RHIC forward (RHICf) experiment

Zero degree particle measurements at STAR

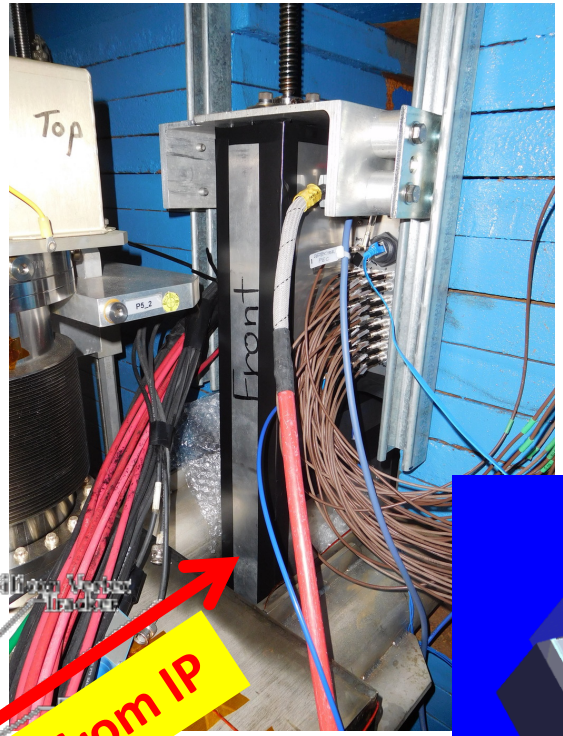
Takashi Sako (ISEE/KMI Nagoya University)
for the RHICf collaboration

