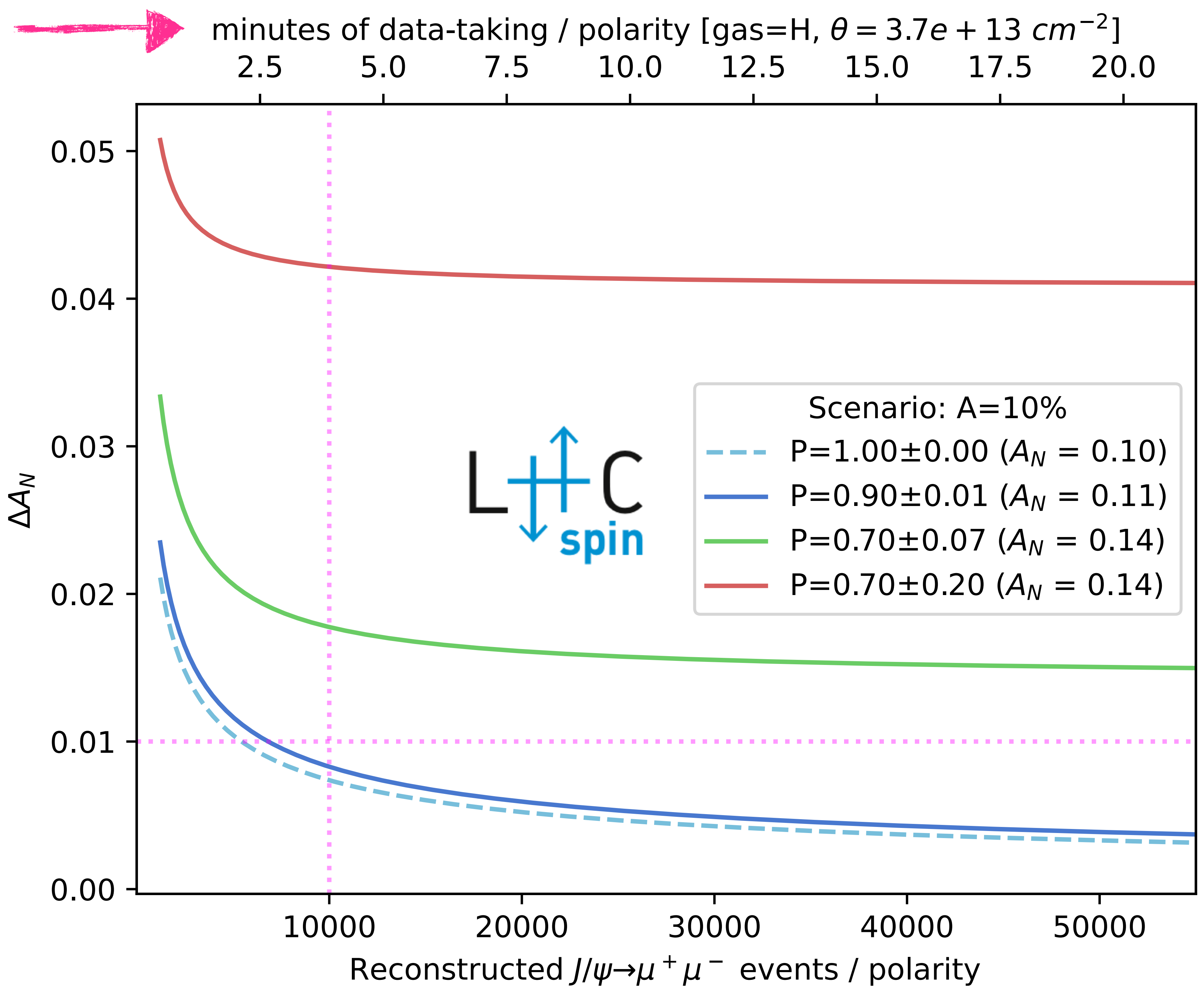
- Convert the expected rate into the uncertainty on a TSSA at LHCspin:

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

- 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 $J/\psi \to \mu^+\mu^-$: 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: $P = 0.90 \pm 0.01$, $\theta \approx 10^{12}/\mathrm{cm}^2$

