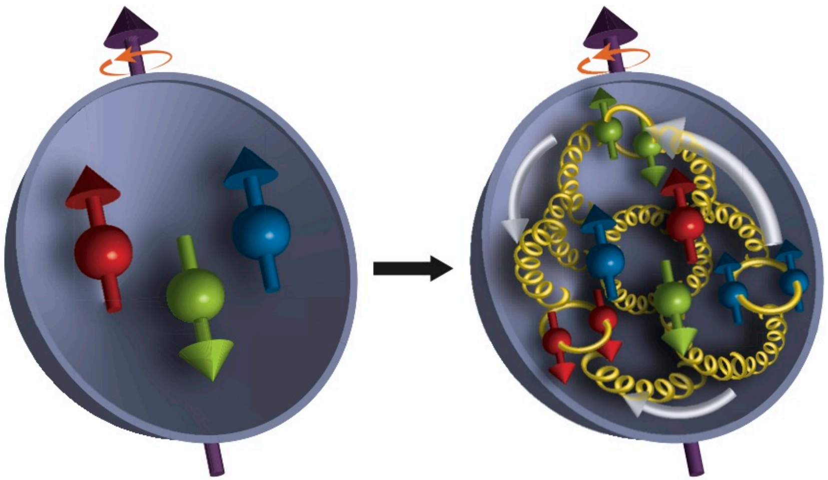
Inclusive $pp \to \pi^0 X$ measurement for the SPD physics program



The nucleon spin carried only by quarks:

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma$$

Quark contribution to the spin:

$$\Delta\Sigma \sim 0.20 - 0.30$$

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

$\frac{1}{2}\Delta\Sigma + \Delta G$: Quark and gluon spin components

$L_q + L_g$: Orbital angular momenta of quarks and gluons

$$\Delta G = \int \Delta g(x) dx$$ (x: gluon momentum fraction)

ΔG → A key ingredient in the proton helicity sum rule

Gluon contribution to the nucleon spin might be greater than the contribution from quarks.

Advantages of π^0 measurements in $p + p \rightarrow \pi^0 + X$ collisions:

- easily identified by reconstructing the invariant mass of decay photons:

  $m_{\pi^0} = 135\ \text{MeV},\ \pi^0 \rightarrow \gamma\gamma$ (98.8%).

- large statistics

π^0 for polarization:

- Inclusive π^0 production can be used for polarimetry purposes in the energy range covered by SPD.

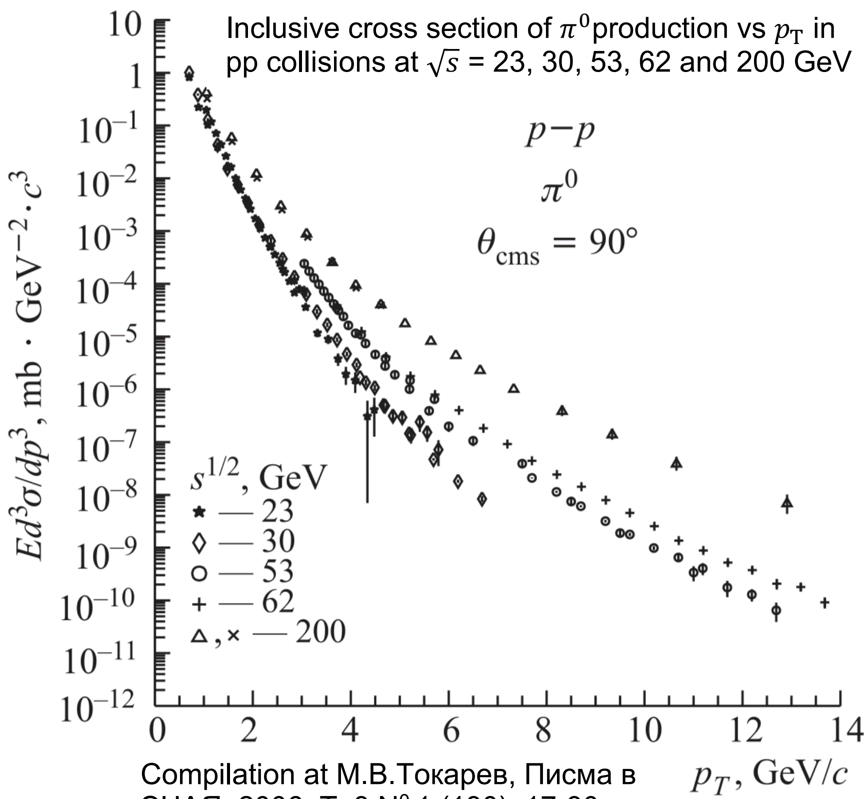
- The Single Spin Asymmetry (SSA) is a measure of the beam polarization in the intersection point. The sign is related to the polarization of the valence quarks of pions.

