Polarimetry with π^0 in the SPD

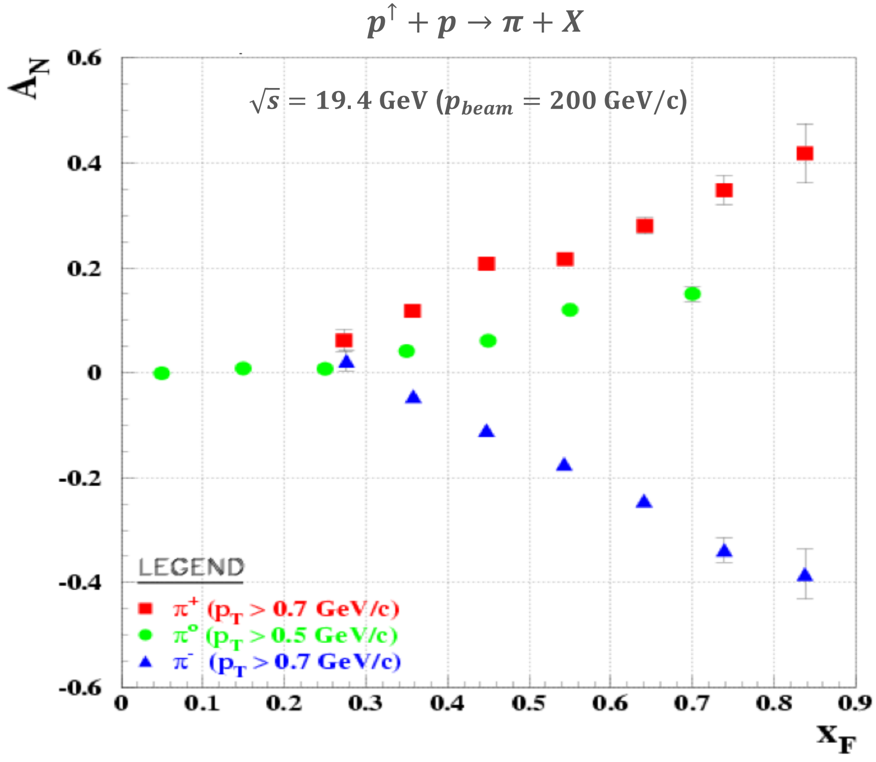
Inclusive π^0production from pp interactions

Single Spin Asymmetry (SSA): $A_N^{\pi^0} \longrightarrow$ probes the spin structure of the proton.

In the early 70's was believed that SSA (A_{N}) was nearly vanishing in the framework of pQCD.

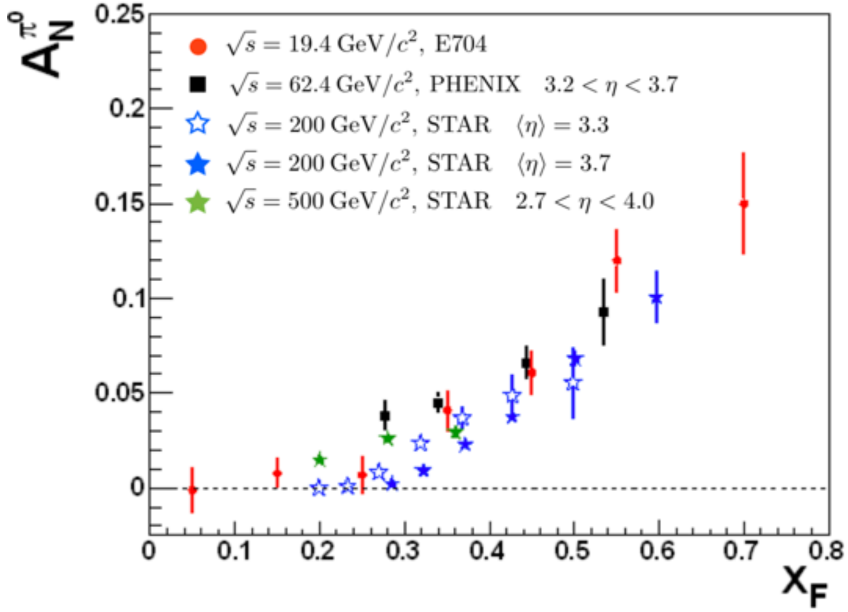
$$A_{\mathrm{N}} = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

In 1991 the E704 experiment, with $\boldsymbol{p}^{\uparrow}$ at higher p_{T} values, extended the results on large A_{N}.



E704: Adams et al. Phsy. Lett. B264(1991)462

A_{N} nearly independent of $\sqrt{s}$



The single spin pion asymmetry of the process $p^{\uparrow} + p \rightarrow \pi^0 + X$ is considered one of the best tests to verify perturbative regime by QCD.

Extraction of A_N

$p^{\uparrow} + p \rightarrow \boldsymbol{\pi^0} + X$ $\phi = 2\pi$

The cross section of hadron production in polarized $p^{\uparrow} + p$ collisions, is modified in azimuth.

$$\frac{d\sigma}{d\phi} = \frac{d\sigma}{d\phi_0}(1 + \underbrace{P \cdot A_{\mathrm{N}} \cdot \cos\phi)}_{\text{Azimuthal cosine modulation}}$$

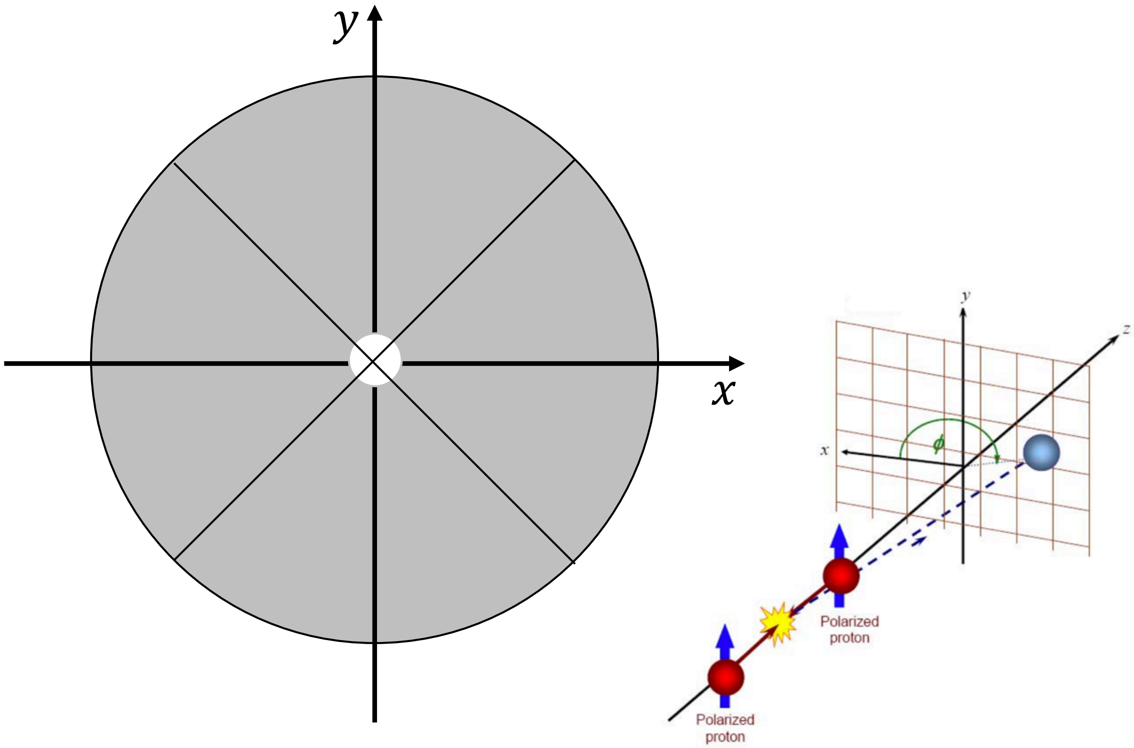
$$N_{\boldsymbol{\pi^0}}(\phi) = A(1 + B\cos\phi)$$

