Neutron A_N in pp and pA

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RBRC Workshop: Emerging Spin and Transverse Momentum Effects in p+p and p+A Collisions

2016-02-10 @ BNL

Content

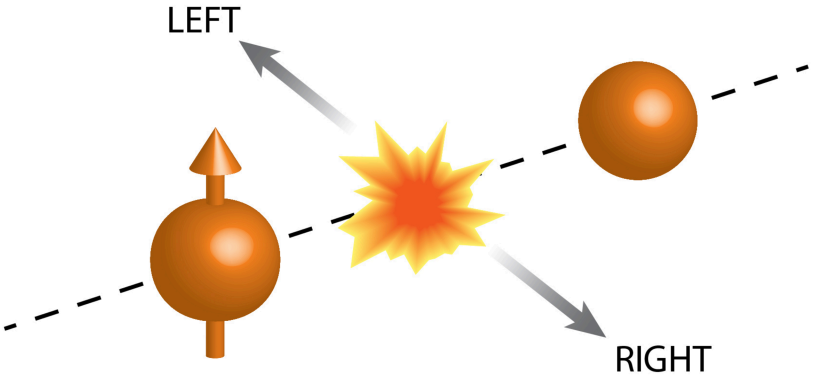
- $\boldsymbol{A_N}$ definition
- PHENIX Forward Neutron Measurement

- $\boldsymbol{A_N}$ for $\mathbf{p}^{\uparrow} + \mathbf{p} \rightarrow \mathbf{n} + \mathbf{X}$
  - Result
  - Theory

- $\boldsymbol{A_N}$ for $\mathbf{p}^{\uparrow} + \mathbf{A} \rightarrow \mathbf{n} + \mathbf{X}$ in Run15
  - Result
  - Discussions

Single Transverse Spin Asymmetry A_N

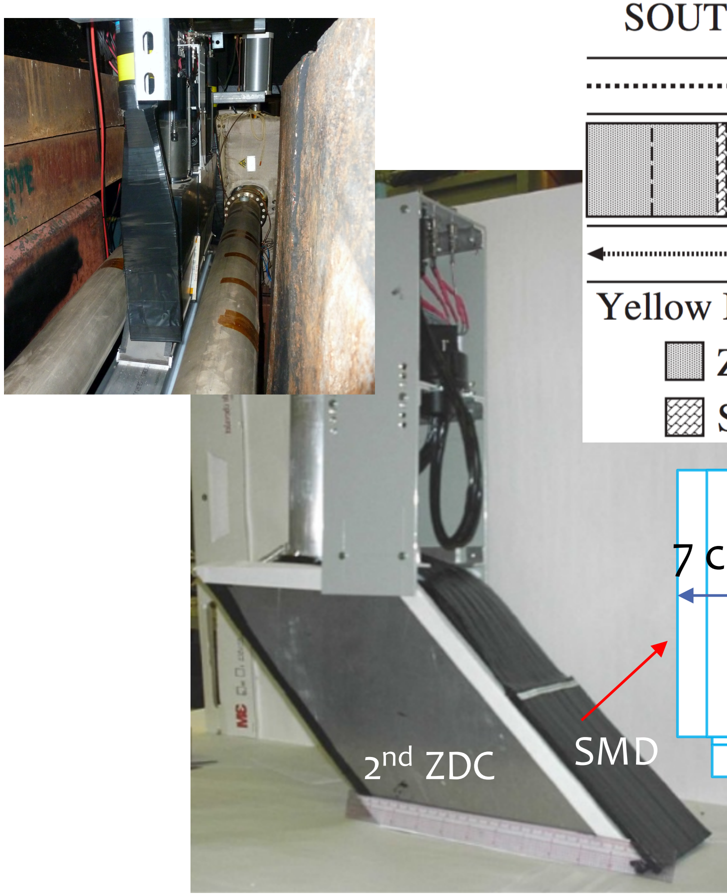
$$A_N \equiv \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

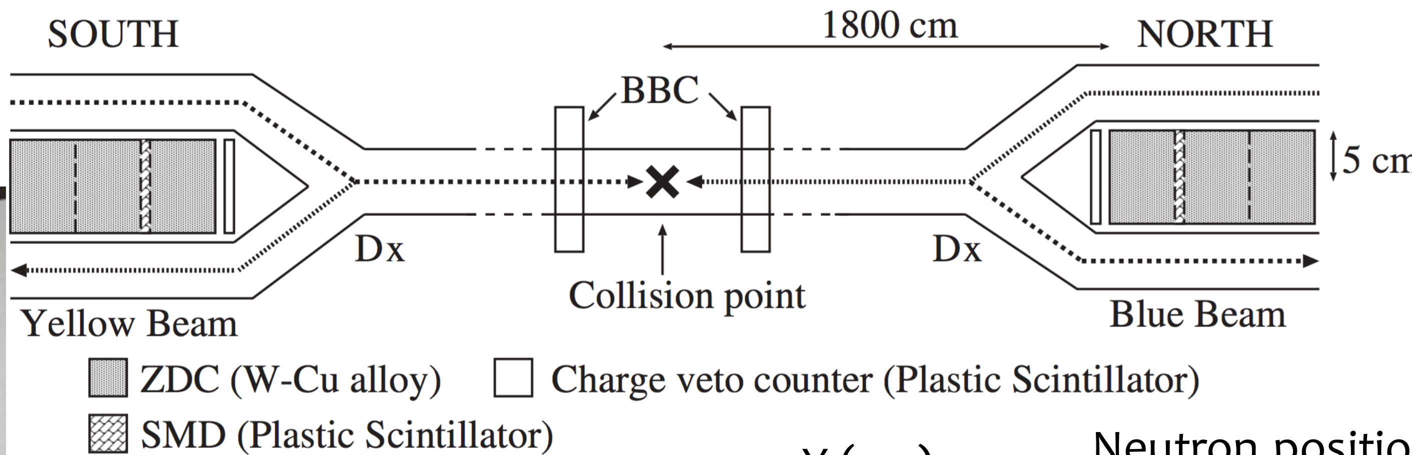


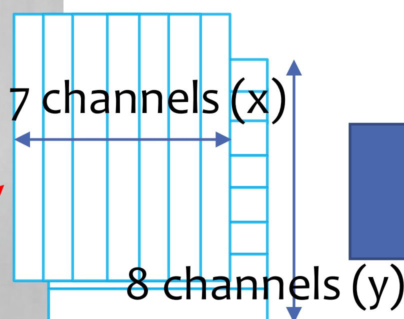
Also,

$$A_N = \frac{\sigma_L^{\uparrow} - \sigma_L^{\downarrow}}{\sigma_L^{\uparrow} + \sigma_L^{\downarrow}} = \frac{\sigma_R^{\downarrow} - \sigma_R^{\uparrow}}{\sigma_R^{\downarrow} + \sigma_R^{\uparrow}} = \frac{\sigma_L^{\uparrow} - \sigma_R^{\uparrow}}{\sigma_L^{\uparrow} + \sigma_R^{\uparrow}} = \frac{\sqrt{\sigma_L^{\uparrow}\sigma_R^{\downarrow}} - \sqrt{\sigma_L^{\downarrow}\sigma_R^{\uparrow}}}{\sqrt{\sigma_L^{\uparrow}\sigma_R^{\downarrow}} + \sqrt{\sigma_L^{\downarrow}\sigma_R^{\uparrow}}}$$