π^0 for physics:

- Phenomenology of SSA in inclusive processes

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

Inclusive cross section of π^0 production vs p_T in pp collisions at $\sqrt{s}$ = 23, 30, 53, 62 and 200 GeV

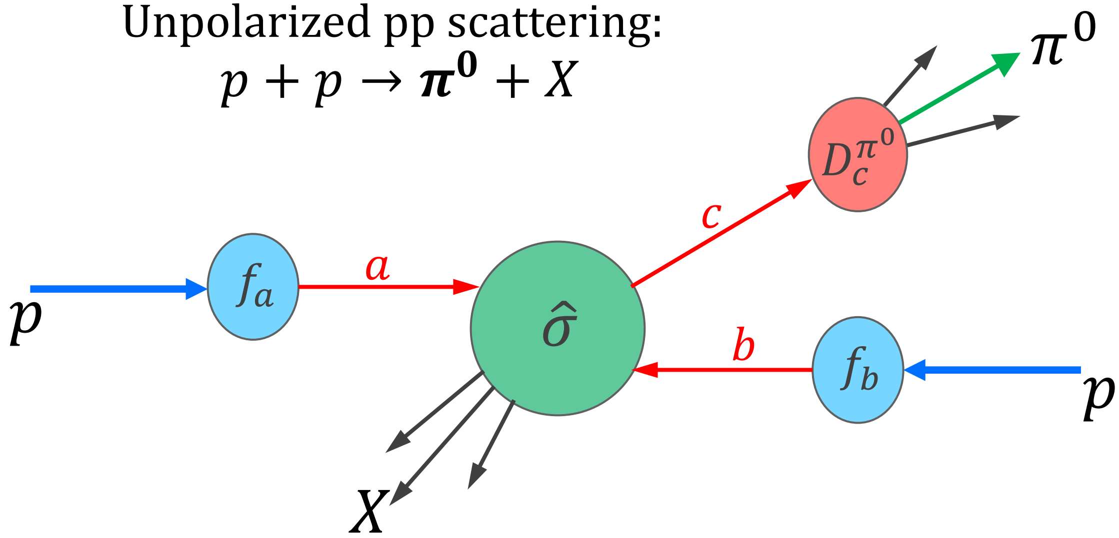


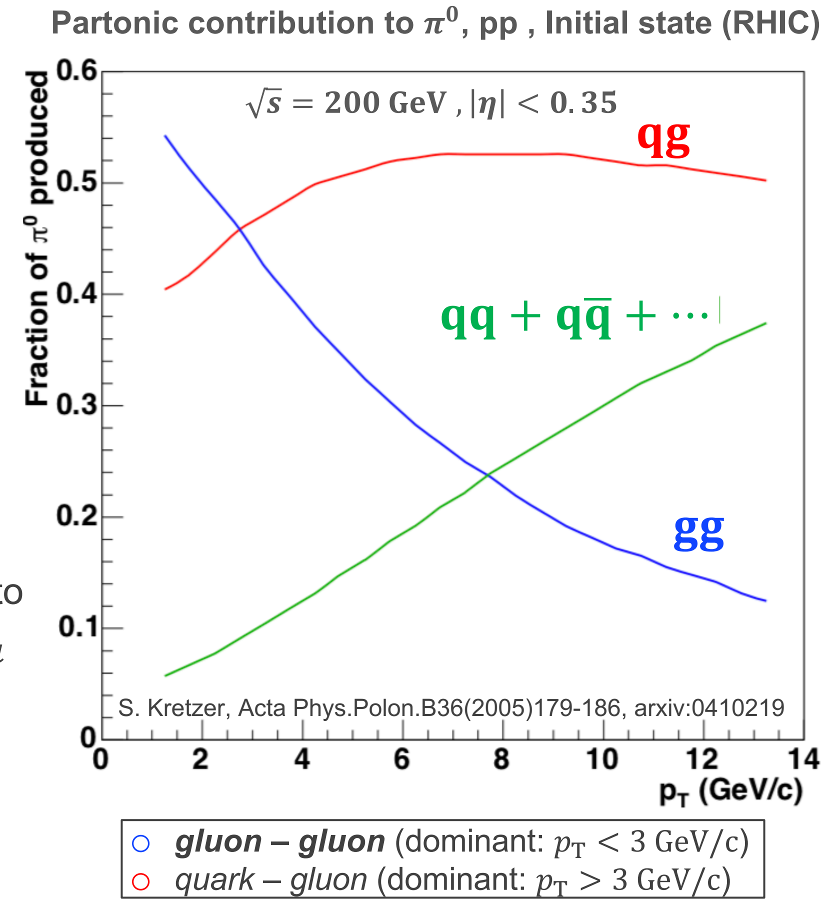
Compilation at М.В.Токарев, Писма в ЭЧАЯ. 2006. Т. 3 N⁰ 1 (130), 17-30

- The low SPD center of mass energy ($\sqrt{s} = 27\ GeV$), compared to that from STAR ($\sqrt{s} = 200\ GeV$) allows to probe a higher *x* region.

Unpolarized pp scattering:

$$p + p \rightarrow \boldsymbol{\pi^0} + X$$





The cross section of large momentum-transfer reactions may be factorized into long- and short-distance contributions, Depending on the factorization scale $\boldsymbol{\mu}$

Soft processes → long; **Hard** processes → short

Depending on the factorization scale $\boldsymbol{\mu}$.
The parton with $\boldsymbol{p_T} < \boldsymbol{\mu}$ is considered part of the initial or final hadron structure

$$d\sigma = \sum_{a,b,c} \int dx_a \int dx_b \int dz_c \cdot \underbrace{f_a(x_a,\mu) f_b(x_b,\mu)}_{\text{PDF}} \cdot \underbrace{d\hat{\sigma}^{ab\rightarrow c}\left(x_a P_A, x_b P_B, P_{\pi^0}/z_c, \mu\right)}_{\text{Underlying pQCD elementary interactions (partonic cross sections)}} \cdot \underbrace{D_{\pi^0/c}(z_c,\mu)}_{\text{FF}}$$

PDF

Underlying ***pQCD*** elementary interactions (partonic cross sections)