$$A_N = \frac{B}{P}$$

$N_{\boldsymbol{\pi^0}}(\phi)$: Yield of π^0

P: Beam polarization

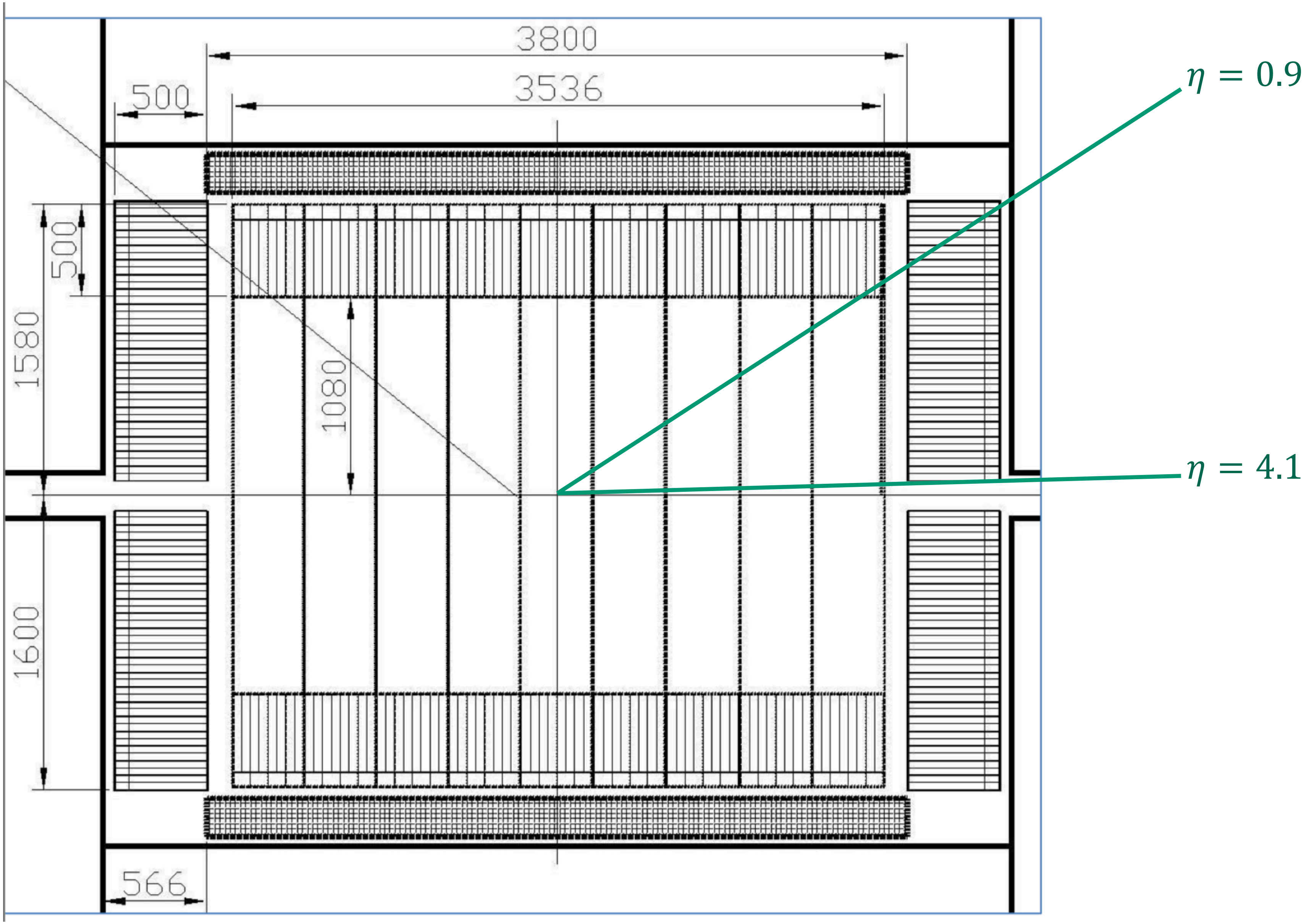
- *P* ~ 0.7 was assumed



- The spin dependent π^0 yields for each bin are extracted from the invariant mass spectra in different x_{F} sub-ranges for each ϕ bin.
- The invariant mass was fitted with a **polynomial** function for the background and a **normalized Gaussian** distribution representing the signal peak.

Settings

Geometry proposed by Oleg Gravishchuk at the SPD collaboration meeting, 14.12.2022 (*)
(ECAL endcaps are located inside of RS)



(*) *https://indico.jinr.ru/event/2616/contributions/14882/attachments/11631/19200/SPD_ECAL_12.12.2021_v_1.pdf*

Settings

$$\boldsymbol{p + p \rightarrow \underset{\gamma\gamma}{\underset{\swarrow\downarrow}{\pi^0}} + X}$$

$\boldsymbol{Pythia}$ 8244

$\sqrt{s} = 27\ GeV, 10^8$ events

$E^{\gamma}_{min} = 400\ \mathrm{MeV}$

$0.9 \leq \eta \leq 4.1$

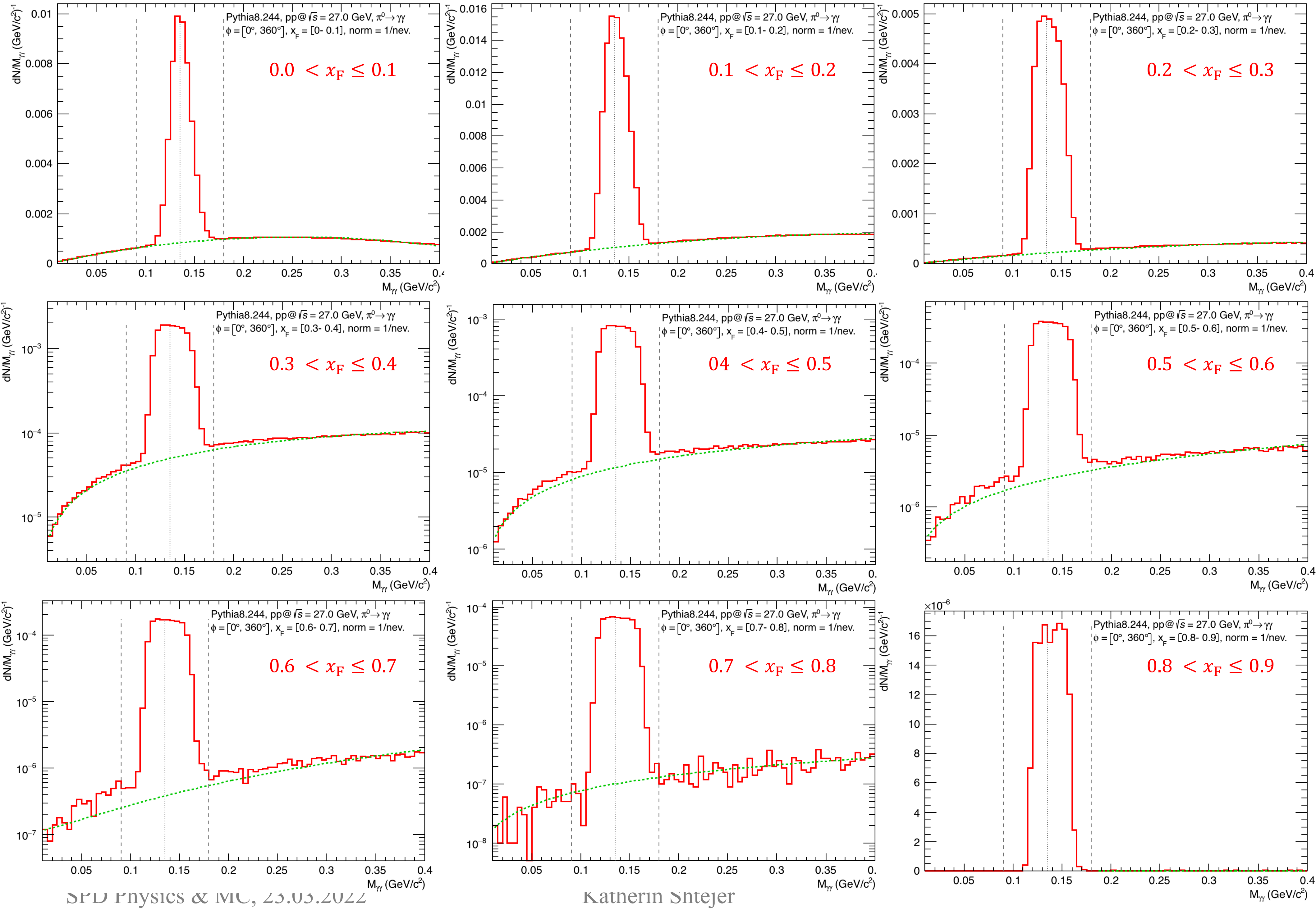
$p_{\mathrm{T}} > 0.5\ \mathrm{GeV/c}$

Uniform distribution to smear the vertex in $\Delta Z = \pm 30\ cm$

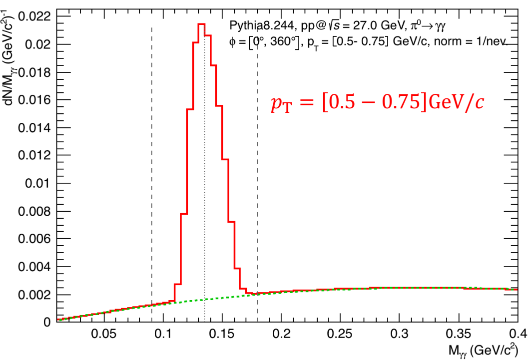
Gaussian smearing on E_γ according to the ECAL Endcap energy resolution: $\approx \dfrac{5.4\%}{\sqrt{E}}$