PHENIX Forward Neutron Detector

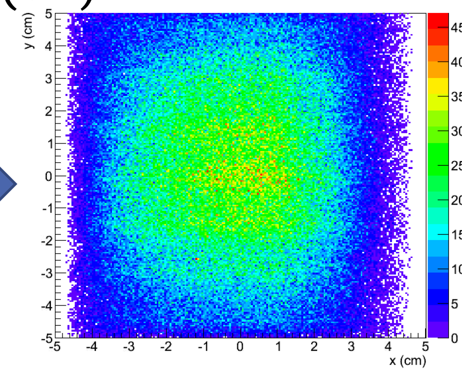






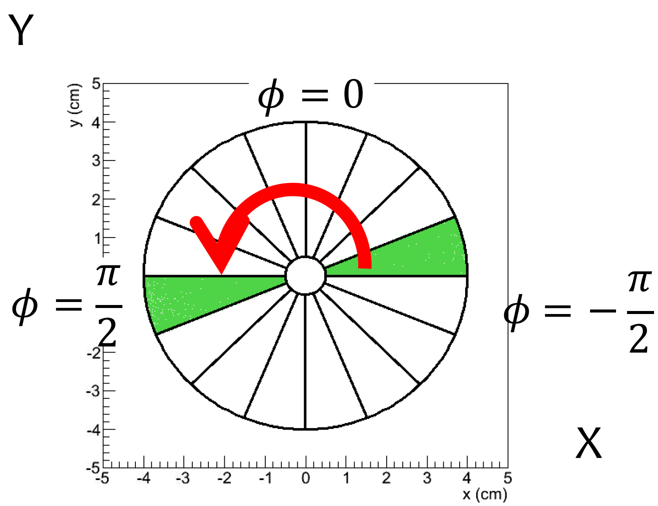
Centroid of shower

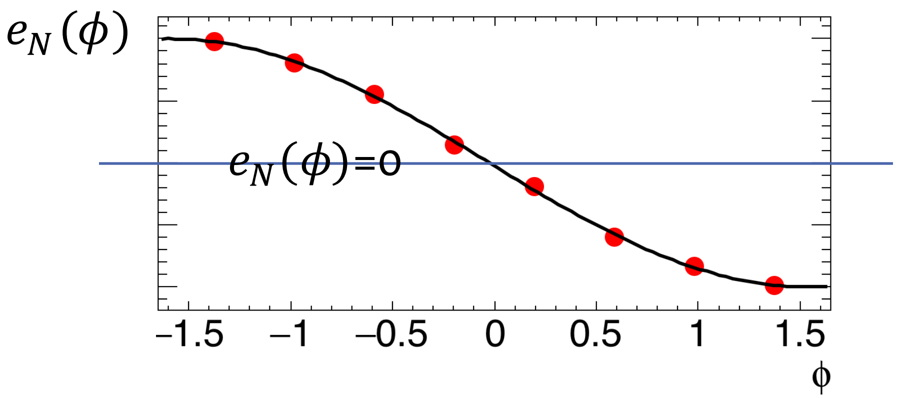
Neutron position



10 cm x 10 cm

A_N Measurement





$$A_N = \frac{\sqrt{\sigma_L^{\uparrow}\sigma_R^{\downarrow}} - \sqrt{\sigma_L^{\downarrow}\sigma_R^{\uparrow}}}{\sqrt{\sigma_L^{\uparrow}\sigma_R^{\downarrow}} + \sqrt{\sigma_L^{\downarrow}\sigma_R^{\uparrow}}}$$

$$e_N(\phi) \equiv \frac{\sqrt{N_\phi^{\uparrow}N_{\pi-\phi}^{\downarrow}} - \sqrt{N_\phi^{\downarrow}N_{\pi-\phi}^{\uparrow}}}{\sqrt{N_\phi^{\uparrow}N_{\pi-\phi}^{\downarrow}} + \sqrt{N_\phi^{\downarrow}N_{\pi-\phi}^{\uparrow}}}$$

$$A_N = \frac{e_N(\phi)}{\sin(\phi - \phi_0)} \frac{1}{C_{\phi(correction)}} \frac{1}{P}$$

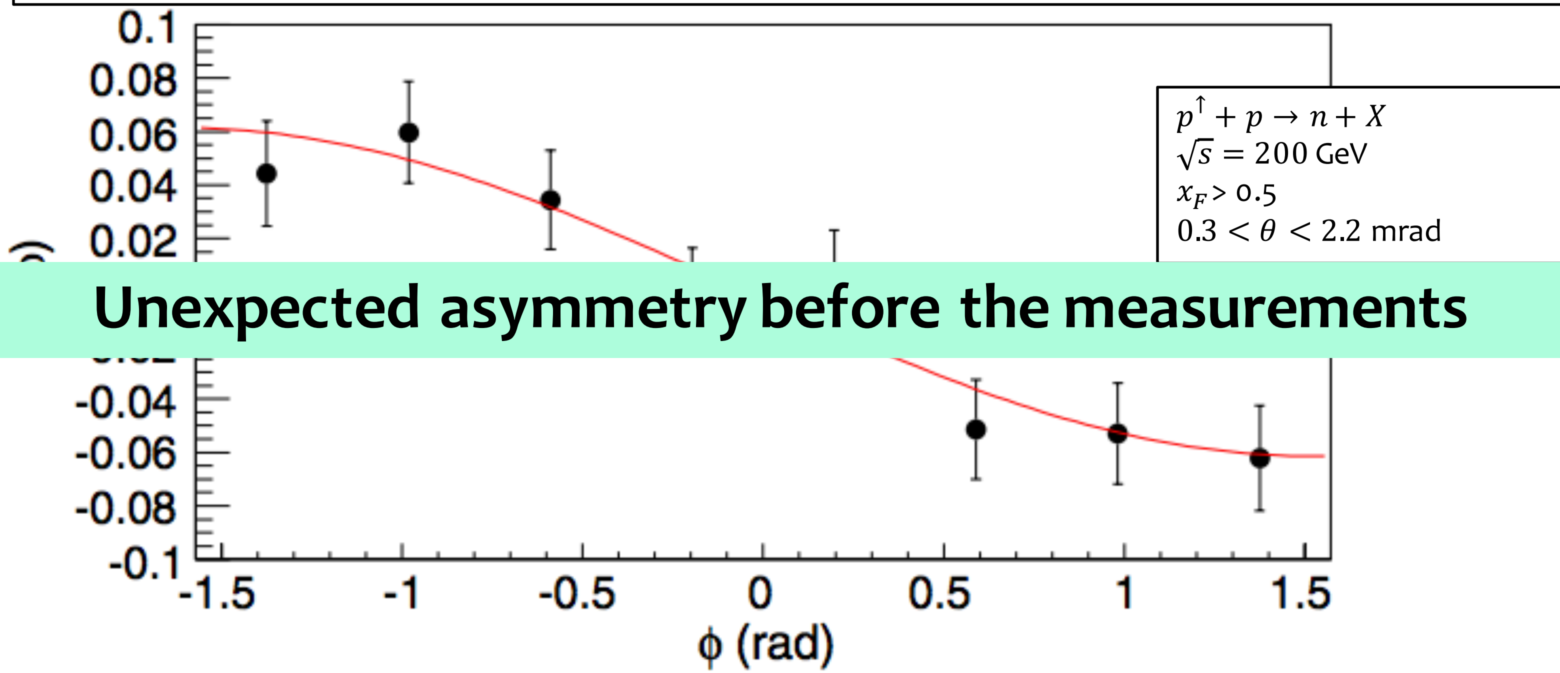
$$A_N \quad p^{\uparrow} + p \rightarrow n + X$$

HIGH ENERGY POLARIZED PROTON-PROTON COLLISIONS

$A_N^{p^{\uparrow}+p\rightarrow n+X}$ Measured

- **Discovered @ RHIC IP12 experiment (2002)**
- **Measured @ PHENIX with dedicated neutron detectors (2006)**

Published: PRD 88, 032006 (2013)

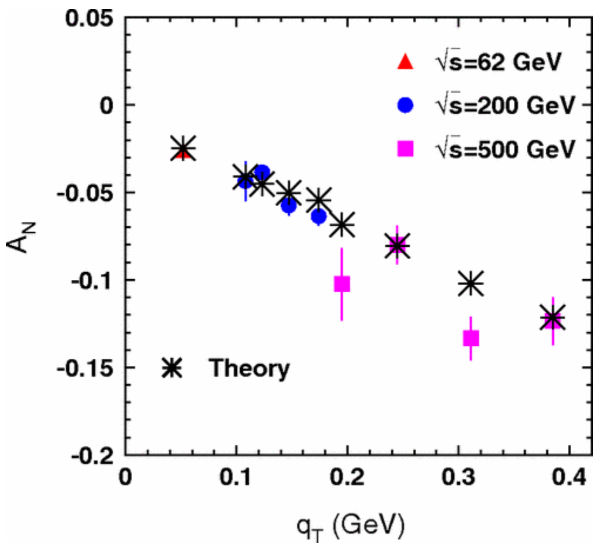


Unexpected asymmetry before the measurements

$p + p \rightarrow n + X$ Theory & PHENIX Data

$-t \lesssim 0.5 \frac{\mathrm{GeV}^2}{\mathrm{c}^2}$ at ZDC (for 200 GeV, pQCD not applicable)

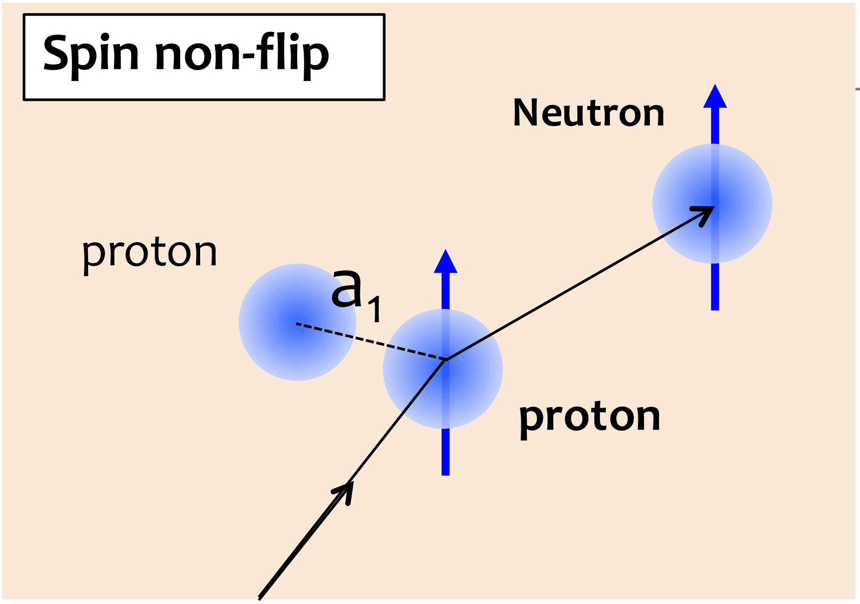
There are theories to describe cross-section, and A_N of very forward neutron production **: One Pion Exchange model in Regge framework explain pp collision data well.**