FF

PDF, FF: Sensitive to non-perturbative physics (info. about the nucleon structure)

$$d\hat{\sigma}^{ab\rightarrow c} = d\hat{\sigma}^{(0)} + \frac{\alpha_s}{\pi^0} d\hat{\sigma}^{(1)} + \cdots$$

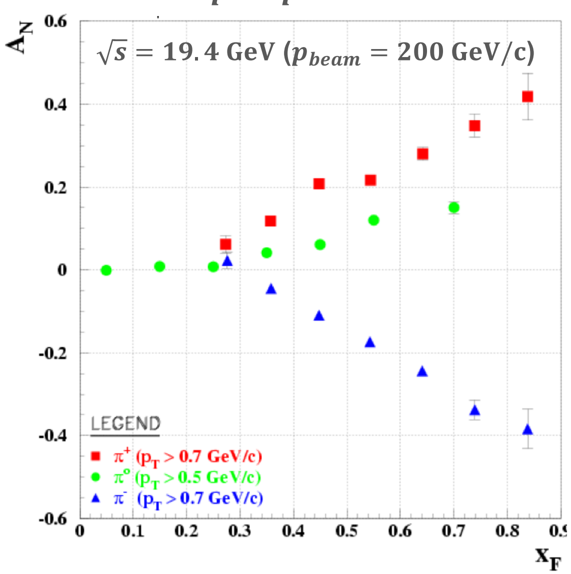
Transverse SSA for inclusive π^0 production in pp interactions

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

$$A_{\rm N}^{\pi^0} = \frac{d\Delta\sigma}{d\sigma} = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} \xrightarrow{\text{experimentally}} A_{\rm N}^{\pi^0} = \frac{1}{P}\frac{(N^{+} - LN^{-})}{(N^{+} + LN^{-})}$$

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

$p^{\uparrow} + p \rightarrow \pi + X$



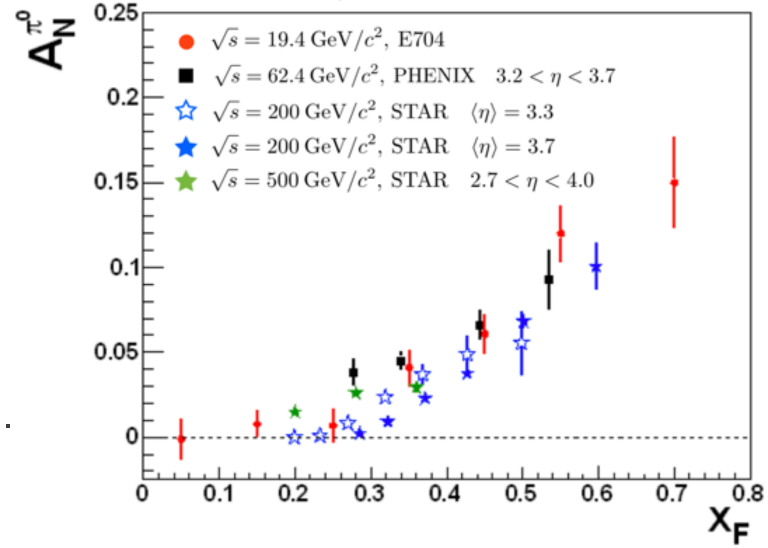
E704: Adams et al. Phsy. Lett. B264(1991)462

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

$A_{\rm N}$ becomes large for large values of x_1.
- positive effect for π^+(u quarks)
- negative effect for π^-(d quarks)

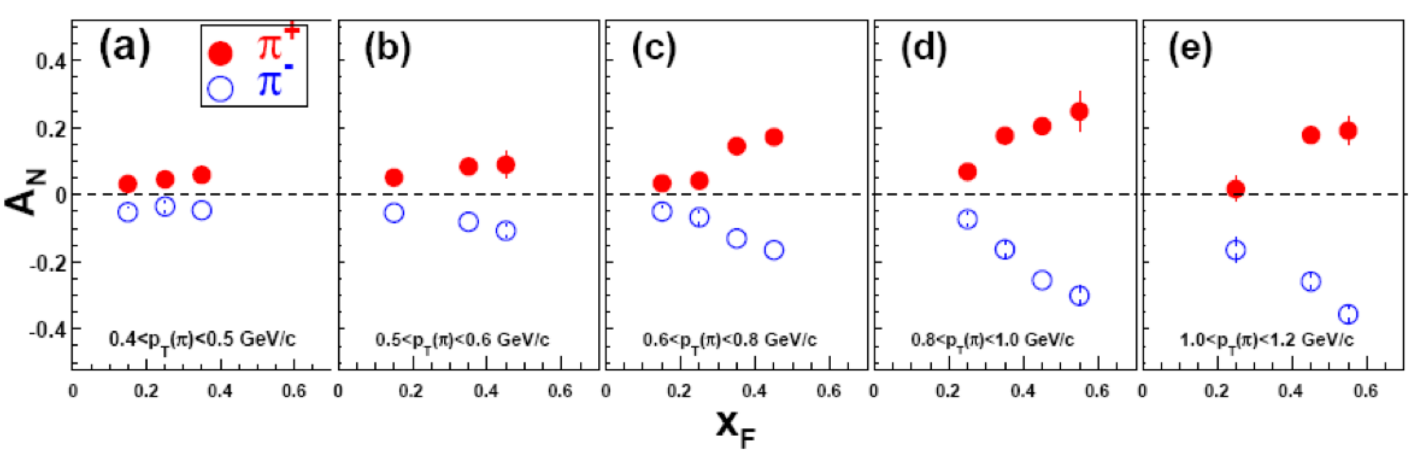
$$x_{\rm F} = \frac{2p_L}{\sqrt{s}} \sim x_1 - x_2$$

$A_{\rm N}$ 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.