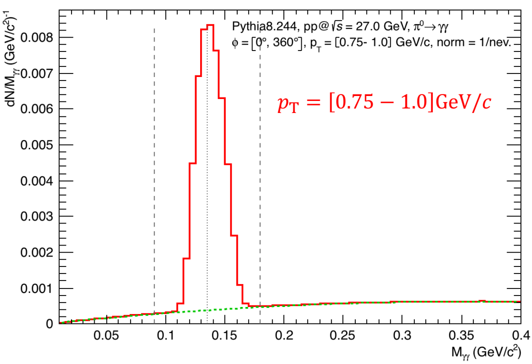
Minimum Bias

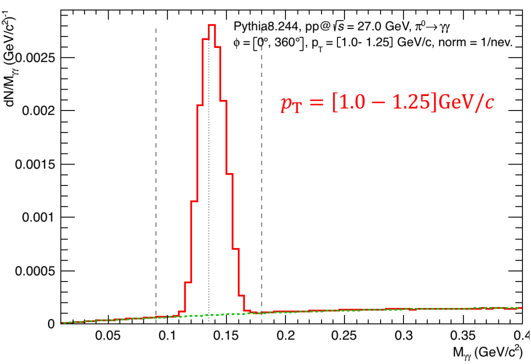
Invariant mass, right endcap, in x_F intervals, $\phi = [0^o - 360^o]$

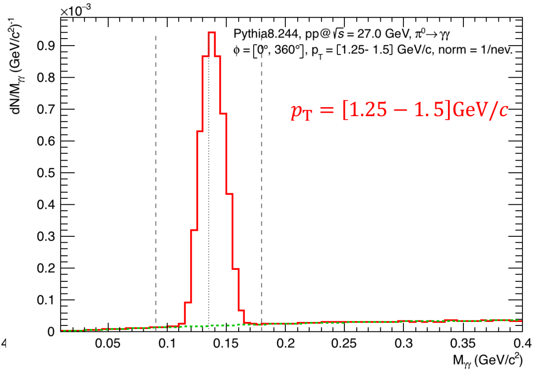


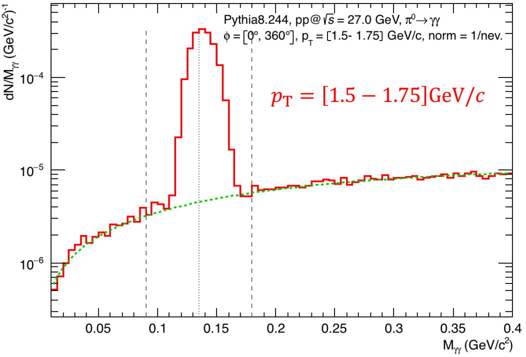
Invariant mass, right endcap, in p_T intervals, $\phi = [0^o - 360^o]$