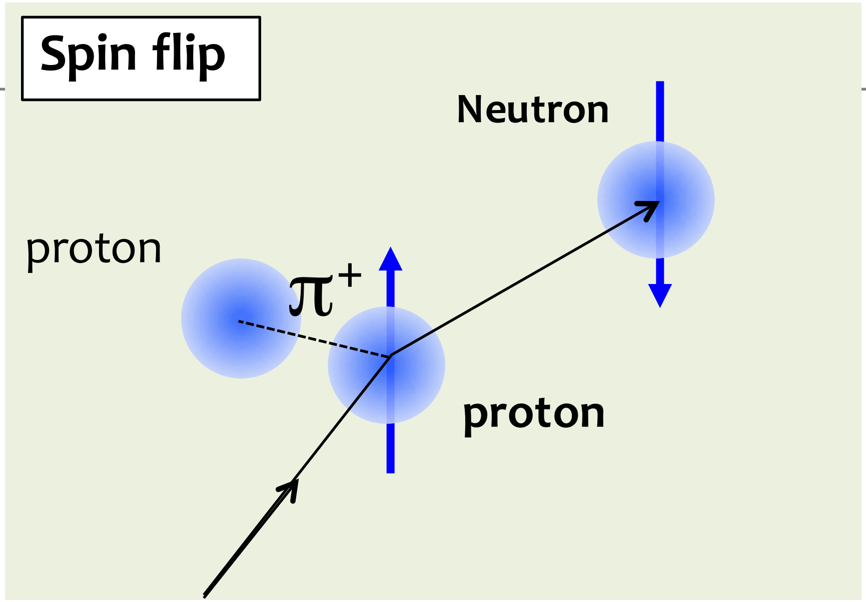


PRD **84**, 114012 (2011)

A_N for PHENIX $p^{\uparrow} + p \rightarrow n + X$ data & Theory

$p^{\uparrow}p$ Forward Neutron A_N





$$A_N \approx \frac{2\,\mathrm{Im}\left(\phi^{*}_{non-flip}\,\phi_{flip}\,\sin\delta\right)}{\left|\phi_{non-flip}\right|^2 + \left|\phi_{flip}\right|^2}$$

δ : phase shift

Theoretical Development

PRD **84**, 114012 (2011)

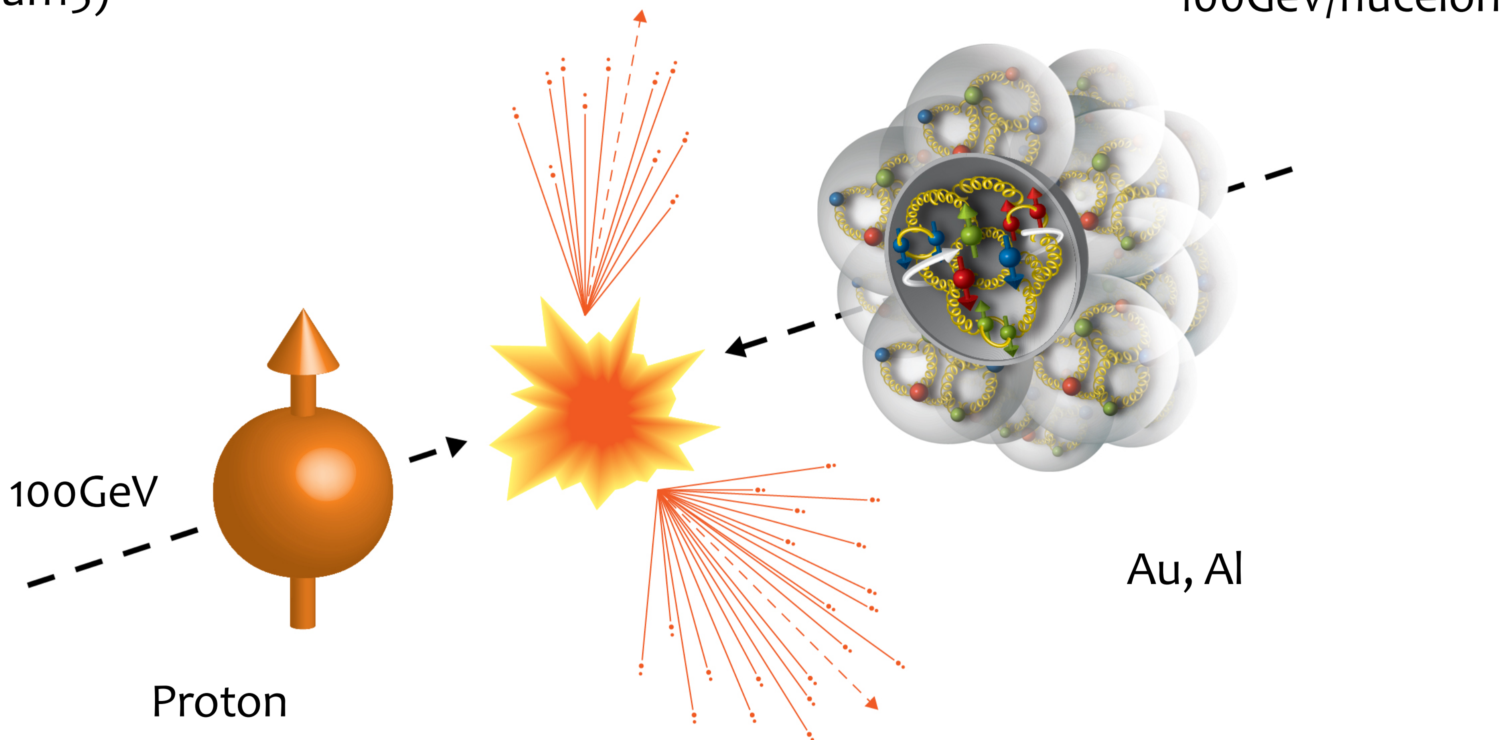
Approach	Cross section description	A_N description	Details
1. One π exchange with Born approximation	△	✗	• π pole $\frac{1}{m_\pi^2 - t}$ at exchange amplitude -> cross section peak at $x_F \cong 0.8$ • Overshoots cross section • $A_N = 0$: No phase shift with Born Approx.
2. One π exchange with absorptive correction	○	△	• Survival probability multiplied to final state function -> suppressed cross section • $A_N \neq 0$, but too small
3. <u>π exchange + Interference btw π and a_1 Reggeon</u>	○	○	• Interference btw π and a_1 makes large A_N • a_1 form factor is not known. A model is applied for this calculation.

$$A_N^{p^\uparrow + A \rightarrow n + X}$$

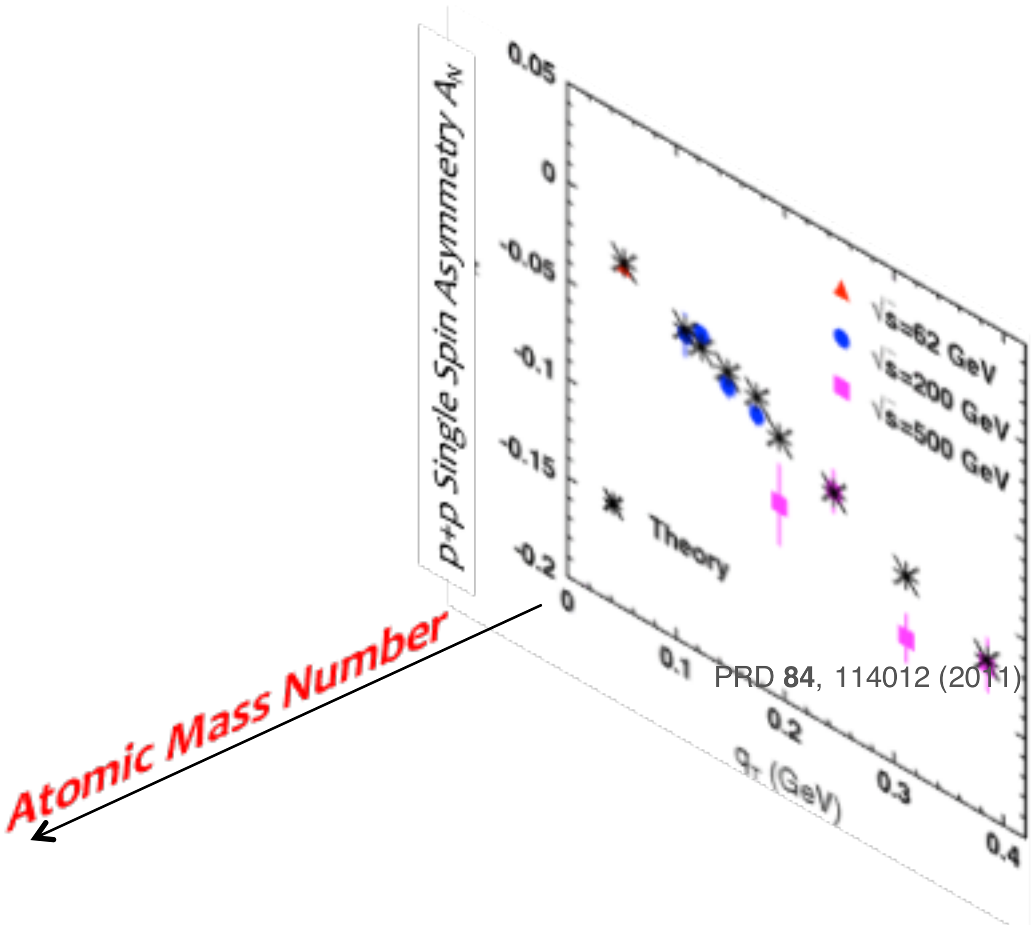
HIGH ENERGY POLARIZED PROTON-NUCLEUS COLLISIONS