$\sqrt{s}$ = **62.4 GeV**, RHIC BRAHMS Coll., Phys.Rev.Lett.101:042001,2008



Transverse SSA for inclusive π^0 production in pp interactions

Approaches to describe the underlying physics of the transverse *SSA*:

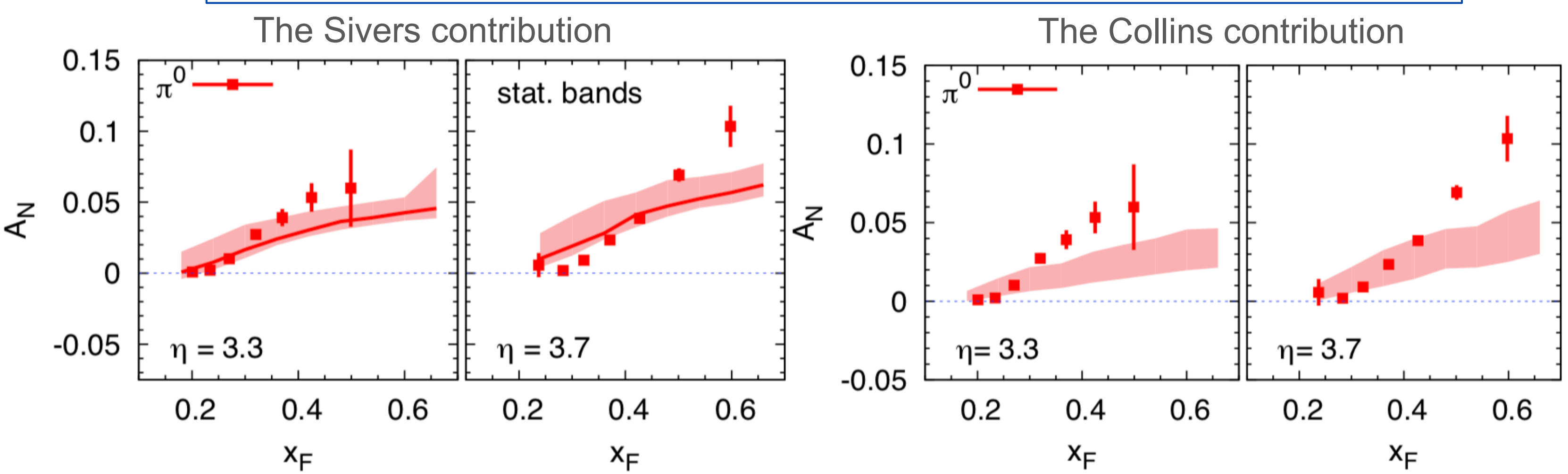
- "twist-3" approach
  - Collinear QCD factorization scheme
  - Single scale processes (p_T)
  - Quark – gluon – quark correlations (PDF)
  - Hadronization processes (FF)

- GPM
  - Phenomenological generalization of the parton model
  - Two-scale processes (p_T and Q, $p_T \ll$ Q)
  - Transverse momentum dependent distribution functions added to the factorization scheme:
    - TMD PDFs ← Sivers effect
    - TMD FF ← Collins effect

    Difficult to disentangle for $pp \rightarrow \pi X$. Both, in principle, may contribute to A_N

Results showed in the review arXiv: 1512.05379 (2015)