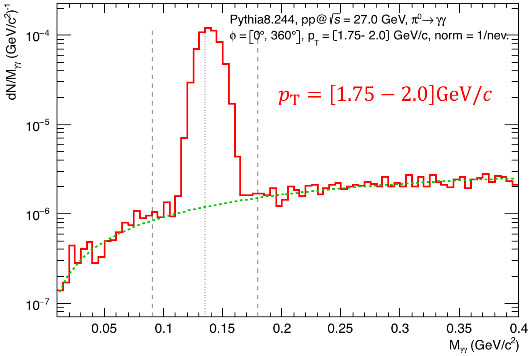


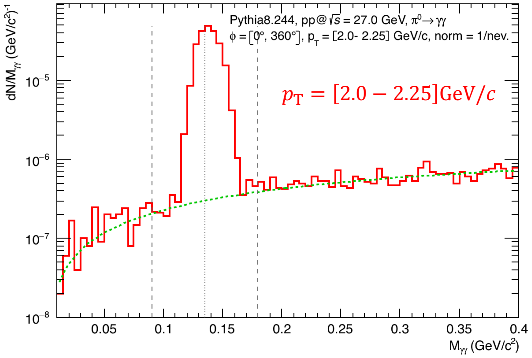


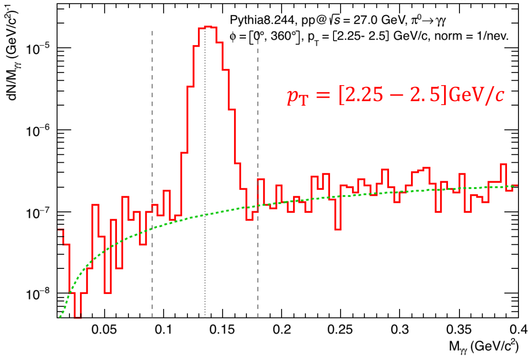


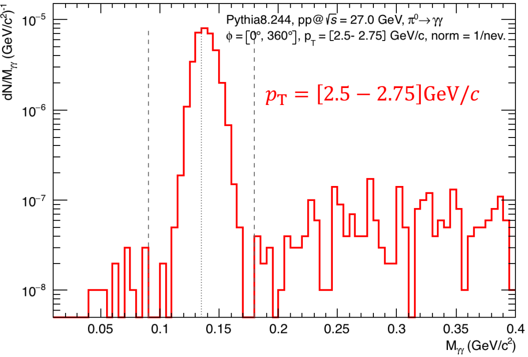


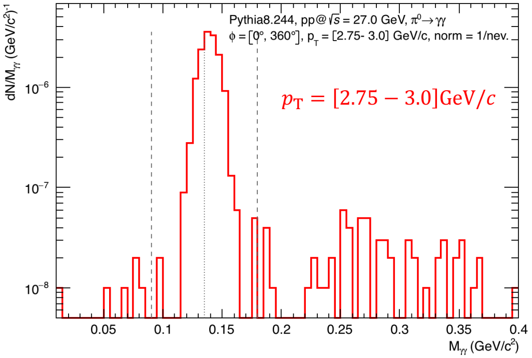


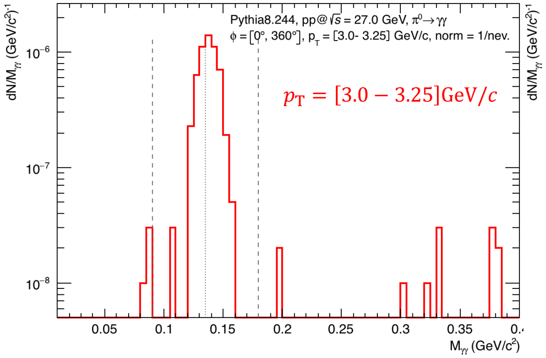


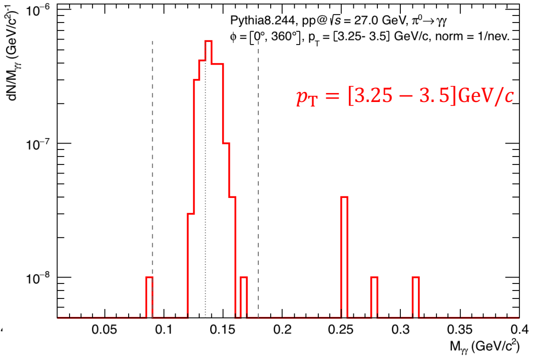


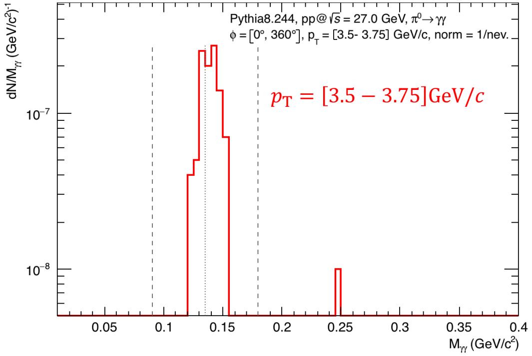


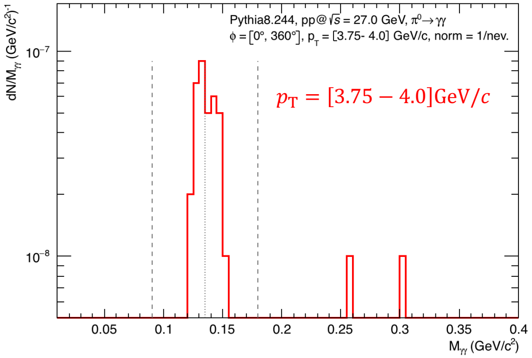




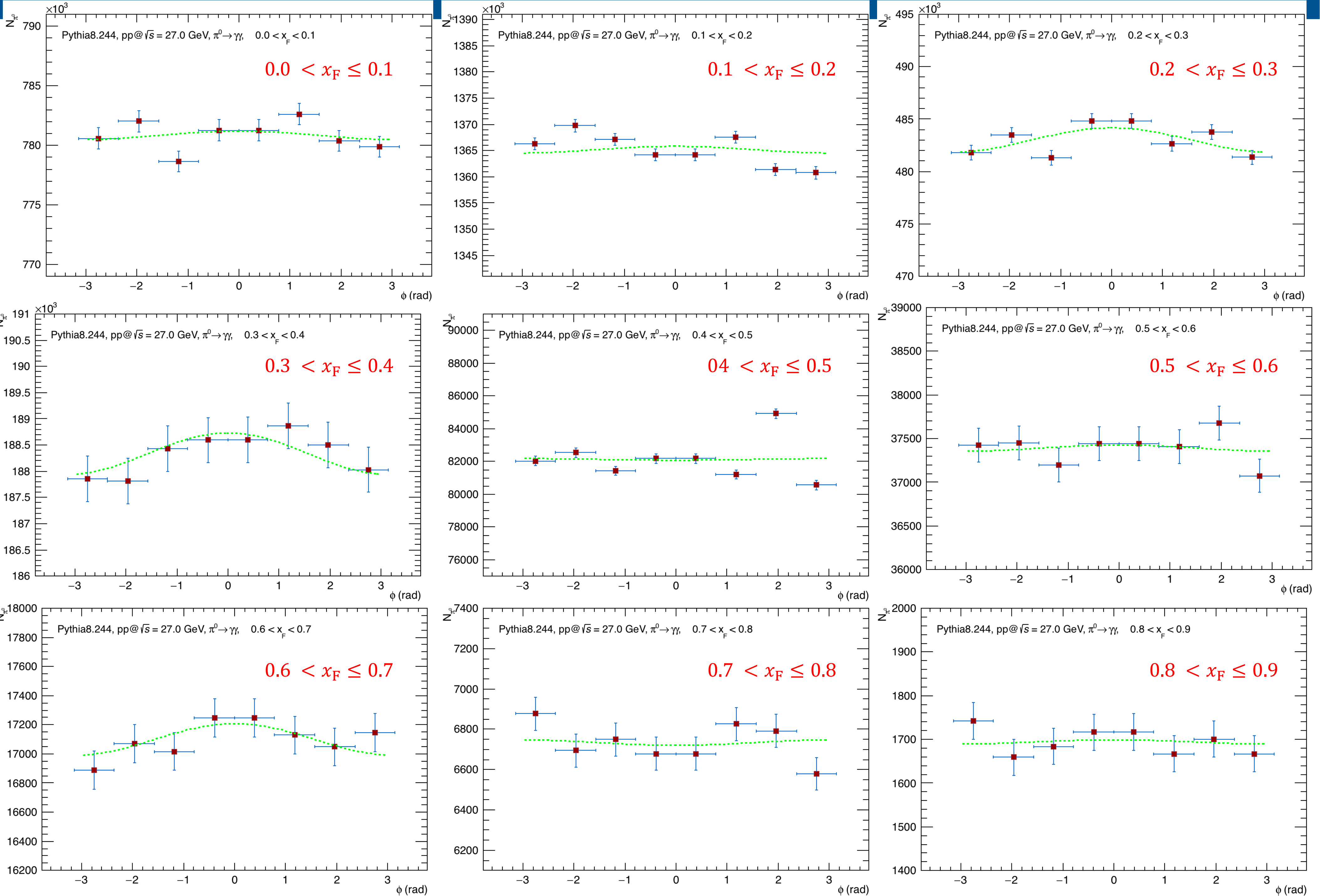




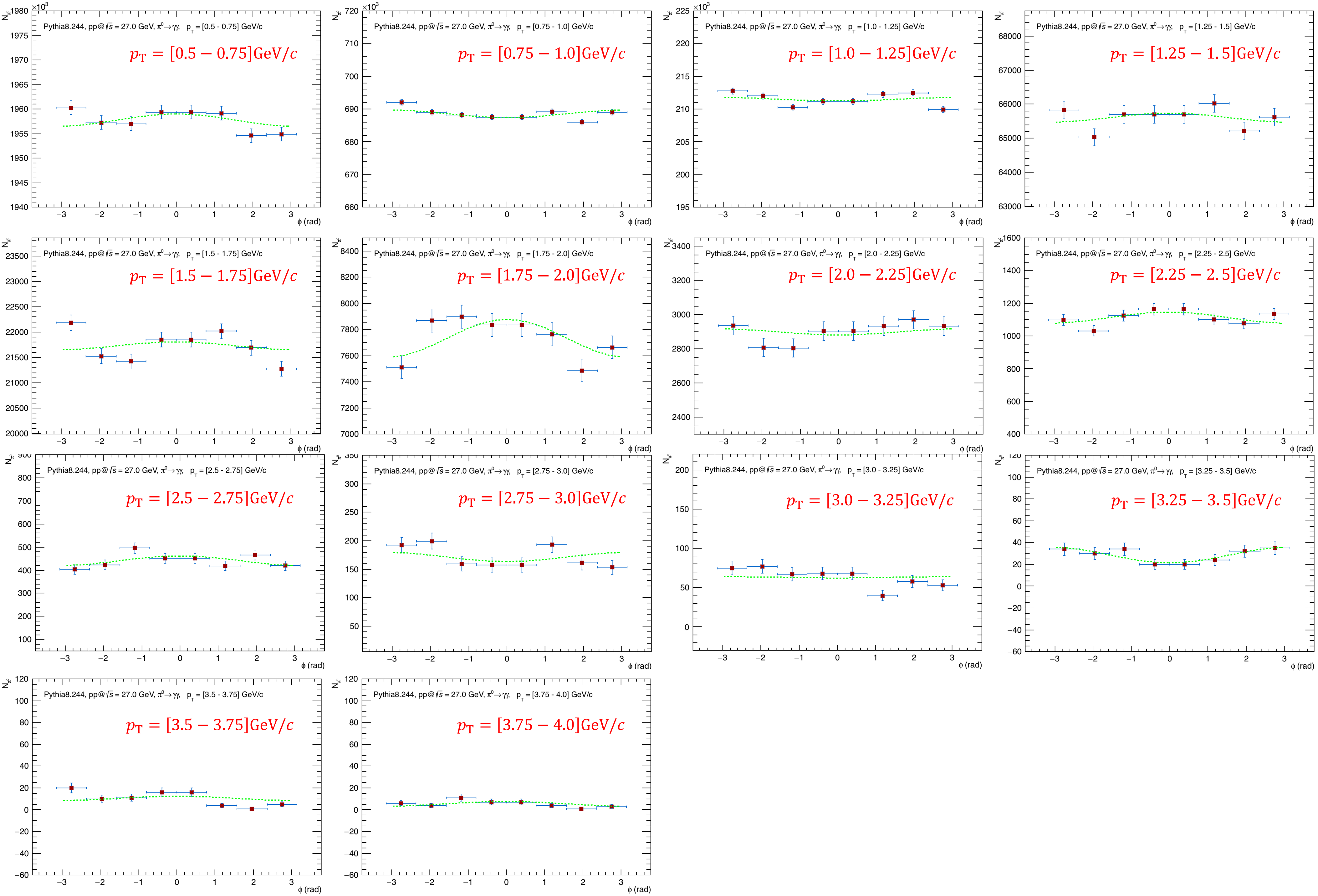




Azimuthal cosine modulation of π^0 yields in x_F intervals

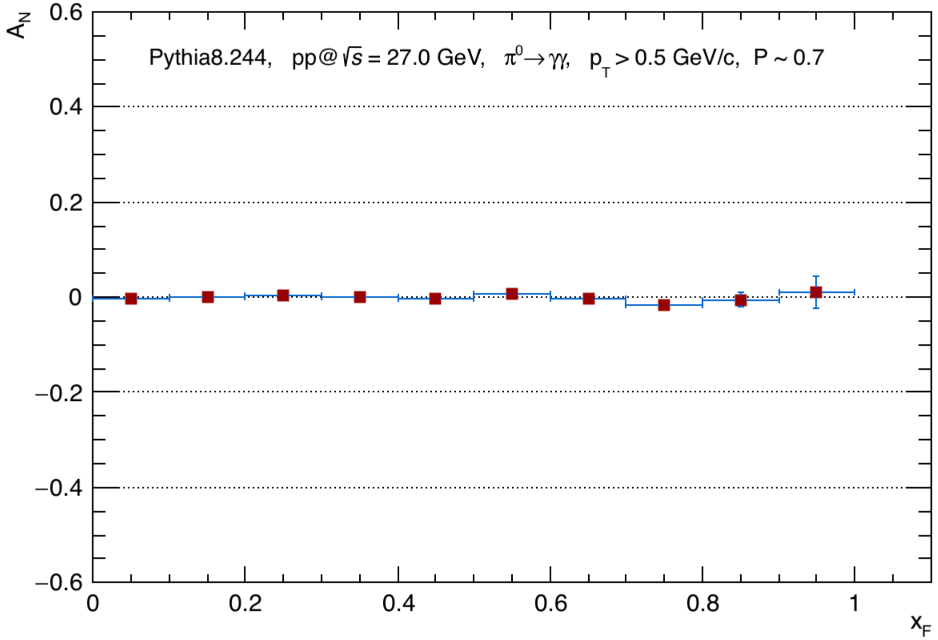


Azimuthal cosine modulation of π^0 yields in p_T intervals

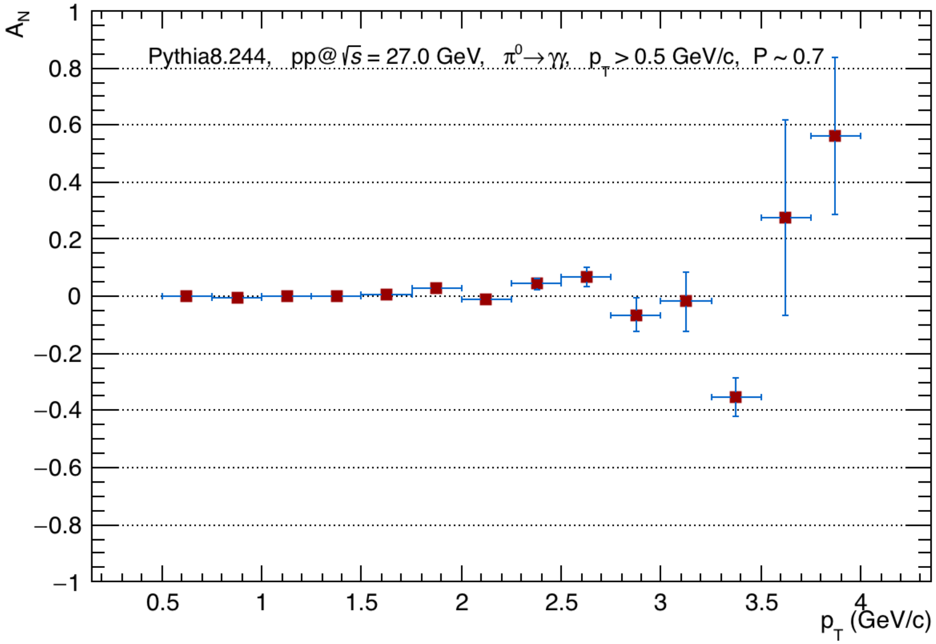


A_N in the ECAL endcap

A_N in x_F intervals



A_N in p_T intervals



Relative error for A_N

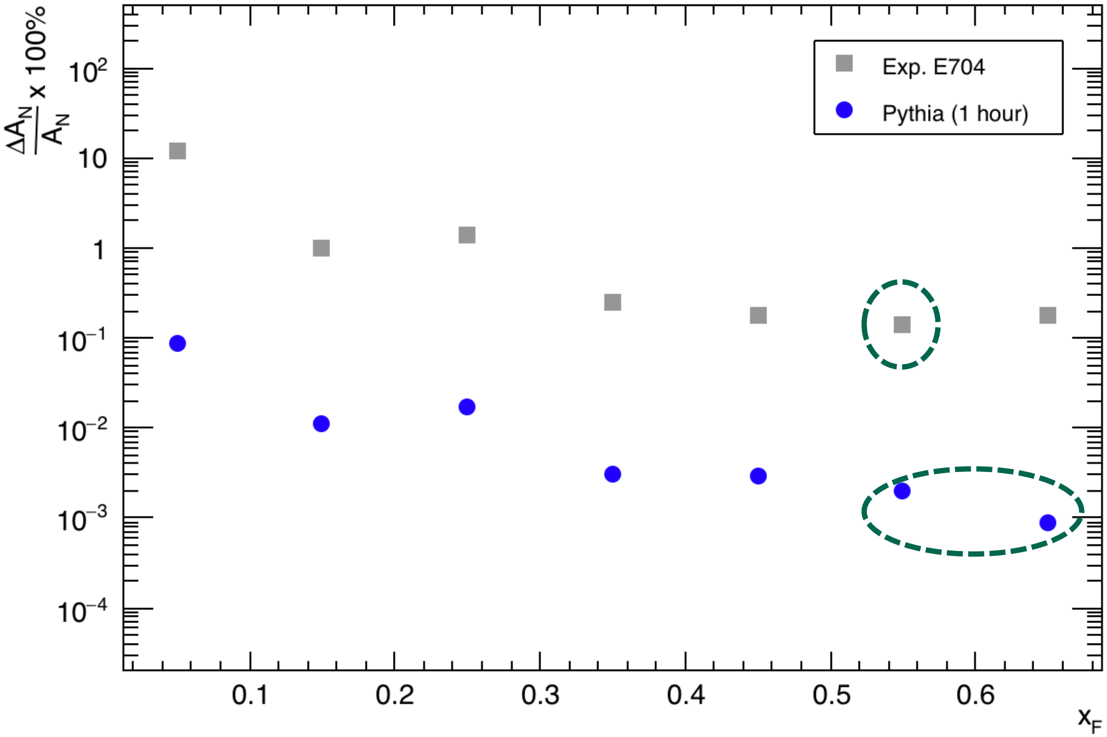
By using the measured A_N from the E704 experiment at $\sqrt{s} = 19.4$ GeV, we can estimate the relative error of $\frac{\Delta A_N}{A_N}$ *vs.* x_F

$$\frac{\Delta A_N}{A_N} \sim \frac{\Delta P}{P}$$

ΔA_N → Pythia

A_N → E704

ΔA_N scaled to 1 hour of data-taking (Pythia and SPDRoot)