The First Attempt to Measure Asymmetries in pA Collision

2015 (Run15)



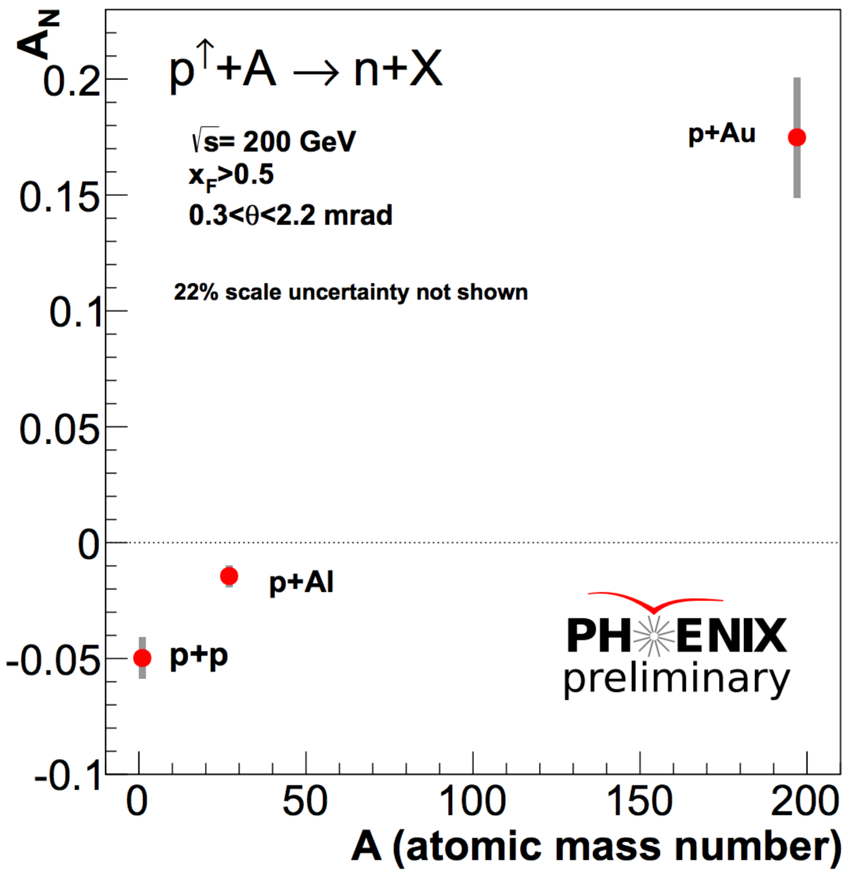
Atomic Mass Dependence



PRD **84**, 114012 (2011)

The first attempt in Run15 (2015) at RHIC.

$A_N^{p^{\uparrow}+A \to n+X}$ PHENIX result



Result from Run15:

- p+p, p+Al, p+Au @ $\sqrt{s} = 200$ GeV
- Unexpectedly strong A dependence!

Theory:

- Observed asymmetries cannot be explained by current framework, which successfully describes p+p results
- Something else is going on

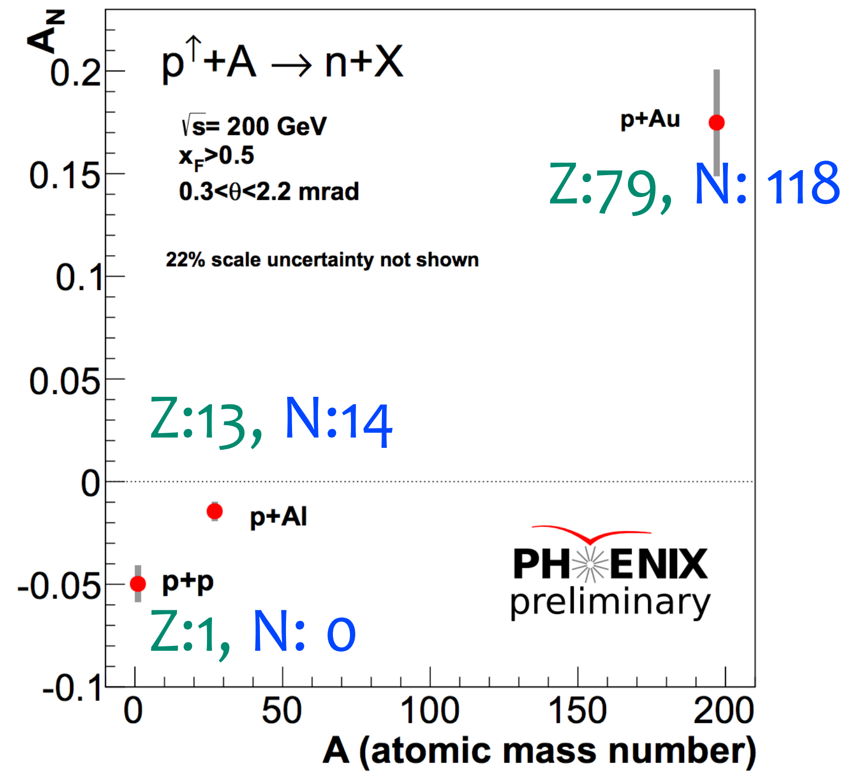
Ideas for A dependence

Naïve expectation

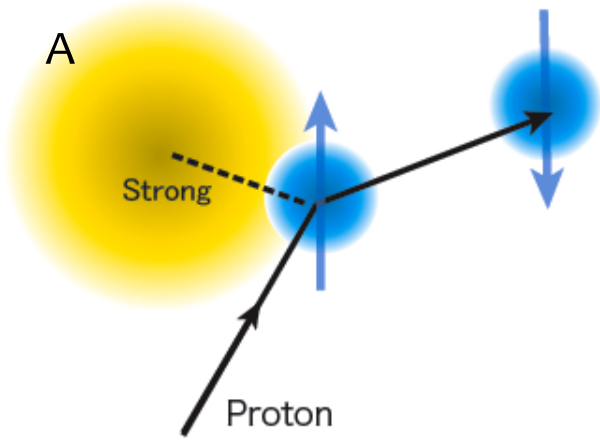
$$A_N^{p^\uparrow+p\to n+X} \neq A_N^{p^\uparrow+n\to n+X} \quad ??$$

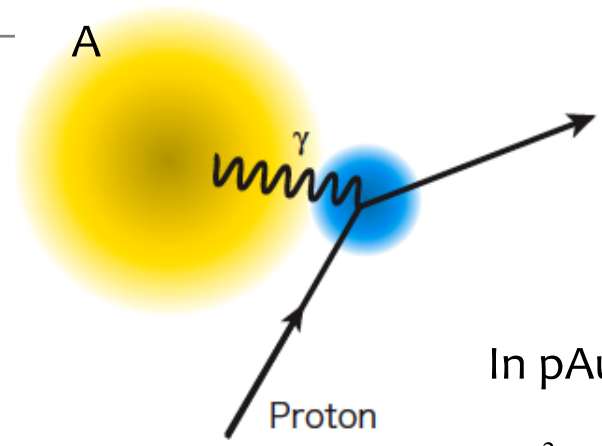
$$A_N^{p^\uparrow+p\to n+X} = -A_N^{p^\uparrow+n\to n+X} \quad ??$$

Isospin Asymmetry?