The GPM scheme compared with STAR data ($\sqrt{s}$ = 200 GeV) at two rapidities

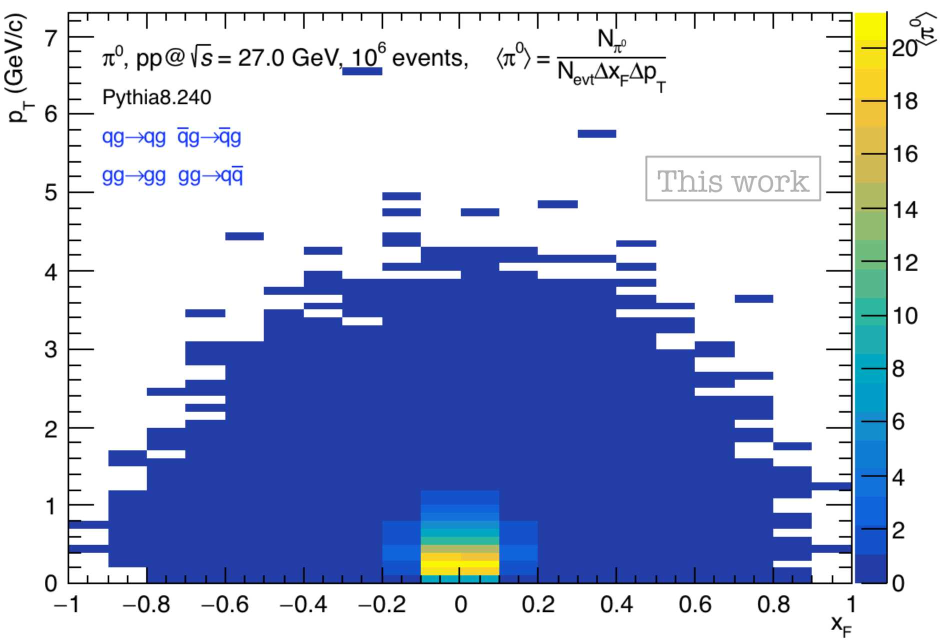


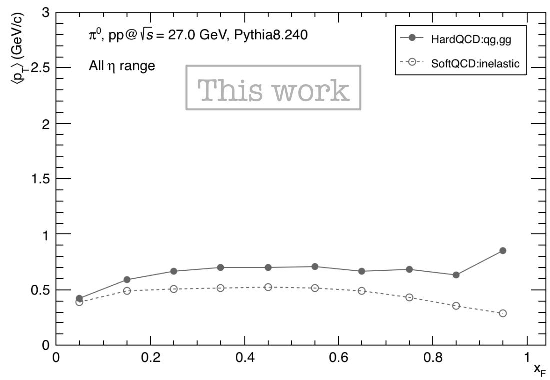
- Sivers functions extracted from SIDIS.
- The SIDIS data give high uncertainties at large x_F

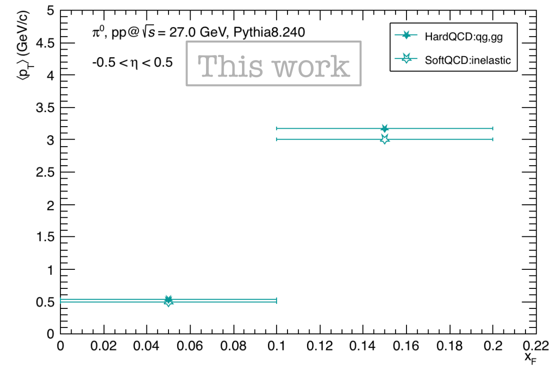
- Sivers effect alone could be able to describe the data, while Collins underestimates the large x_F data
- However, a significant portion of the sizeable inclusive pion asymmetries at forward rapidities is due to a twist-3 piece in the fragmentation, without a counterpart in the TMD sector (not shown here)

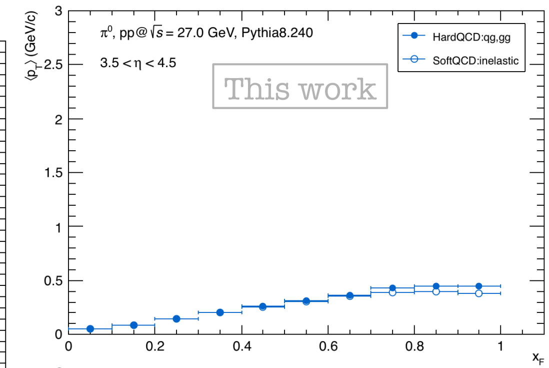
Good measurements of A_N *vs* x_F and A_N *vs* p_T may help to differentiate among the models.

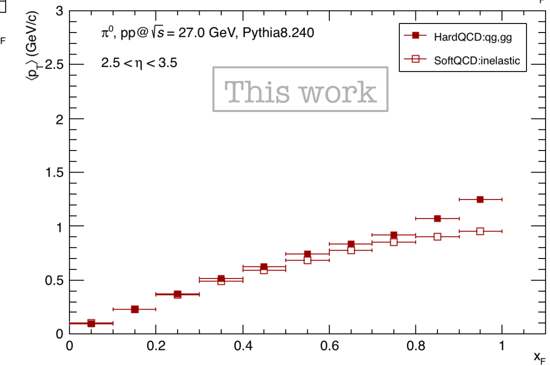
Phase space p_T vs x_F for inclusive $pp \to \pi^0 X$ @ $\sqrt{s} = 27$ GeV