Relative of A_N error estimated for 1 hour

x_F	$\frac{\Delta A_N}{A_N}$ (%)
	Pythia (1h)
0.0 -0.1	8.79
0.1 -0.2	1.09
0.2 -0.3	1.75
0.3 -0.4	0.30
0.4 -0.5	0.29
0.5 -0.6	0.20
0.6 -0.7	0.09

The determination of the polarization is expected to be precise for $0.5 < x_F < 0.7$.

Estimated relative error of the polarization

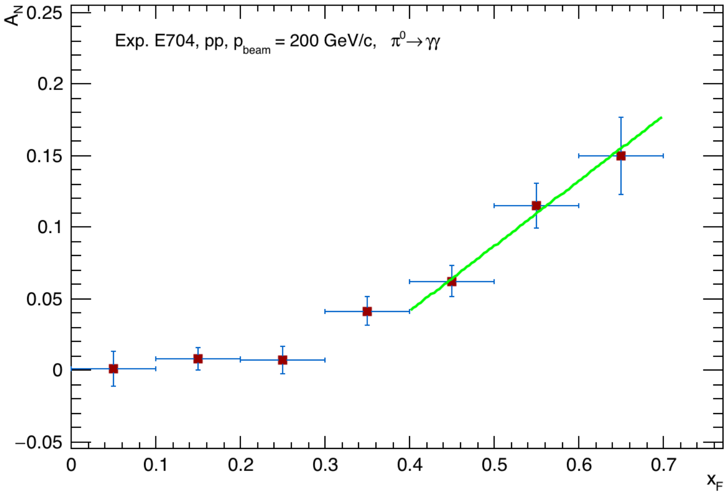
Raw asymmetry:

$$P \cdot A_N \cdot \cos\phi = \epsilon(\phi) \;\Leftrightarrow\; \epsilon(\phi) = \frac{N^{\uparrow}(\phi) - N^{\downarrow}(\phi)}{N^{\uparrow}(\phi) + N^{\downarrow}(\phi)}$$

$$P \cdot A_N \sim \epsilon$$

$$\frac{\Delta A_N}{A_N} \sim \frac{\Delta P}{P}$$

$$\boxed{\frac{\Delta P}{P} = \frac{1}{\sqrt{\sum_i \left(\frac{A_{N_i}}{\Delta A_{N_i}}\right)^2}}}$$



Taking the last 3 points ($0.4 \le x_F \le 0.7$):

$$\frac{\Delta P}{P} \approx 0.00078$$ 0.08% (MC - Pythia)

$$\frac{\Delta P}{P} \approx 0.0935$$ 9.3% (Experiment E704)

Taking the last 4 points ($0.3 \le x_F \le 0.7$):

$$\frac{\Delta P}{P} \approx 0.00074$$ 0.07% (MC - Pythia)

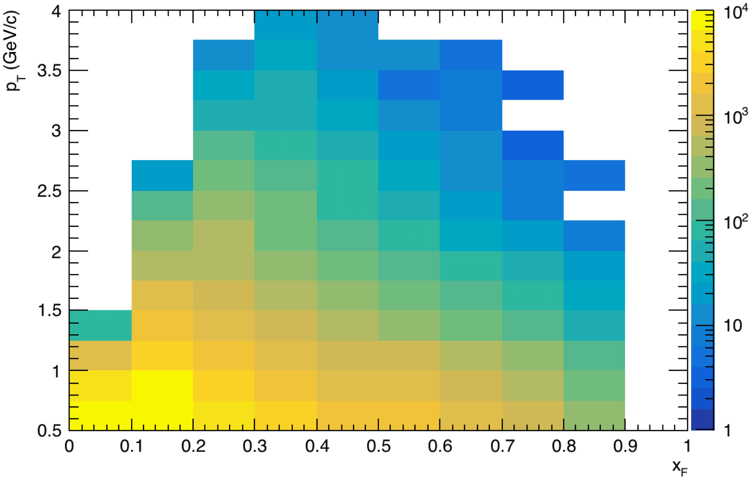
$$\frac{\Delta P}{P} \approx 0.0873$$ 8.7% (Experiment E704)