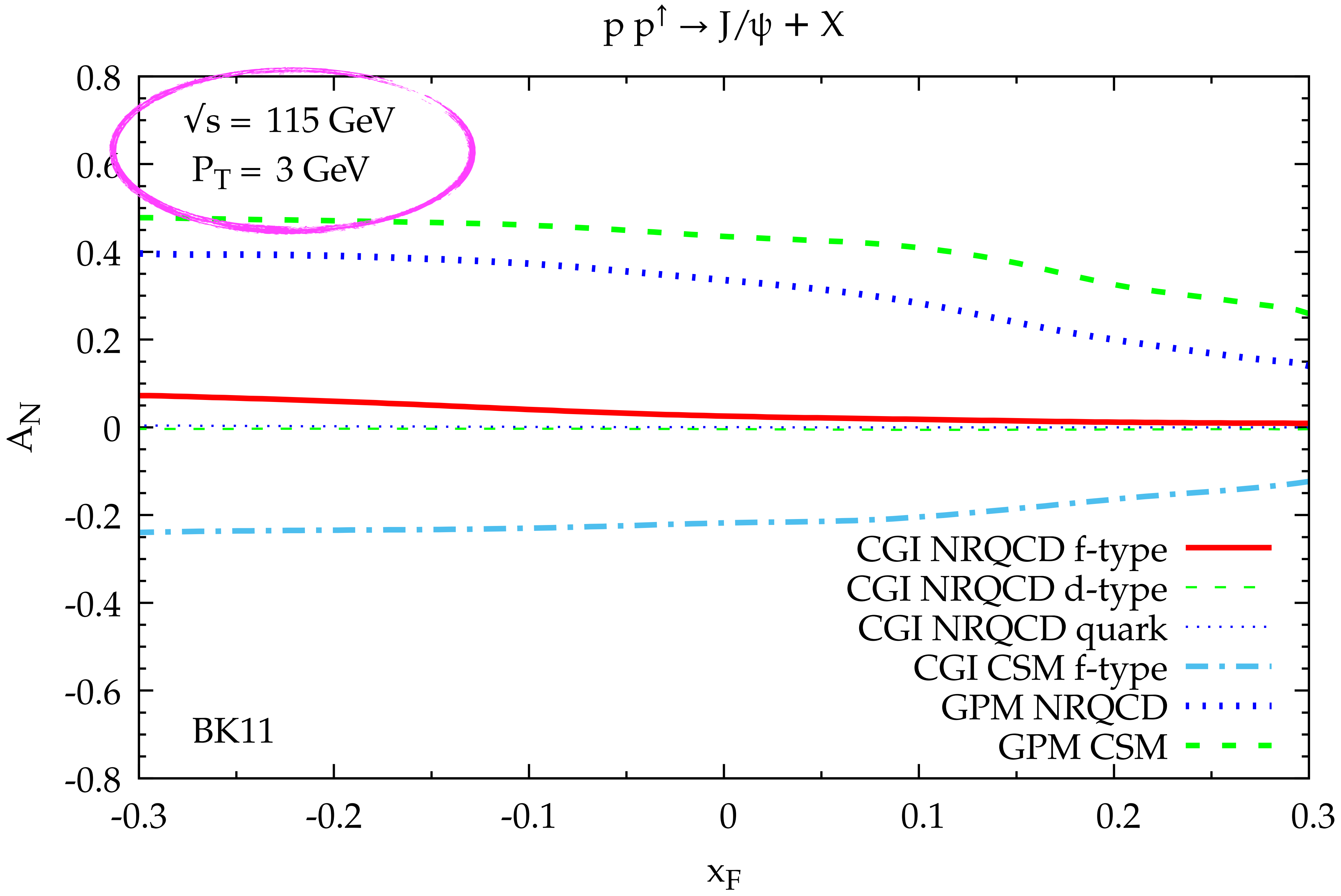




An example measurement: GSF

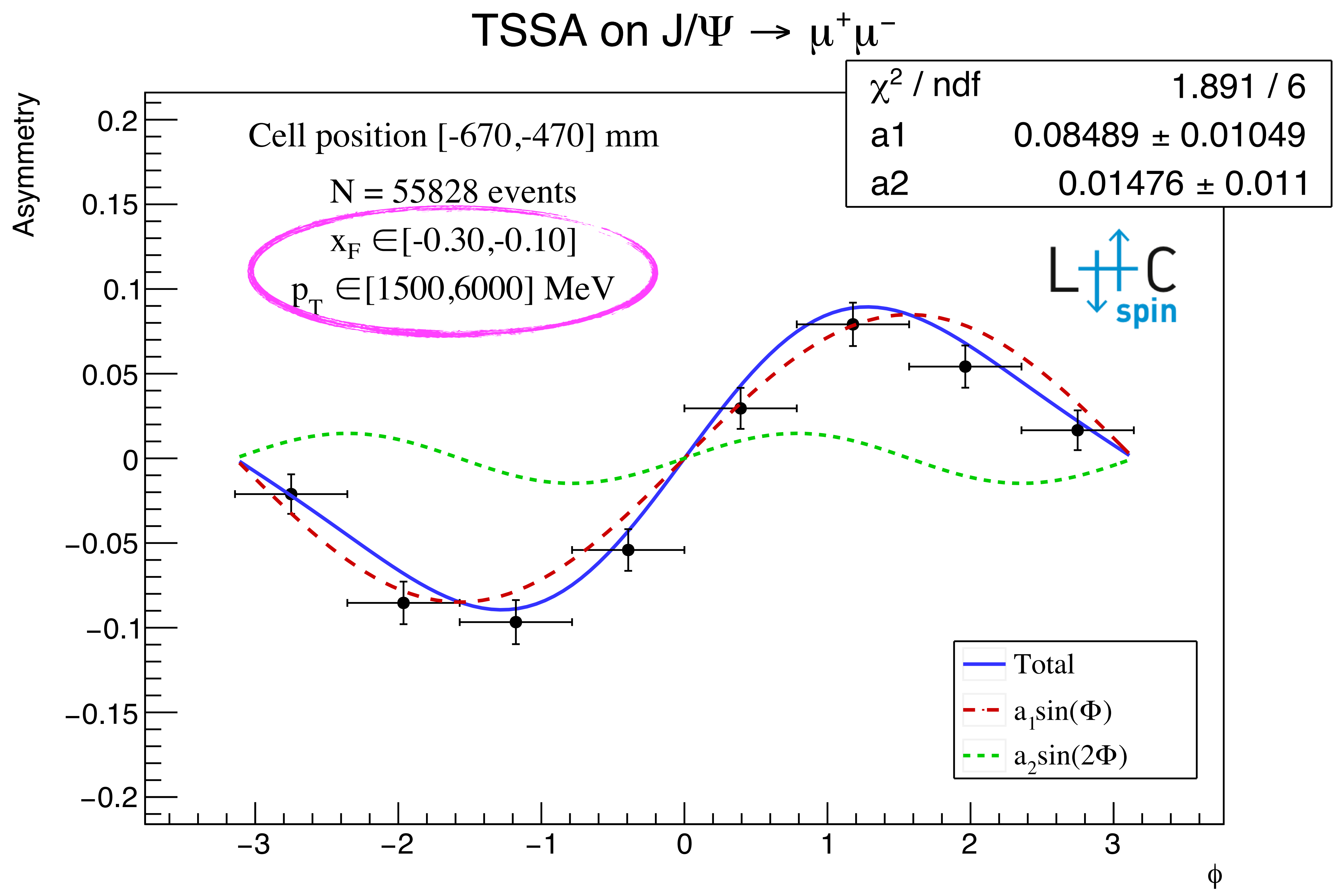
[JHEP 12 (2020) 010]

- Gluon Sivers Function (GSF) can be probed with quarkonia and open heavy-flavour production
- Broad x range at a scale $M_T = \sqrt{M^2 + P_T^2}$ with several unique probes: $\eta_c, \chi_c, \chi_b, J/\psi J/\psi$ …
- A_N predictions on $J/\Psi \to \mu^+\mu^-$ with LHCspin kinematics:



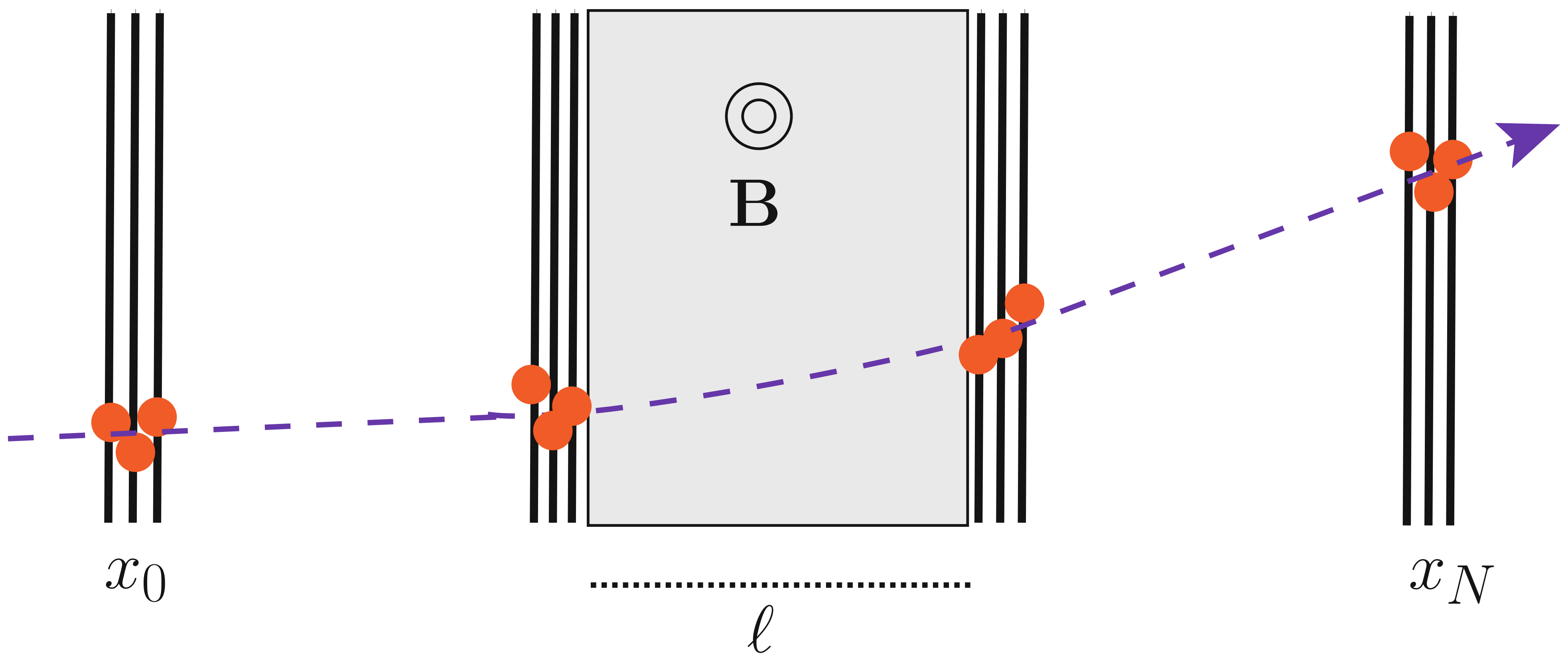
[PRD 102 (2020) 094011]

- This can easily be measured with LHCspin!
- LHCb simulations + emulate the polarisation according to a given model and fit the resulting pseudo-data
- $A_N \sim 0.1 \pm 0.01$ with $4\ x_F \times 2\ p_T \times 8\ \phi$ bins on $J/\Psi \to \mu^+\mu^-$
- $\Delta P = 5\,\%$, negligible in this example