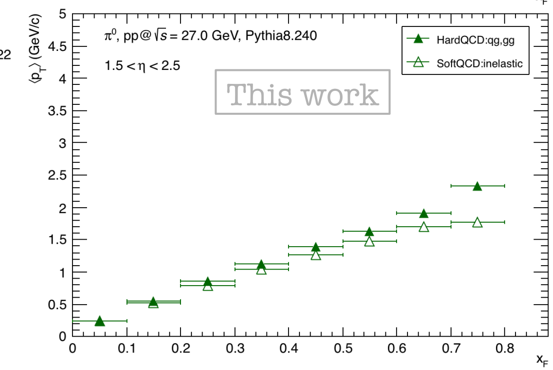


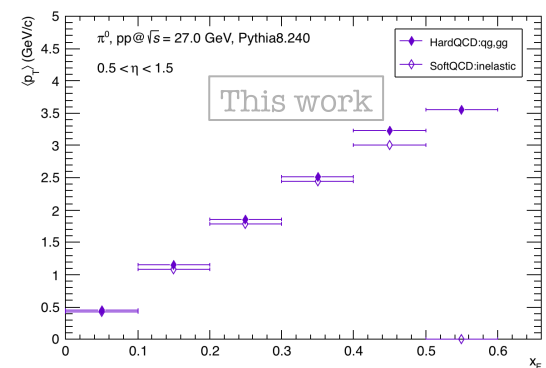


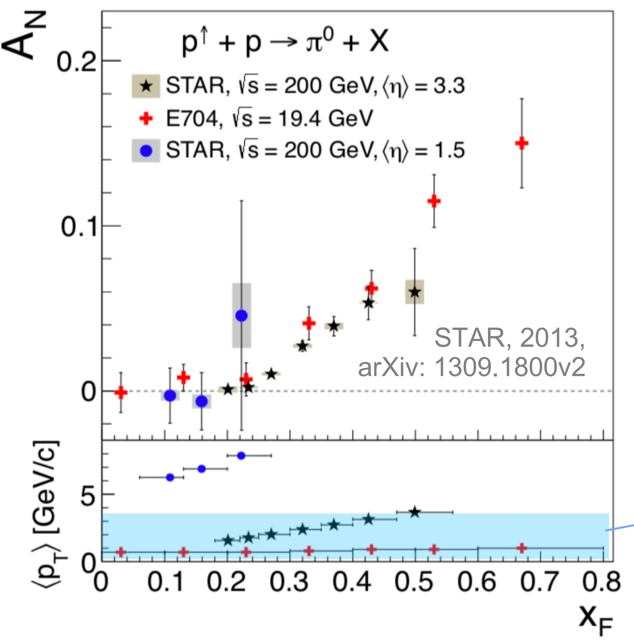






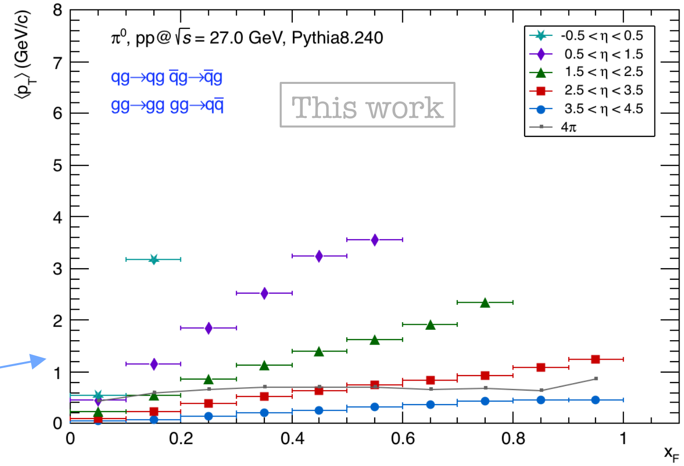






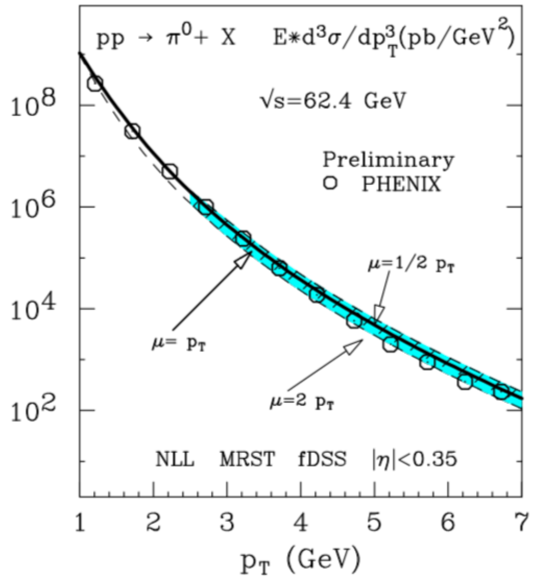
$$x_F = \frac{2p_L}{\sqrt{s}}$$

Monte Carlo, SPD $\sqrt{s} = 27$ GeV



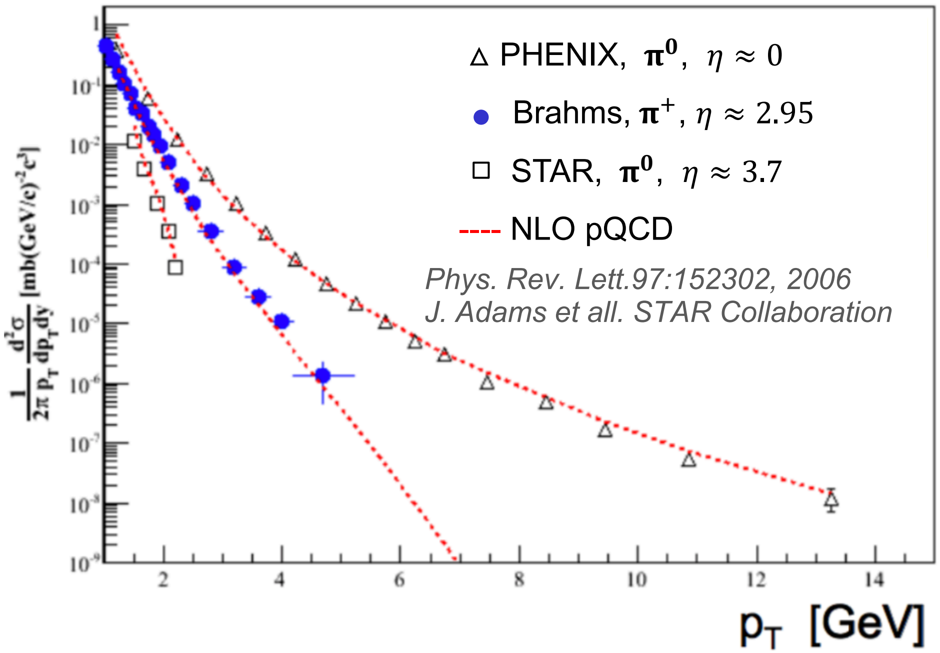
NLO pQCD Cross Sections vs data from RHIC