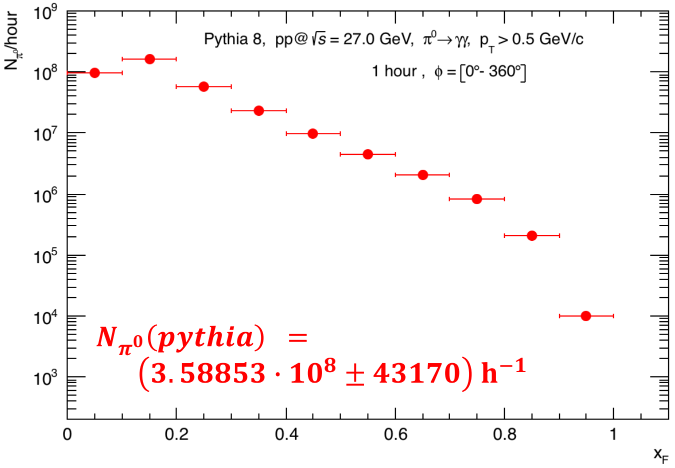
The error of the beam polarization in the experiment ***E704*** *is estimated in* ***10%****, as reported in FERMILAB-Pub-91/15-E[E581,E704]*

From pure Pythia we might define a beam polarization in SPD endcaps with a precision $\Longrightarrow \dfrac{\Delta P}{P} \approx 0.1\%$

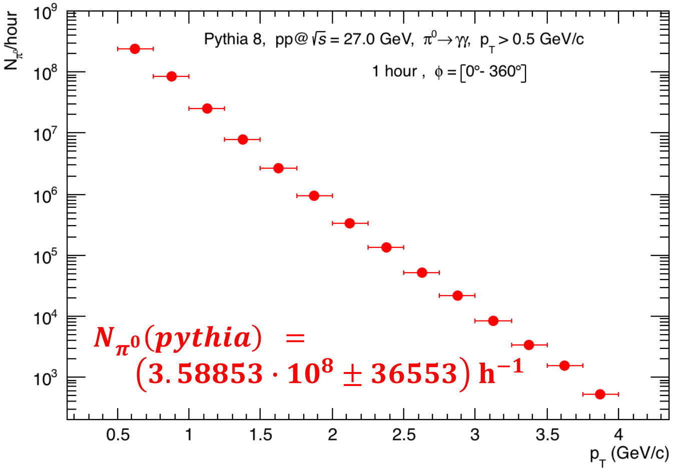
Predicted for 2 minutes from Pythia $\Longrightarrow \dfrac{\Delta P}{P} \approx 0.6\%$

Estimation of π^0 yield in the ECAL endcap

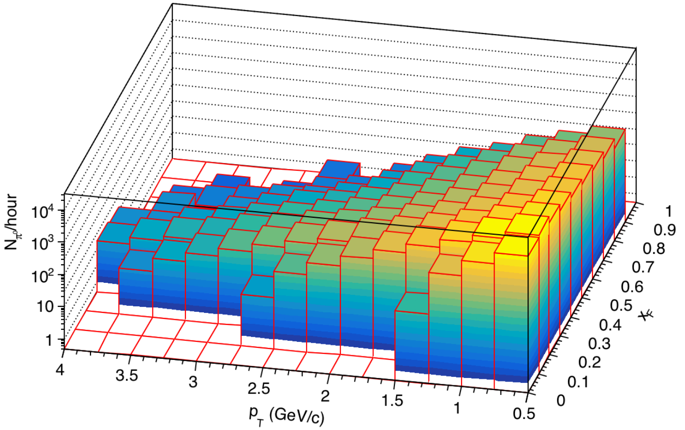


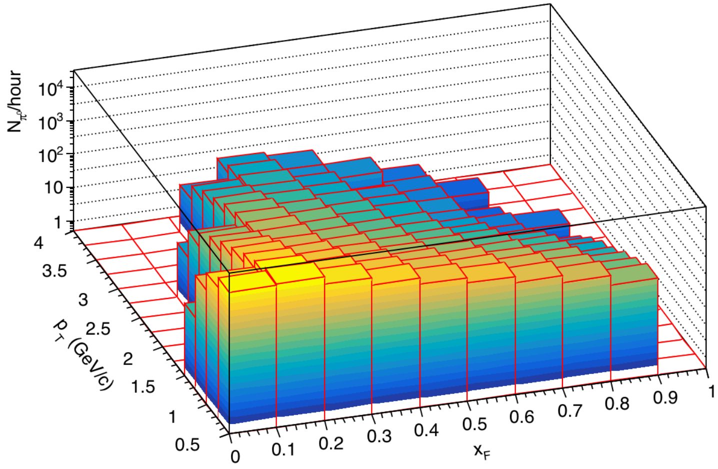


$N_{\pi^0}(pythia) \;=$
$(3.58853 \cdot 10^8 \pm 43170)\ \mathrm{h}^{-1}$



$N_{\pi^0}(pythia) \;=$
$(3.58853 \cdot 10^8 \pm 36553)\ \mathrm{h}^{-1}$

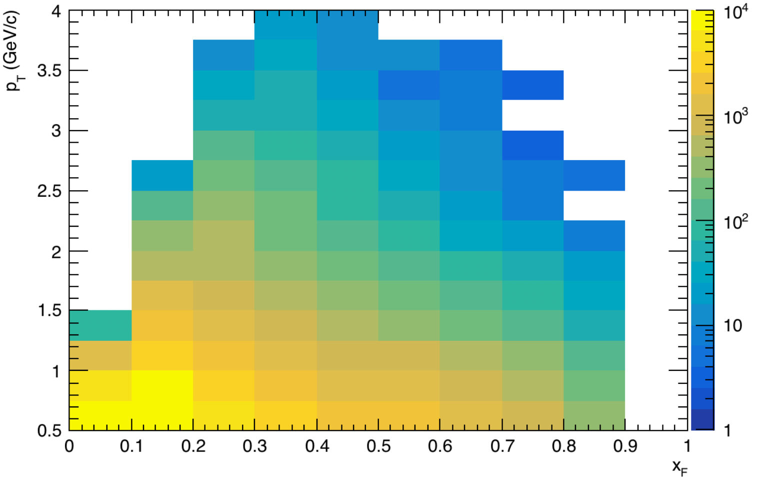


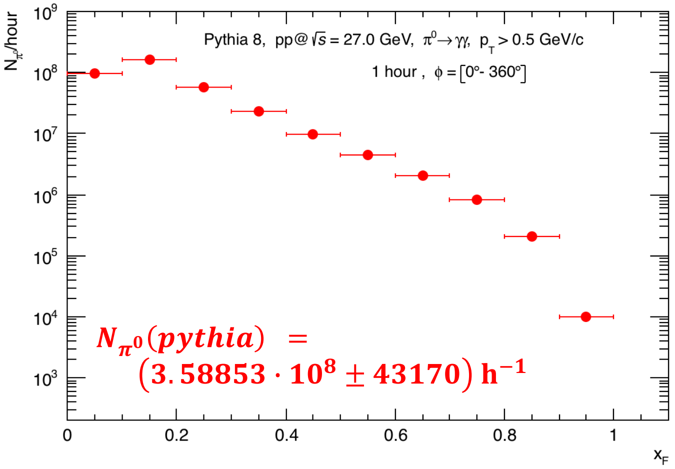


x_F	N_{π^0}(pythia)
0.0 – 0.1	9.47707e+07 ± 9735
0.1 – 0.2	1. 65363e+08 ± 12859
0.2 – 0.3	5.84847e+07 ± 7647
0.3 – 0.4	2.27402e+07 ± 4768
0.4 – 0.5	9.87763e+06 ± 3142
0.5 – 0.6	4.52426e+06 ± 2127
0.6 – 0.7	2.06566e+06 ± 1437
0.7 – 0.8	8.11230e+05 ± 900
0.8 – 0.9	2.05584e+05 ± 453
0.9 – 1.0	9802e+05 ± 99

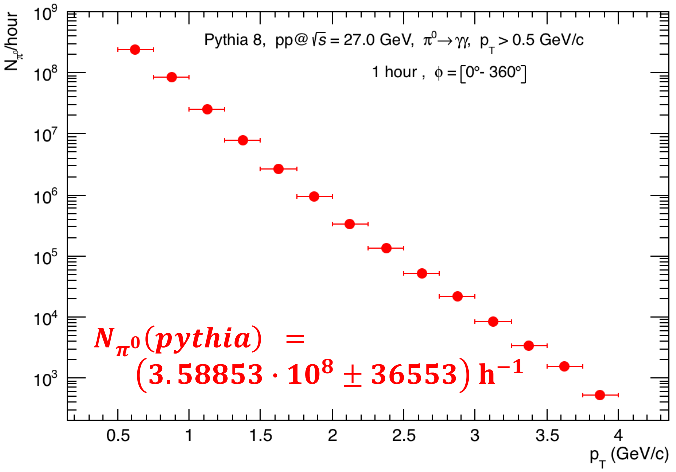
p_T (GeV/c)	N_{π^0}(pythia
0.50 – 0.75	2.37621e+08 ± 15415
0.75 – 1.00	8.35681e+07 ± 9141
1.00 – 1.25	2.55767e+07 ± 5057
1.25 – 1.50	7.97549e+06 ± 2824
1.50 – 1.75	2.63201e+06 ± 1622
1.75 – 2.00	9.20563e+05 ± 959
2.00 – 2.25	3.38356e+05 ± 581
2.25 – 2.50	1.33513e+05 ± 365
2.50 – 2.75	5.2210e+04 ± 228
2.75 – 3.00	2.1423e+04 ± 146
3.00 – 3.25	8242.13 ± 90
3.25 – 3.50	3424.12 ± 58
3.50 – 3.75	1545.4 ± 39
3.75 – 4.00	530.3 ± 23