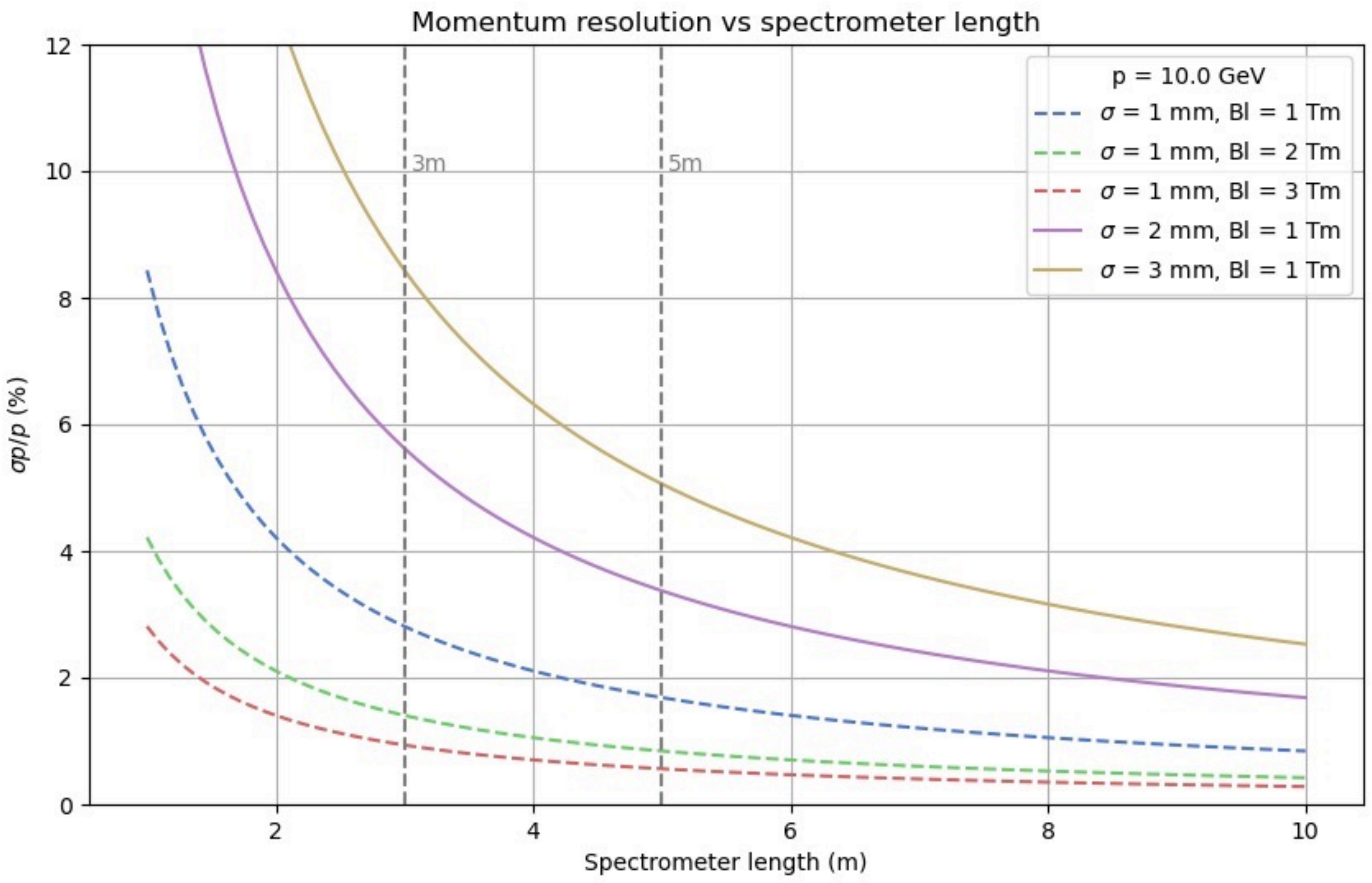


Interaction Region 4: possibilities 1/2

- The IR4 setup will be in-between an R&D setup for LHCspin and an actual detector. This activity would be parallel to LHCb and open to external members. See → talk by Pasquale
- The focus will be on polarimetry and beam interactions, but can we do some physics measurements? Simple considerations here



$$\frac{\delta p}{p} = \frac{8\sigma}{\sqrt{N+1}} \frac{1}{0.3z \cdot Bl \cdot L} p$$



→ can achieve < 1 % resolution within a few meters of lever arm (depending on space constraints) for momenta up to a few GeV and N = 10 hit measurements

note: the single hit resolution of the prototype sciFi modules already installed at IR4 is around $150\ \mu$m