QED Process
Ultra Peripheral Collision (UPC)

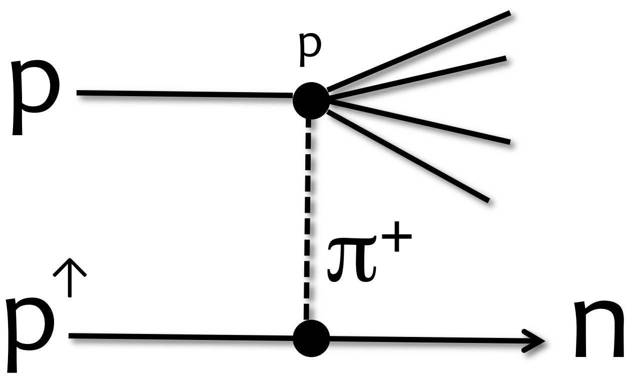


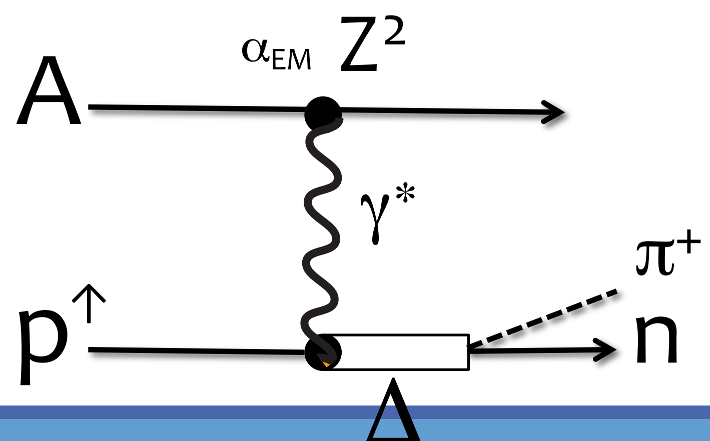


$t \rightarrow 0$

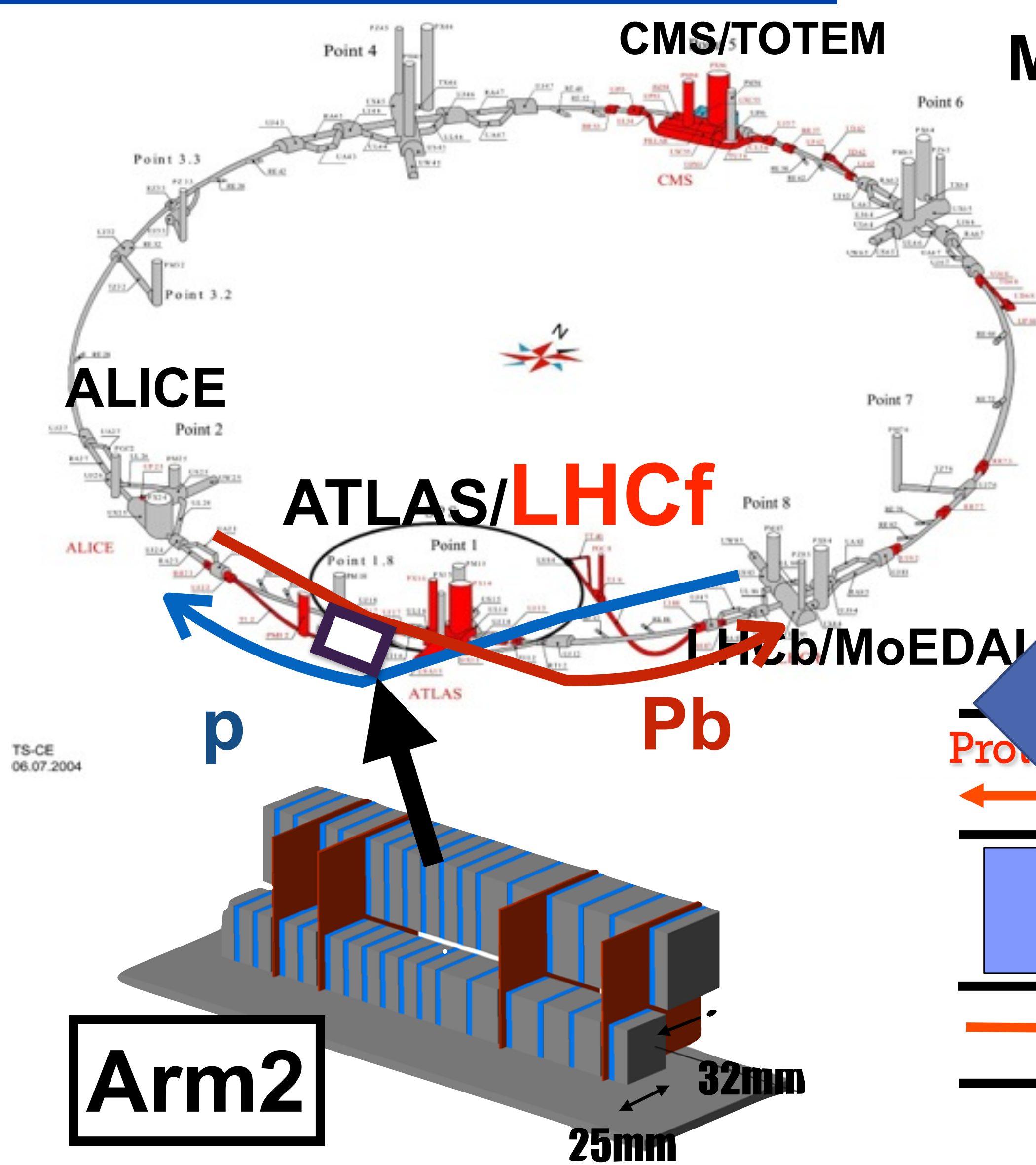
In pAu case

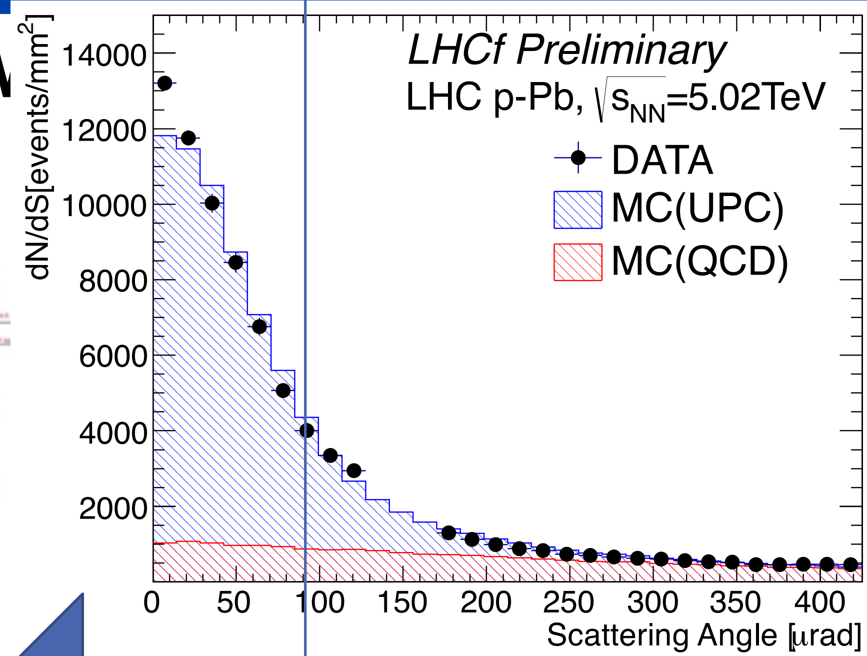
$$Z^2 \bullet \alpha_{EM} \sim 79^2/137 \sim 45$$

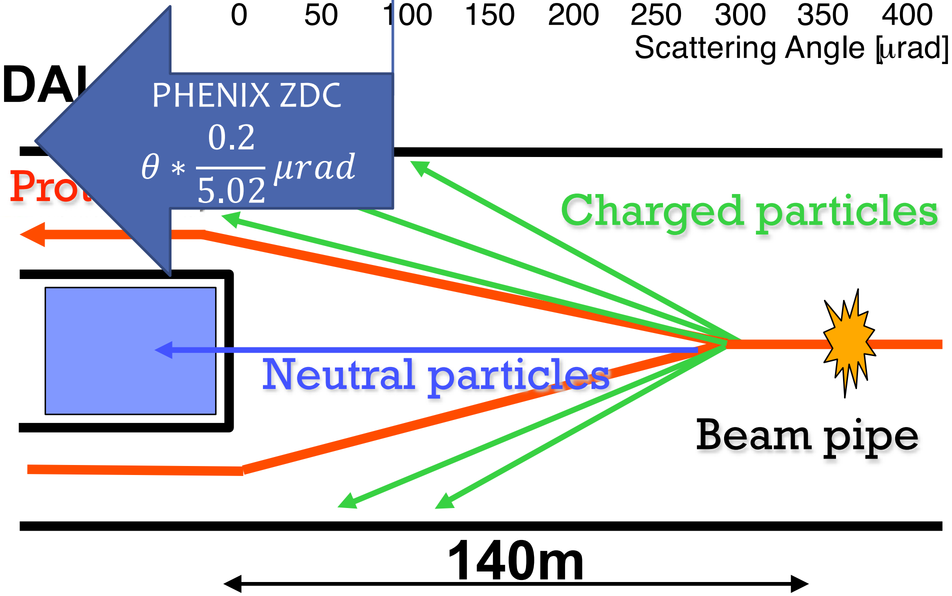




The LHCf experiment







UPC Monte Carlo

Eur. Phys. J. C (2015) 75:614
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Special Article - Tools for Experiment and Theory

Forward hadron production in ultra-peripheral proton–heavy-ion collisions at the LHC and RHIC