Estimation of π^0 yield in the ECAL endcap

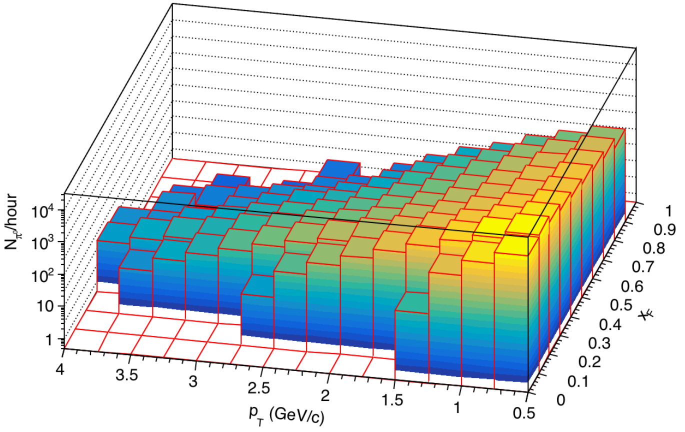


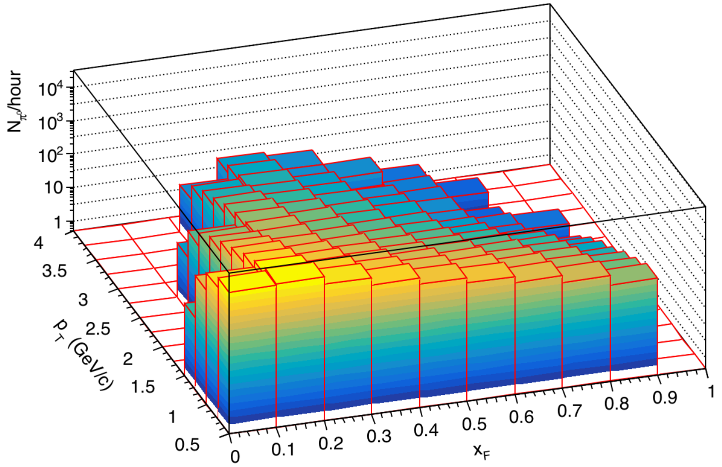


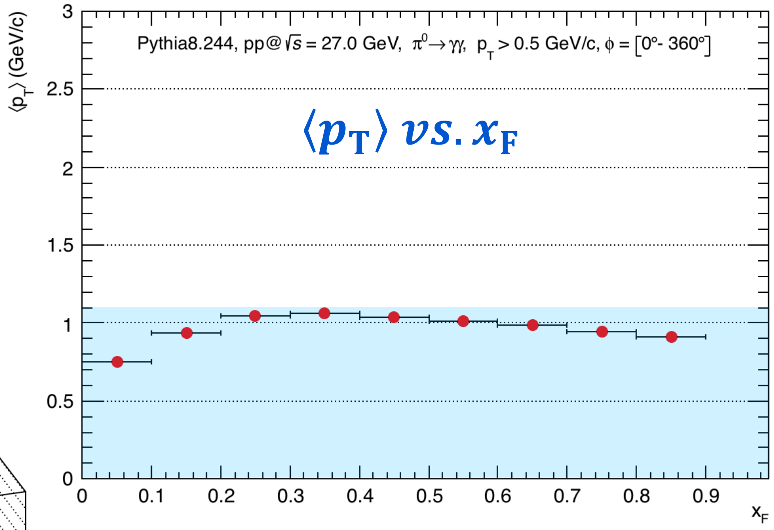
$$N_{\pi^0}(pythia) = (3.58853 \cdot 10^8 \pm 43170)\ \mathrm{h}^{-1}$$



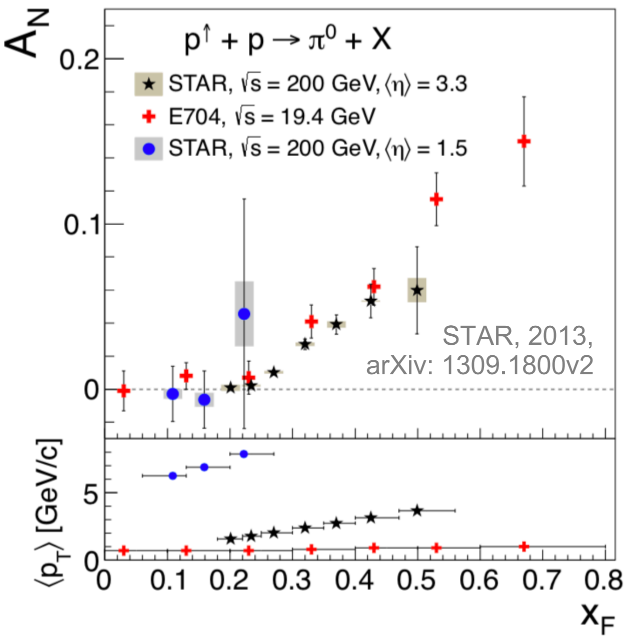
$$N_{\pi^0}(pythia) = (3.58853 \cdot 10^8 \pm 36553)\ \mathrm{h}^{-1}$$