Phenix, p + p @ $\sqrt{s} = 62.4$ GeV



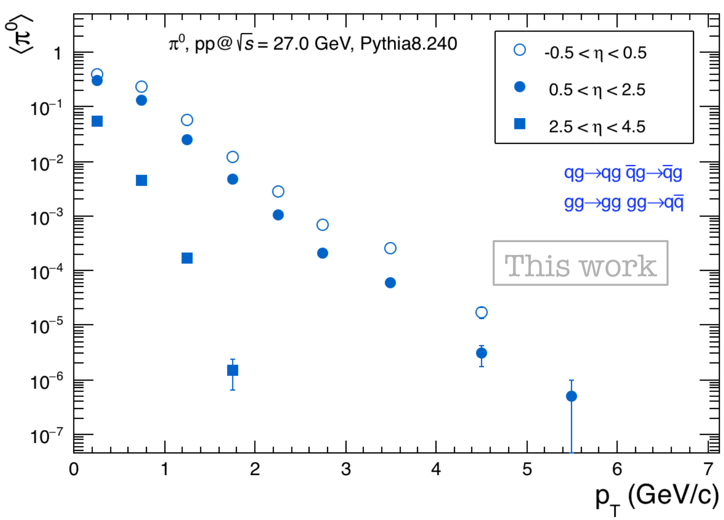
Phys. Rev. D76:094021, 2007
D. de Florian, W. Vogelsang, F. Wagner

RHIC, p + p @ $\sqrt{s} = 200$ GeV

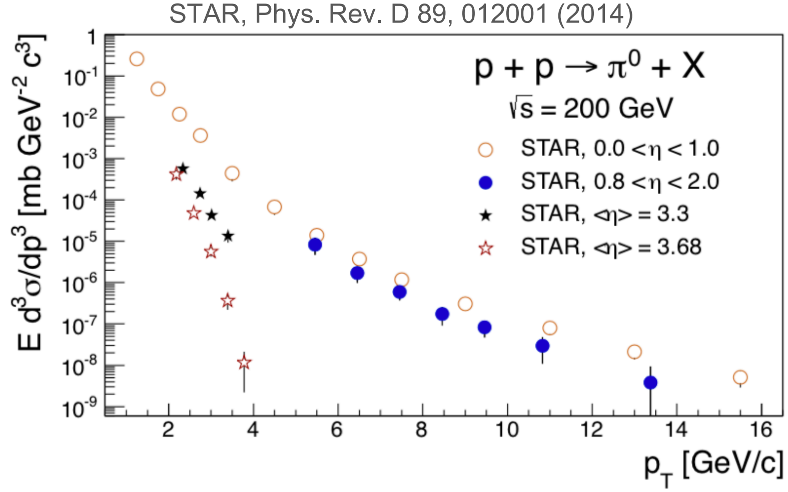


Perturbative predictions (NLO pQCD) of the inclusive cross section describe the data!

Monte Carlo, SPD $\sqrt{s} = 27$ GeV



STAR, Phys. Rev. D 89, 012001 (2014)



Double helicity asymmetry of inclusive π^0 from pp collisions

Double helicity asymmetry: $A_{LL}^{\pi^0}$

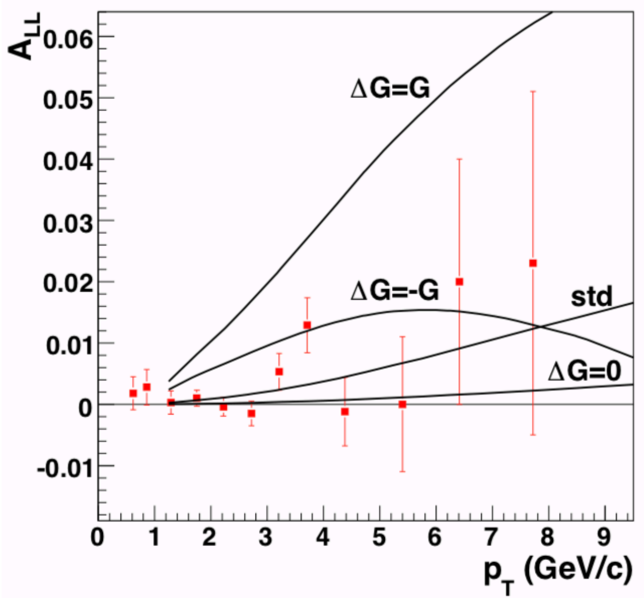
$$A_{LL}^{\pi^0} = \frac{d\Delta\sigma}{d\sigma} = \frac{d\sigma^{++} - d\sigma^{+-}}{d\sigma^{++} + d\sigma^{+-}}$$

experimentally

$$A_{\mathrm{LL}}^{\pi^0} = \frac{1}{P_1 P_2} \frac{(N_{++} + N_{--}) - (N_{+-} + N_{-+})}{(N_{++} + N_{--}) + (N_{+-} + N_{-+})}$$

- is a promising tool to determine the spin-dependent gluon density in the nucleon.
- Sensitive to Δg through the contributions from polarized quark-gluon and gluon-gluon scatterings.

The “low” SPD center of mass energy ($\sqrt{s} = 27$ GeV), compared to that from STAR ($\sqrt{s} = 200$ GeV) allows to probe a higher *x* region.