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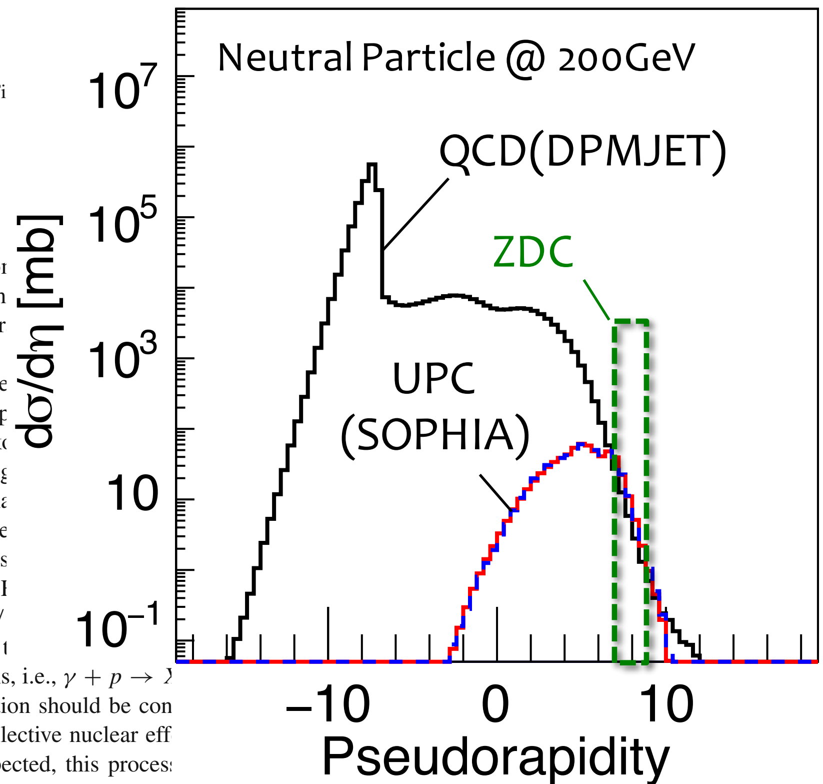
Abstract We present a hadron production study in the forward rapidity region in ultra-peripheral proton–lead ($p+\mathrm{Pb}$) collisions at the LHC and proton–gold ($p+\mathrm{Au}$) collisions at RHIC. The present paper is based on the Monte Carlo simulations of the interactions of a virtual photon emitted by a fast moving nucleus with a proton beam. The simulation consists of two stages: the STARLIGHT event generator simulates the virtual photon flux, which is then coupled to the SOPHIA, DPMJET, and PYTHIA event generators for the simulation of particle production. According to these Monte Carlo simulations, we find large cross sections for ultra-peripheral collisions particle production, especially in the very forward region. We show the rapidity distributions for charged and neutral particles, and the momentum distributions for neutral pions and neutrons at high rapidities. These processes lead to substantial background contributions to the investigations of collective nuclear effects and spin physics. Finally we propose a general method to distinguish between proton–nucleus ($p+A$) inelastic interactions and ultra-peripheral collisions which implements selection cuts based on charged-particles

virtual photons emitted fro
may anyway interact with
usually referred to as ultr
Ref. [1,2] for a review).
UPCs, so far, have bee
the gluon distribution in p
photoproduction of quark
collisions can probe a hig
density in protons at sma
momentum fraction of the
measurements already exis
tion at the CERN Large I
$p+\mathrm{Pb} \rightarrow p+\mathrm{Pb}+J/$
has been paid, in UPCs, t
photon–proton interactions, i.e., $\gamma+p \rightarrow X$
less such particle production should be con
in the investigation of collective nuclear eff
large cross section is expected, this process
vides significant background events to pure $p+A$ inelastic
interaction events (hereafter "hadronic interaction", unless
peripheral $d+\mathrm{Au}$ collisions [4], which amounted to ~10 %



Predicts comparable yields between QCD and UPC processes

Full Description

$$A_N \propto 2\,\mathrm{Im}\left\{\phi^{*}_{flip}\phi_{non-flip}\sin\delta\right\}$$

$$\phi_{flip} = \phi^{EM}_{flip} + \phi^{had}_{flip}$$

$$\phi_{non-flip} = \phi^{EM}_{non-flip} + \phi^{had}_{non-flip}$$

δ : relative phase of amplitudes

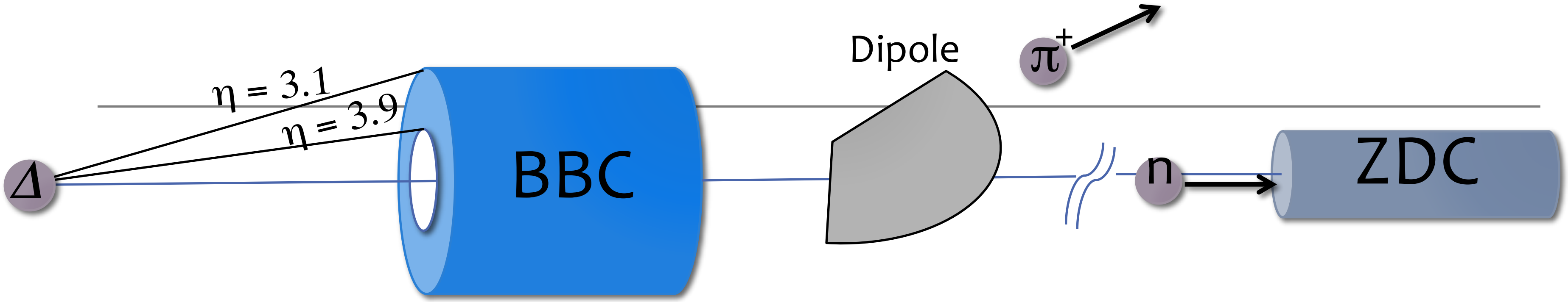
$$A_N \propto 2\,\mathrm{Im}\left(\phi^{EM*}_{flip} + \phi^{had*}_{flip}\right)\left(\phi^{EM}_{non-flip} + \phi^{had}_{non-flip}\right)$$

$$= 2\,\mathrm{Im}\left(\underbrace{\phi^{EM*}_{flip}\phi^{had}_{non-flip}\sin\delta_1 + \phi^{had*}_{flip}\phi^{EM}_{non-flip}\sin\delta_2}_{\text{Elastic (polarimeter)}} + \underbrace{\phi^{EM*}_{flip}\phi^{EM}_{non-flip}\sin\delta_3}_{\Delta^{\uparrow} \rightarrow n + \pi^{+}\ \text{asymmetry?}} + \phi^{had*}_{flip}\phi^{had}_{non-flip}\sin\delta_4\right)$$

For pp:

$$A_N \approx \mathrm{Im}\left(\phi^{had*}_{flip}\phi^{had}_{non-flip}\sin\delta\right) \qquad \phi^{EM} \rightarrow 0$$

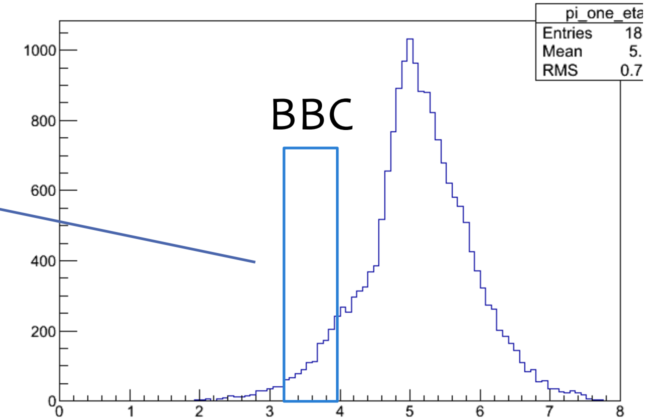
Can we identify UPC events?



Most of decayed pions go through BBC hole and will be swept away by the dipole magnet (DX).

Very little coincidence measurements of final state from resonance.