Interaction Region 4: possibilities 2/2

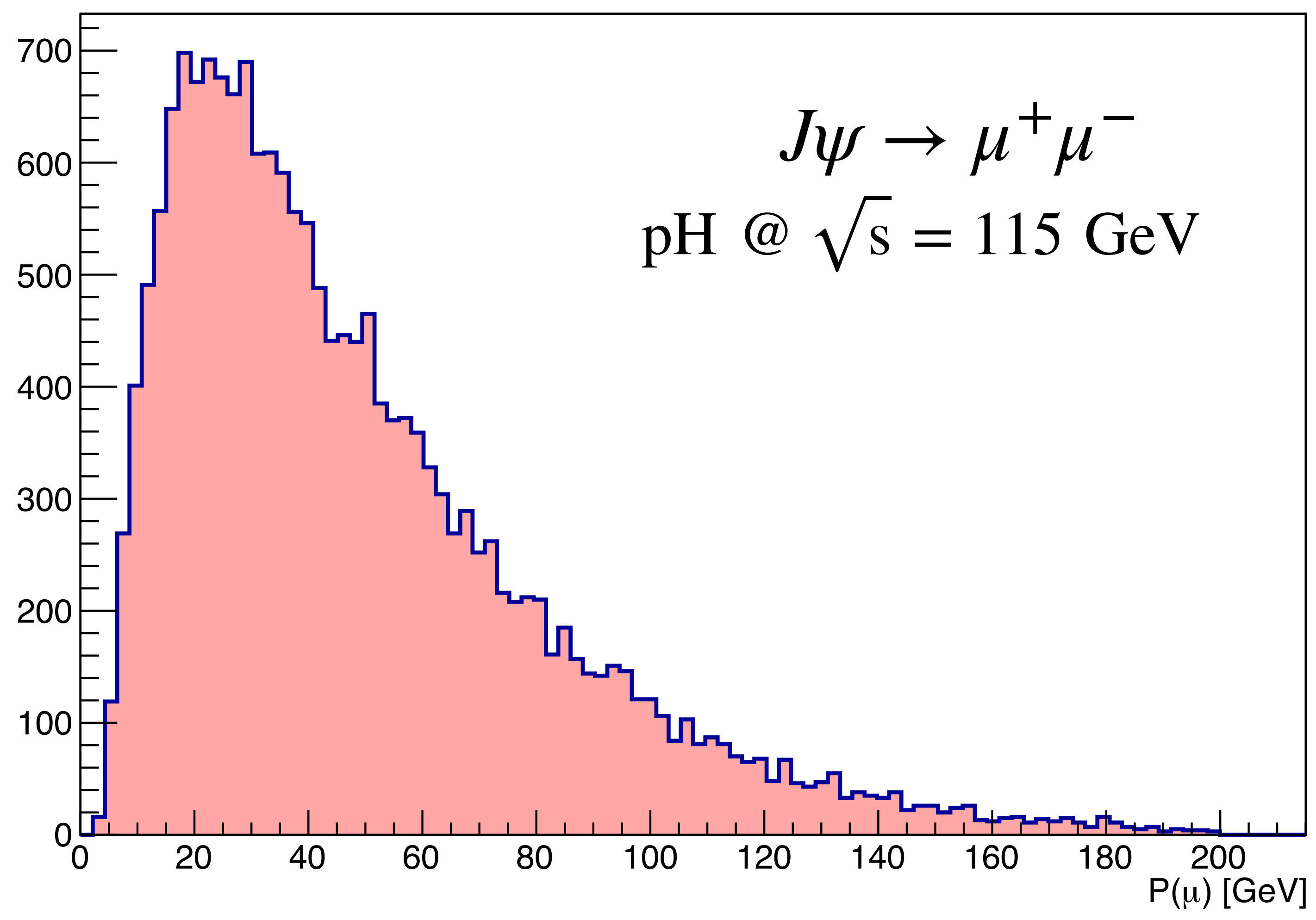
→ if $\delta p/p = 1\,\%$ then $\delta m \approx 40$ MeV at the J/ψ mass

- Neglecting errors from B knowledge, tracker alignment and the MS (which if equal to the spatial contribution means $\delta m \approx 56$ MeV)