The double helicity is only relevant for pT > 2 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$\bar{\text{p}}$S	$p+\bar{p}$	UA2	1982	540	1.5 – 4.4		
(FNAL) proton synchrotron	$p+p$ $\bar{p}+p$ (fixed)	E268	1976	13.6 – 19.4	1.0 – 5.0		
		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 $p+p \rightarrow \pi^0 + X$ and $p+\bar{p} \rightarrow \pi^0 + X$ ($\eta \approx 0$)

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

Tunes depending on the
selected QCD processes

HardQCD:qg2qg $qg \to qg$ $\bar{q}g \to \bar{q}g$

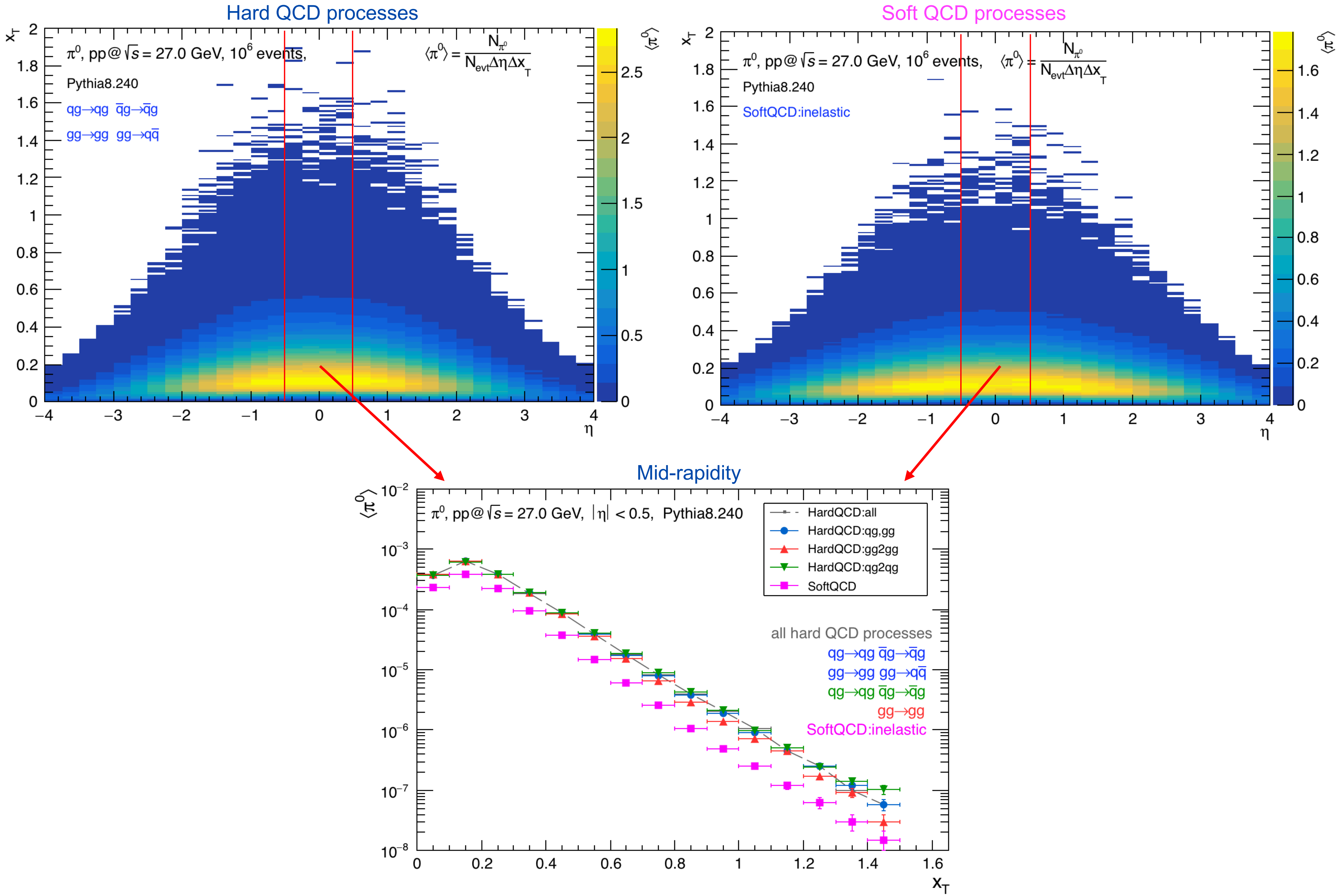
HardQCD:gg2qqbar $gg \to q\bar{q}$

HardQCD:gg2gg $gg \to gg$

SoftQCD:inelastic

BACKUPS

Pythia 8.240



Hard QCD processes
π^0, pp@$\sqrt{s}$ = 27.0 GeV, 10^6 events,
Pythia8.240
qg→qg q̄g→q̄g
gg→gg gg→qq̄
$\langle\pi^0\rangle = \frac{N_{\pi^0}}{N_{evt}\Delta\eta\Delta x_T}$
x_T
η
Soft QCD processes
π^0, pp@$\sqrt{s}$ = 27.0 GeV, 10^6 events,
Pythia8.240
SoftQCD:inelastic
$\langle\pi^0\rangle = \frac{N_{\pi^0}}{N_{evt}\Delta\eta\Delta x_T}$
Mid-rapidity
π^0, pp@$\sqrt{s}$ = 27.0 GeV, $|\eta| < 0.5$, Pythia8.240
HardQCD:all
HardQCD:qg,gg
HardQCD:gg2gg
HardQCD:qg2qg
SoftQCD
all hard QCD processes
qg→qg q̄g→q̄g
gg→gg gg→qq̄
qg→qg q̄g→q̄g
gg→gg
SoftQCD:inelastic
$\langle\pi^0\rangle$
x_T