η_π distribution of $n+\pi^+$ events

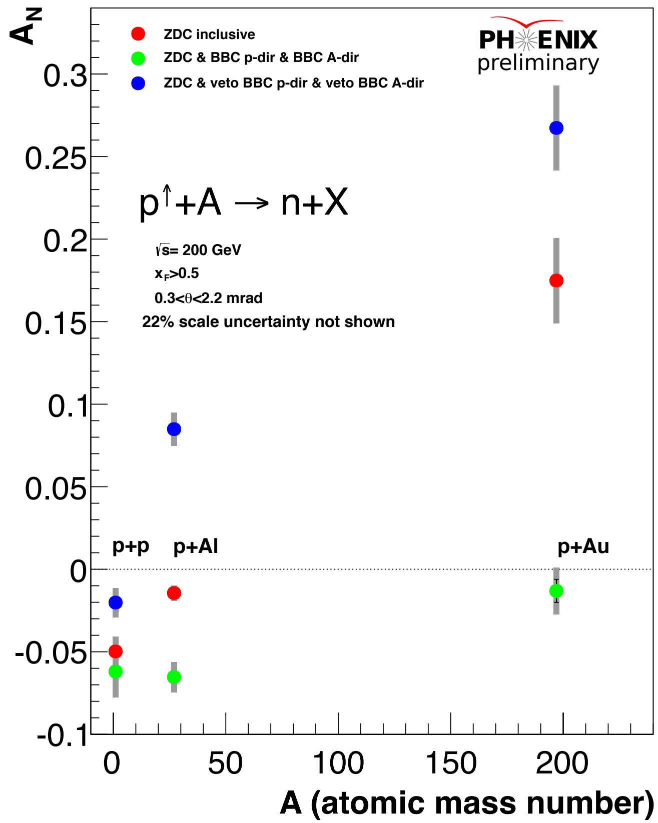


π^+ Rapidity

Simulation by Gaku Mitsuka

Itaru's slide

$A_N^{p^\uparrow + A \rightarrow n + X^{???}}$ BBC correlations

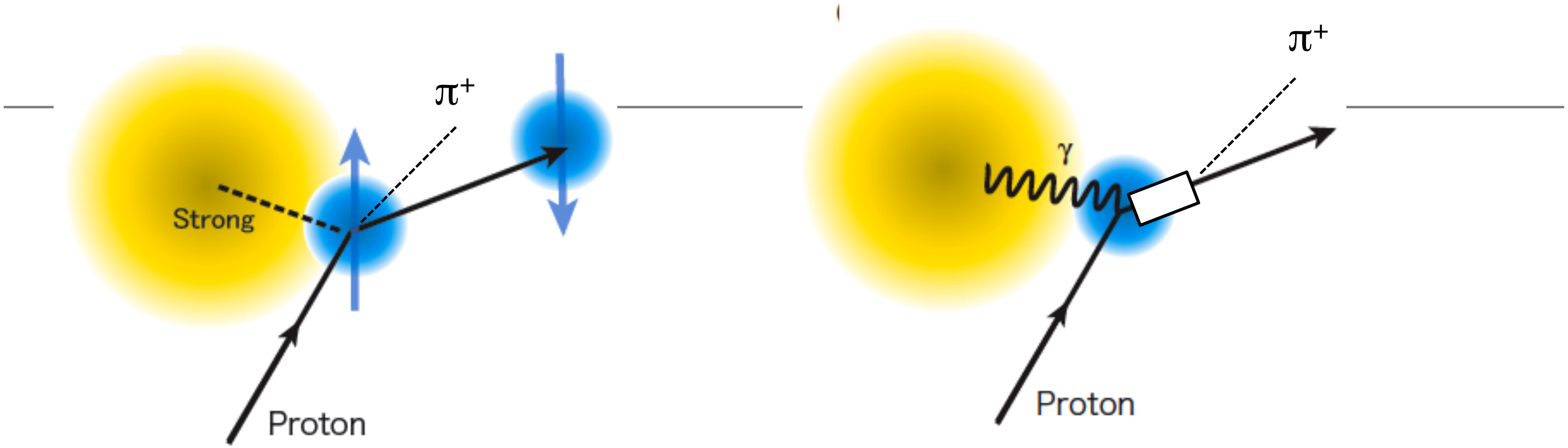


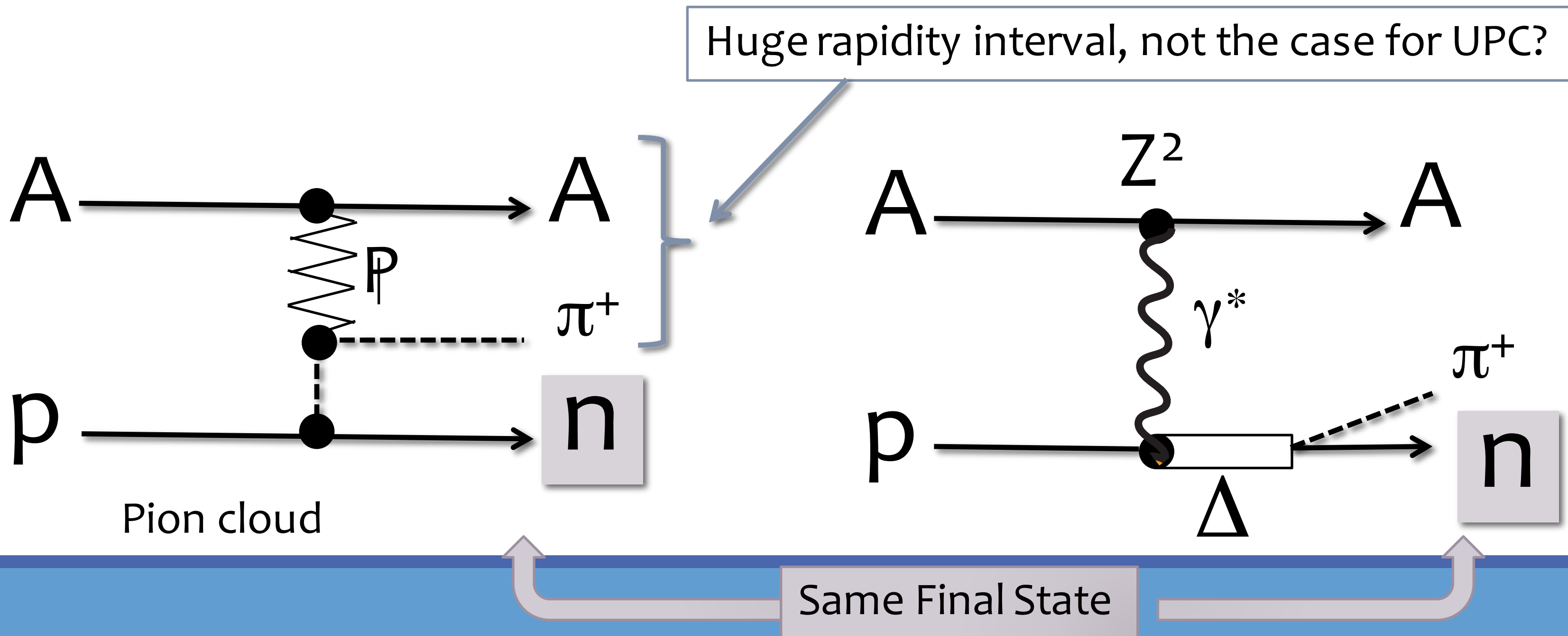
ZDC inslusive

UPC enhanced

UPC suppressed

Coulomb-Nuclear Interference





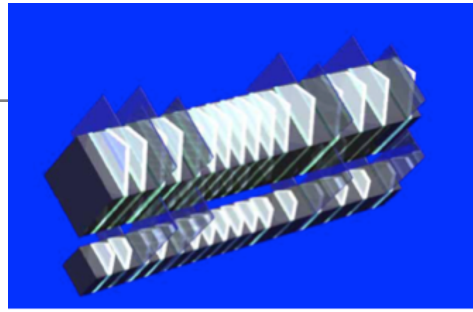
Summary

- A_N of PHENIX $\mathrm{p}^{\uparrow} + \mathrm{p}$ data are well described interference between π and a_1 Reggeon in a OPE model.
- In Run15, forward neutron A_N was measured for $\mathrm{p}^{\uparrow} + \mathrm{p},\ \mathrm{Al},\ \&\ \mathrm{Au}$ collisions @ $\sqrt{s} = 200$ GeV: the first asymmetry measurement in high energy polarized proton-nucleus collision
- A_N changes sign from p+p to p+Au, A_N magnitude increases by factor of ~3 from p+p to p+Au.
- Simulation studies indidate significant UPC events in forward neutron production in p+A.
- A_N behaved quite differently by enhancing/suppressing UPC like events (BBC correlation)
- The A_N result is quite unexpected from current theory. Theoretical development is ongoing.
- How A_N evolution behaves as a function of A is a big question (how it behaves btw Al & Au).

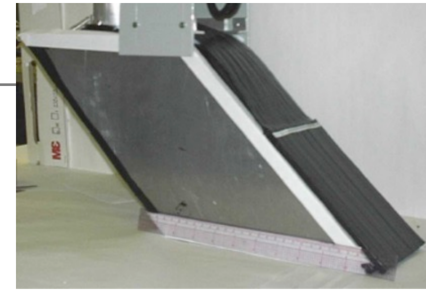
Thank you!