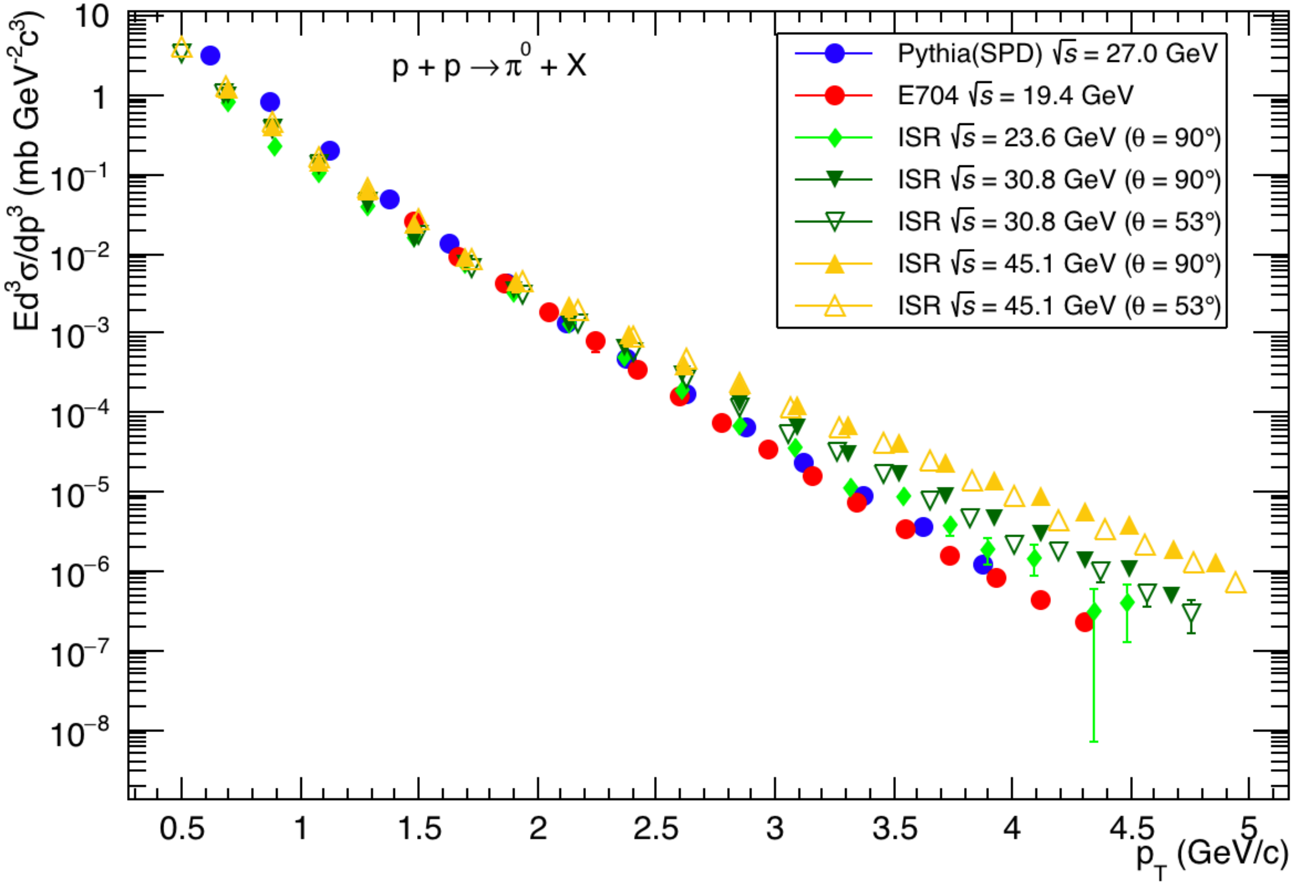


$\langle p_T \rangle$ *vs.* x_F



STAR, 2013,
arXiv: 1309.1800v2

Cross Section

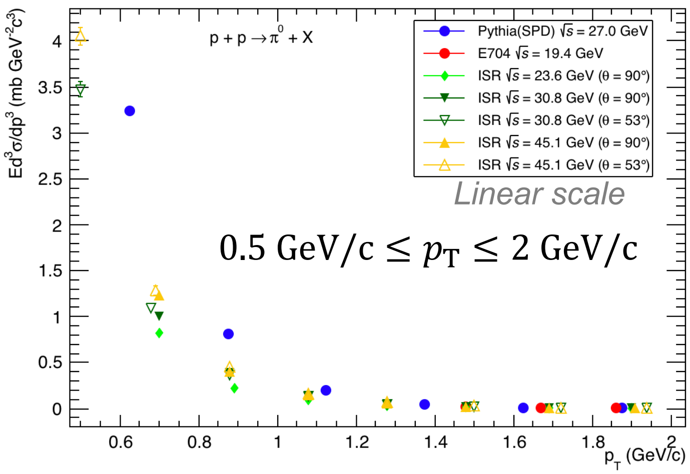


Pythia, this simulation

1994, E704 Coll. JHEP 94-88

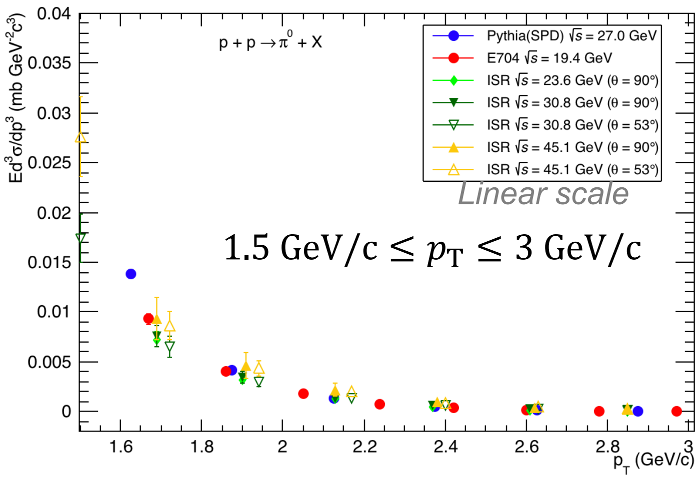
1975, ISR Coll. Nucl.Phys.B98

$$E\frac{d^3\sigma}{dp^3} = \frac{1}{2}\frac{1}{2\pi}\frac{1}{\Delta\eta\Delta p_T}\frac{1}{\langle p_T\rangle}\frac{1}{BR}\frac{N}{\mathcal{L}}$$



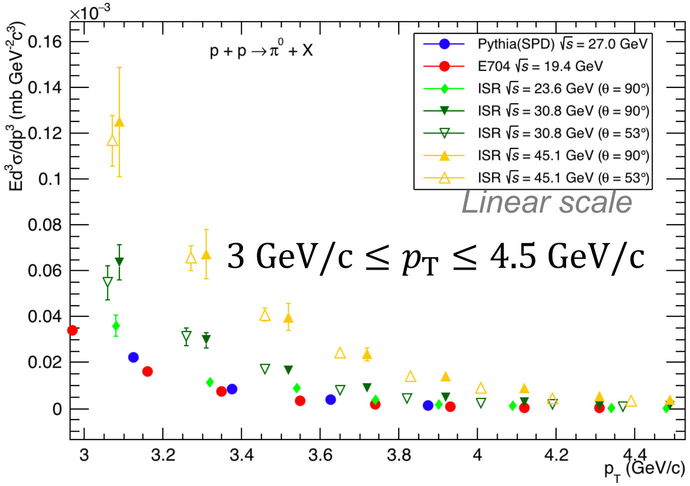
Linear scale

$0.5 \text{ GeV/c} \le p_T \le 2 \text{ GeV/c}$



Linear scale

$1.5 \text{ GeV/c} \le p_T \le 3 \text{ GeV/c}$



Linear scale

$3 \text{ GeV/c} \le p_T \le 4.5 \text{ GeV/c}$

Historical overview

Measurement of $p + p \rightarrow \pi^0 + X$ and $p + \bar{p} \rightarrow \pi^0 + X$

Accelerator	Beam	Experiment	Paper year	$\sqrt{s}$ [GeV]	p_T [GeV/c]	Kinematic region	Observables
(CERN) ISR	$p + p$	Eggert et al.	1975	23.6 - 62.9	0.5 – 7.6		
		CCRS	1975	23.5 – 62.4	2.5 – 7.5		
		R806	1979	30.6 – 62.4	3 - 10		
		R807	1983	63	4.8 – 11.4		
(CERN) SPS	fixed p	NA24	1987	23.7	1.3 – 6.0		
		WA70	1988	22.9	4.0 – 6.5		
		UA6	1998	24.3	4.1 – 7.7		
(CERN) Sp$\bar{p}$S	$p + \bar{p}$	UA2	1982	540	1.5 – 4.4		
(FNAL) proton synchrotron	$p + p$	E268	1976	13.6 – 19.4	1.0 – 5.0		
	$\bar{p} + p$ (fixed)	E704	1996	19.4	2.5 – 4.1		
(FNAL) Tevatron	fixed p	E706	2003	31.5, 38.7	1 - 10		
RHIC	$p + p$	PHENIX	2003	200	1 - 14	$\lvert\eta\rvert < 0.35$	σ_{incl}
	$p + p$		2004	200	> 1	$3.4 < \eta < 4.0$	σ_{incl}, A_N
	$p + p$		2005	200	1 - 5	$\lvert\eta\rvert < 0.35$	σ_{incl}, A_N
	$p + p$		2006	200	1 - 5	$\lvert\eta\rvert < 0.35$	A_{LL}
	$p + p$		2007	200	0.5 - 20	$\lvert\eta\rvert < 0.35$	σ_{incl}, A_{LL}
	$p + p$		2009	200	1 - 12	$\lvert\eta\rvert < 0.35$	ΔG from A_{LL}
	$p + p$		2009	62.4	1 - 4	$\lvert\eta\rvert < 0.35$	σ_{incl}, A_{LL}

Historical overview

Measurement of $p + p \to \pi^0 + X$ and $p + \bar{p} \to \pi^0 + X$

Accelerator	Beam	Experiment	Paper year	$\sqrt{s}$ [GeV]	Kinematic region p_T [GeV/c]		Observables
					$\boldsymbol{p}_{\mathbf{T}}$ [GeV/c], $\boldsymbol{x}_{\mathbf{F}}$, η		
RHIC	$p + p$	STAR	2003	200	$1 < p_{\mathrm{T}} < 14$	$\lvert\eta\rvert < 0.35$	σ_{incl}
	$p + p$		2003	200	$1 < p_{\mathrm{T}} < 3$ $0.2 < x_{\mathrm{F}} < 0.6$	*forward*	A_N
	$p + p$		2007	200	$3 < p_{\mathrm{T}} < 11$, $p_{\mathrm{T}} < 3$	$0.1 < \eta < 0.9$	A_{LL}
	$p + p$		2008	200	$1.2 < p_{\mathrm{T}} < 4$, $0.3 < x_{\mathrm{F}} < 0.6$	$\eta \approx 3.7$	A_N
	$p + p$		2009	200	$p_{\mathrm{T}} > 1$, $x_{\mathrm{F}} > 0.2$	$2.5 < \eta < 4$	A_N
	$p + p$		2009	200	$1 < p_{\mathrm{T}} < 3.5$, $x_{\mathrm{F}} > 0.4$	$\eta \approx -4.1$	A_N
	$p + p$		2009	200	$3.7 < p_{\mathrm{T}} < 11$	$0 < \eta < 1$	σ_{incl}, A_{LL}
	$p + p$		2010	200	$0.35 < p_{\mathrm{T}} < 10$	$0 < \eta < 1$	σ_{incl}
	$p + p$		2014	200	$0.4 < x_{\mathrm{F}} < 0.75$	$\eta \approx 3.68$	σ_{incl}, A_N
	$p + p$		2014	200	$5 < p_{\mathrm{T}} < 12$	$0.8 < \eta < 2$	σ_{incl}, A_N
	$p + p$		2014	500	$2 < p_{\mathrm{T}} < 10$	$2.6 < \eta < 4.2$	A_N
	$p + p$		2016	510	$2 < p_{\mathrm{T}} < 10$	$2.6 < \eta < 4$	Δg from A_{LL}
	$p^{\uparrow} + p \to p\pi^0 X$		2019	200	$1 < p_{\mathrm{T}} < 4$	$2.65 < \eta < 3.9$	A_N