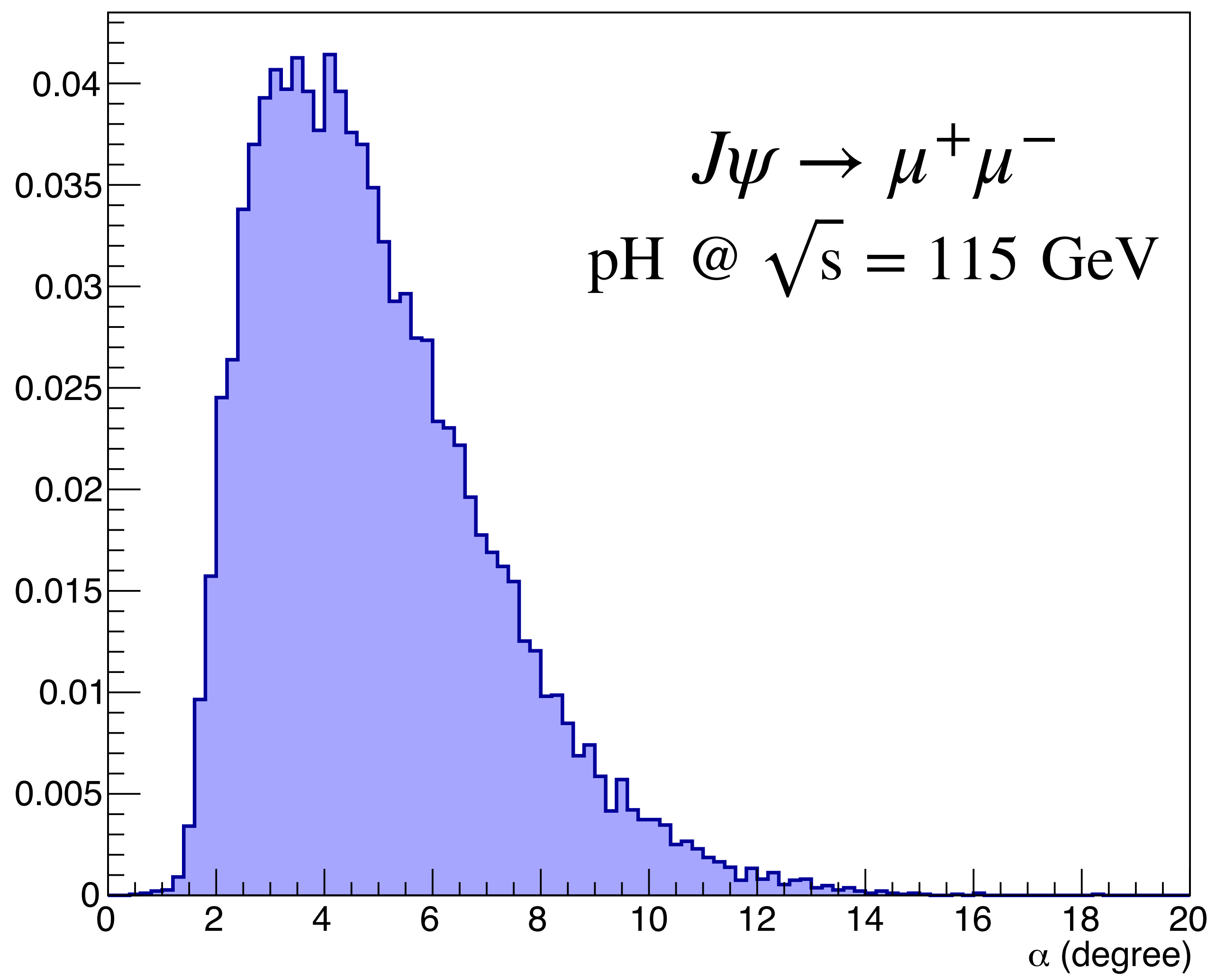
Particle Identification?