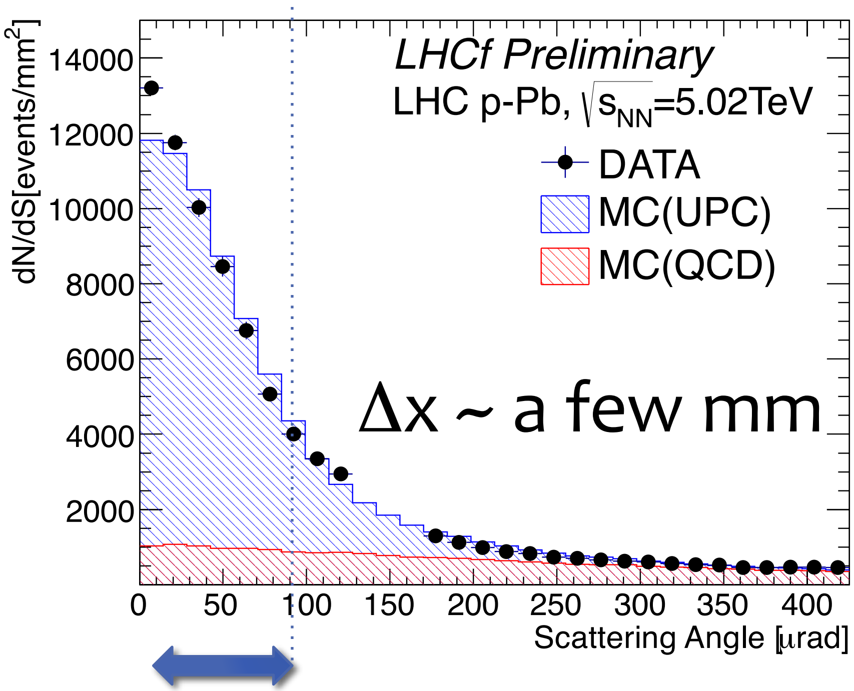
Forward Neutron Angular Distributions

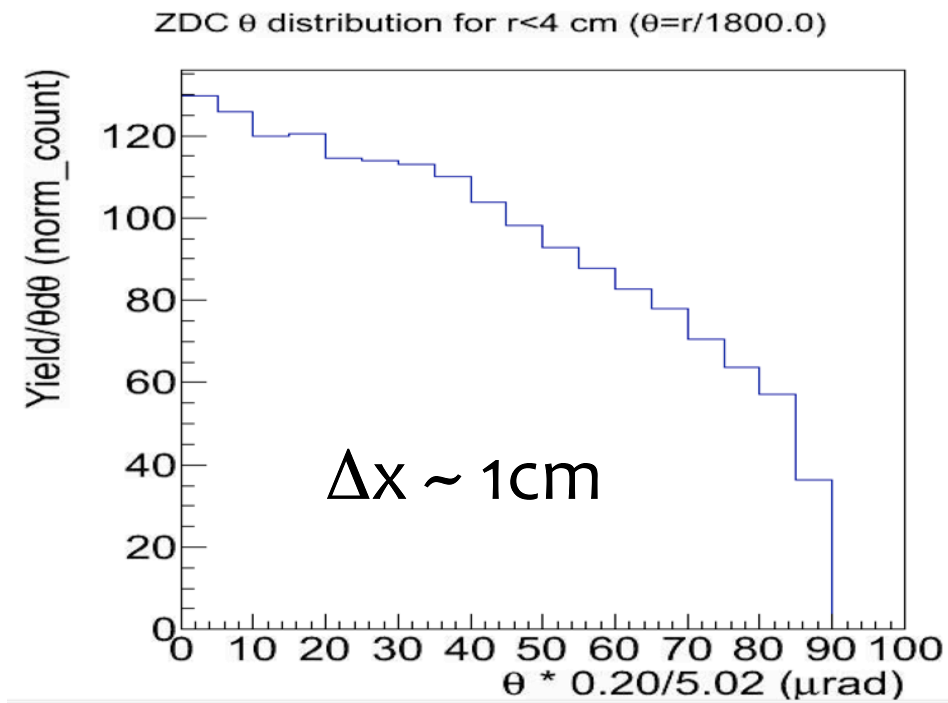
LHCf



PHENIX ZDC

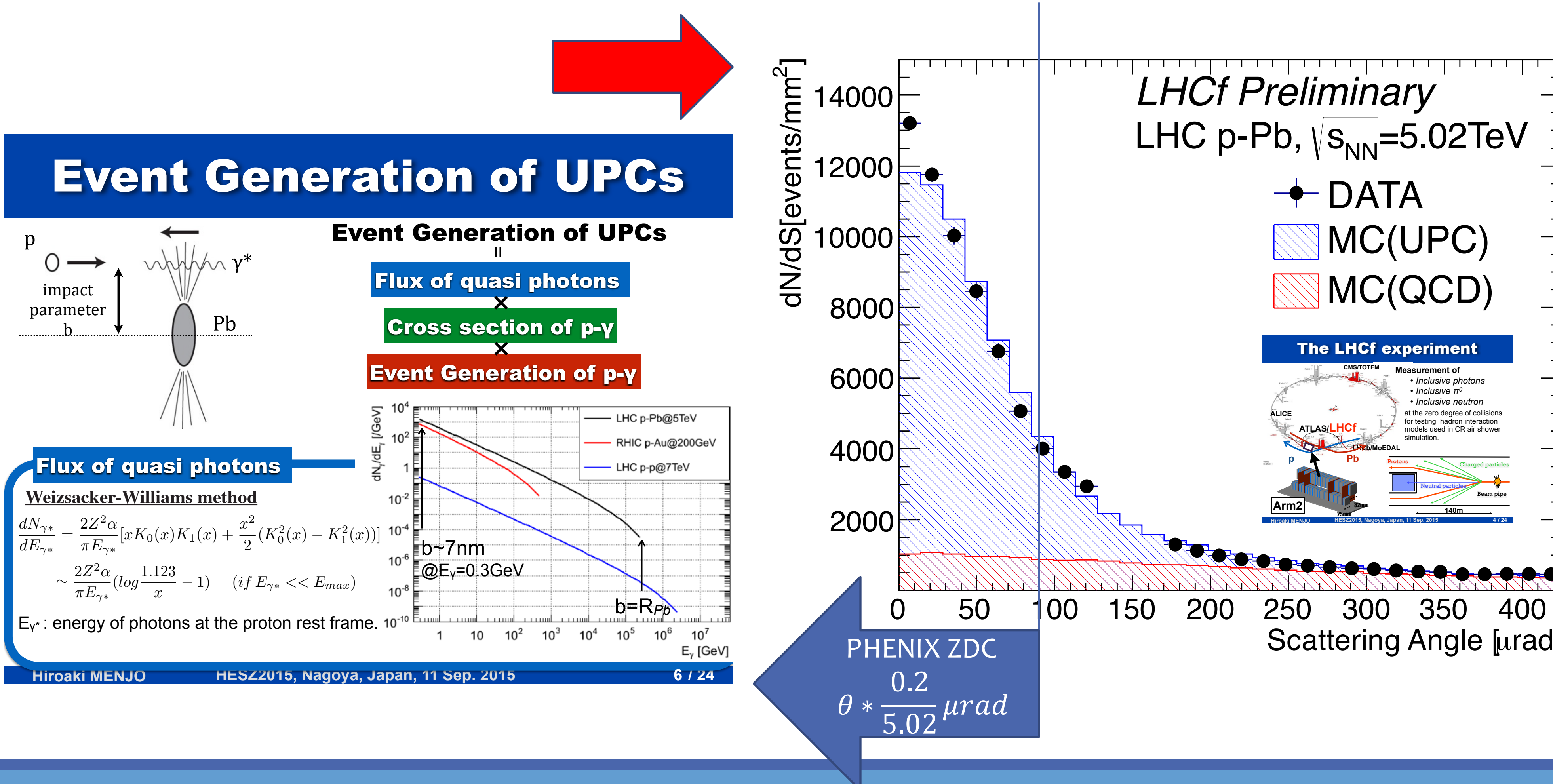






The ZDC acceptance doesn’t reach QCD dominant region.

UPC @ LHC



Event Generation of UPCs
p
impact parameter b
γ*
Pb
Event Generation of UPCs
=
Flux of quasi photons
×
Cross section of p-γ
×
Event Generation of p-γ
Flux of quasi photons
Weizsacker-Williams method
$$\frac{dN_{\gamma*}}{dE_{\gamma*}} = \frac{2Z^2\alpha}{\pi E_{\gamma*}}[xK_0(x)K_1(x) + \frac{x^2}{2}(K_0^2(x) - K_1^2(x))]$$
$$\simeq \frac{2Z^2\alpha}{\pi E_{\gamma*}}(log\frac{1.123}{x} - 1) \quad (if\ E_{\gamma*} << E_{max})$$
E_{γ^*} : energy of photons at the proton rest frame.
dN_γ/dE_γ [/GeV]
E_γ [GeV]
LHC p-Pb@5TeV
RHIC p-Au@200GeV
LHC p-p@7TeV
b~7nm
@E_γ=0.3GeV
b=R_{Pb}
Hiroaki MENJO
HESZ2015, Nagoya, Japan, 11 Sep. 2015
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LHCf Preliminary
LHC p-Pb, $\sqrt{s_{NN}}$=5.02TeV
DATA
MC(UPC)
MC(QCD)
dN/dS[events/mm^2]
Scattering Angle [μrad]
The LHCf experiment
Measurement of
• Inclusive photons
• Inclusive π^0
• Inclusive neutron
at the zero degree of collisions for testing hadron interaction models used in CR air shower simulation.
PHENIX ZDC
$$\theta * \frac{0.2}{5.02}\mu rad$$

Origin of Nonzero A_N

$$A_N \equiv \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} = \frac{\sum_X |< nX|T|\uparrow>|^2 - \sum_X |< nX|T|\downarrow>|^2}{\sum_X |< nX|T|\uparrow>|^2 + \sum_X |< nX|T|\downarrow>|^2}$$

Using $|\uparrow> = \frac{1}{\sqrt{2}}(|+> +i|->)$ & $|\downarrow> = \frac{1}{\sqrt{2}}(|+> -i|->)$,

$$\sum_X |< nX|T|\uparrow>|^2 - \sum_X |< nX|T|\downarrow>|^2 = -\mathbf{2Im}\sum_{\mathbf{X}} < \mathbf{nX}|\boldsymbol{T}|-><+|\boldsymbol{T}^+|\mathbf{nX}>$$

$A_N \neq 0$ if

$\exists$ Nonzero term for interference between spin-flip and nonflip interaction with different phase