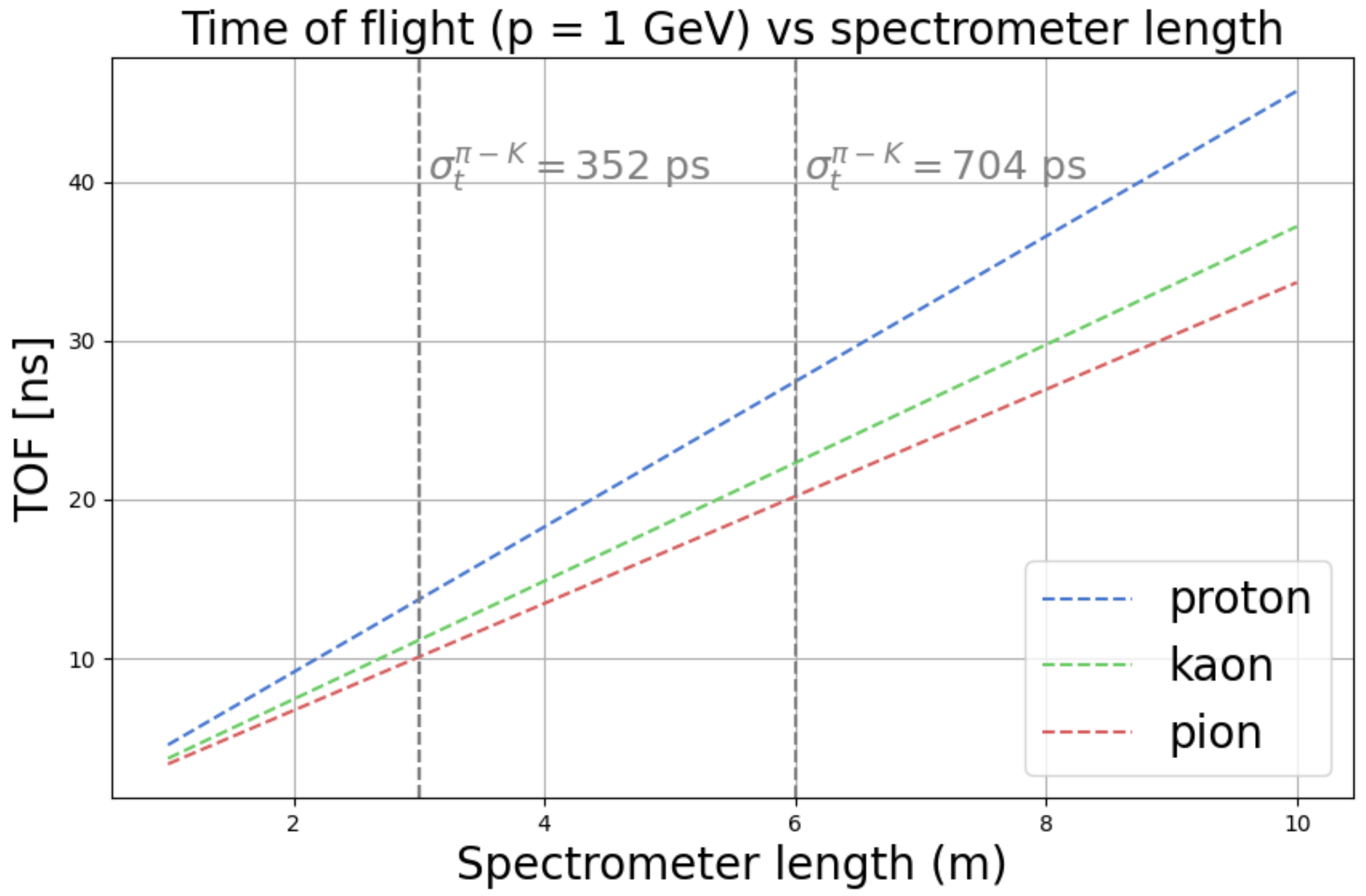
- muons: 3-5 layers of gas chambers w iron walls to filter muons. E.g. from M1 removal at LHCb (2018):
  - GEMs with pad size 1 x 2.5 cm
  - MWPCs with pad size 2 x 5 cm
- hadrons: time resolution for 3σ $\pi - K$ resolution with TOF
  - $p \sim 1$ GeV $\rightarrow$ $\sigma_t = \mathcal{O}(100)$ ps (can)
  - $p \sim 3$ GeV $\rightarrow$ $\sigma_t = \mathcal{O}(10)$ ps (cannot)

momentum



opening angle





Conclusions

- The FT program at LHCb is active since Run 2, now greatly enriched with the SMOG2 cell for Run 3
- SMOG2 early results demonstrate simultaneous beam-gas and beam-beam data-taking with excellent performance
- LHCspin is the natural evolution to extend SMOG2 and to bring spin physics for the first time at the LHC
- Vast physics program with both unpolarised and polarised gases, with plenty of observables & unique final states (only a few examples shown)
- High degree of complementarity with existing facilities & EIC
- A simple setup at IR4 can be a good starting point for the R&D and possibly to make interesting measurements, get in touch if you're interested!