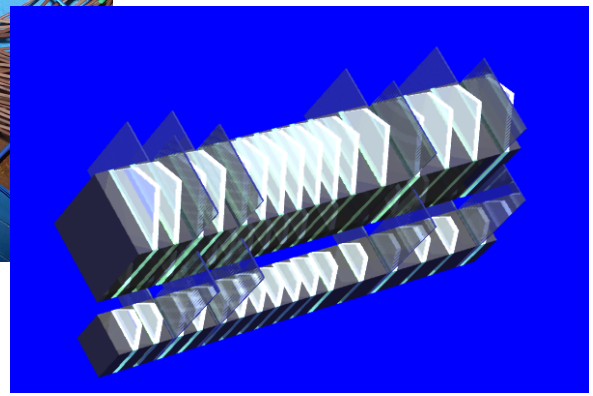
June

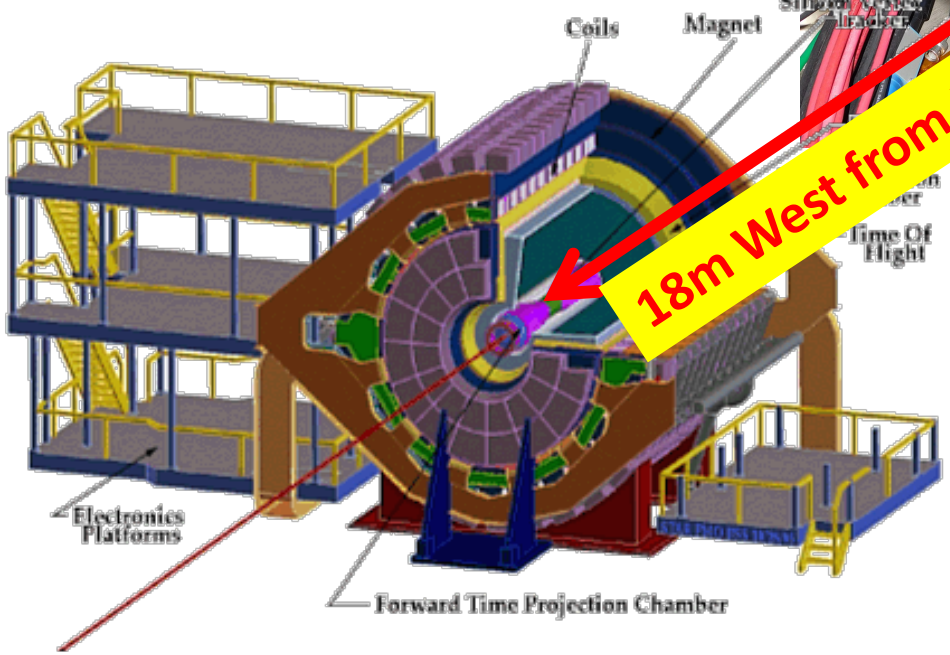
Sun	Mon	Tue	Wed	Thu	Fri	Sat
				1 CeC Trigger setup to 4 pm	2 Physics & CeC	3 Physics & CeC **Physics running Declared ~ 10 am**
4 Physics & CeC	5 Physics & CeC	6 Physics & CeC	7 Physics & CeC to 7:45 am APEX 8 am – 4 pm	8 Physics & CeC Beam Dev. 10 am – 2 pm	9 Physics & CeC	10 Physics & CeC
11 Physics & CeC	12 Physics & CeC	13 Physics & CeC	14 Dump 7:45 am Access 8 am – 4 pm 4 pm -Physics & CeC	15 Physics & CeC	16 Physics & CeC	17 Physics & CeC
18 Physics & CeC	19 Physics & CeC	20 Physics & CeC	21 Physics & CeC till 8 am Access 8 am – 4 pm RHICf pp 510 setup	22 ~~4 pm to 4 pm (24 hrs)~~ RHICf Physics 4 pm	23 RHICf Physics	24 RHICf Physics
25 RHICf Physics ~~2~~ Cryo warm-up	26 RHICf Physics to 8 am ~~18 hrs STAR Calibration~~ ~~3~~ Cryo warm-up Complete End of 21 Cryo wk Run	27 STAR Calibrations to 8 am APEX 8 pm to 8 am Diode testing 8 am – 8 pm	28 APEX 8 pm to 8 am Diode testing 8 am – 8 pm	29 APEX 8 pm to 8 am Diode testing 8 am – 8 pm	30 APEX 8 pm to 8 am Diode testing 8 am – noon Noon, Start Cryo warm-up	July 1 Cryo warm-up

RHICf@STAR interaction point

Compact electro-magnetic sampling calorimeters installed at 18m west from STAR IP

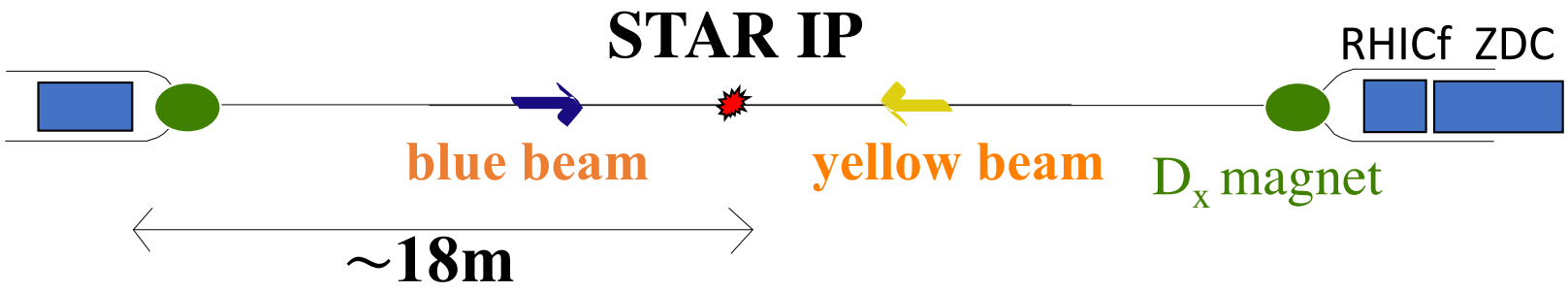


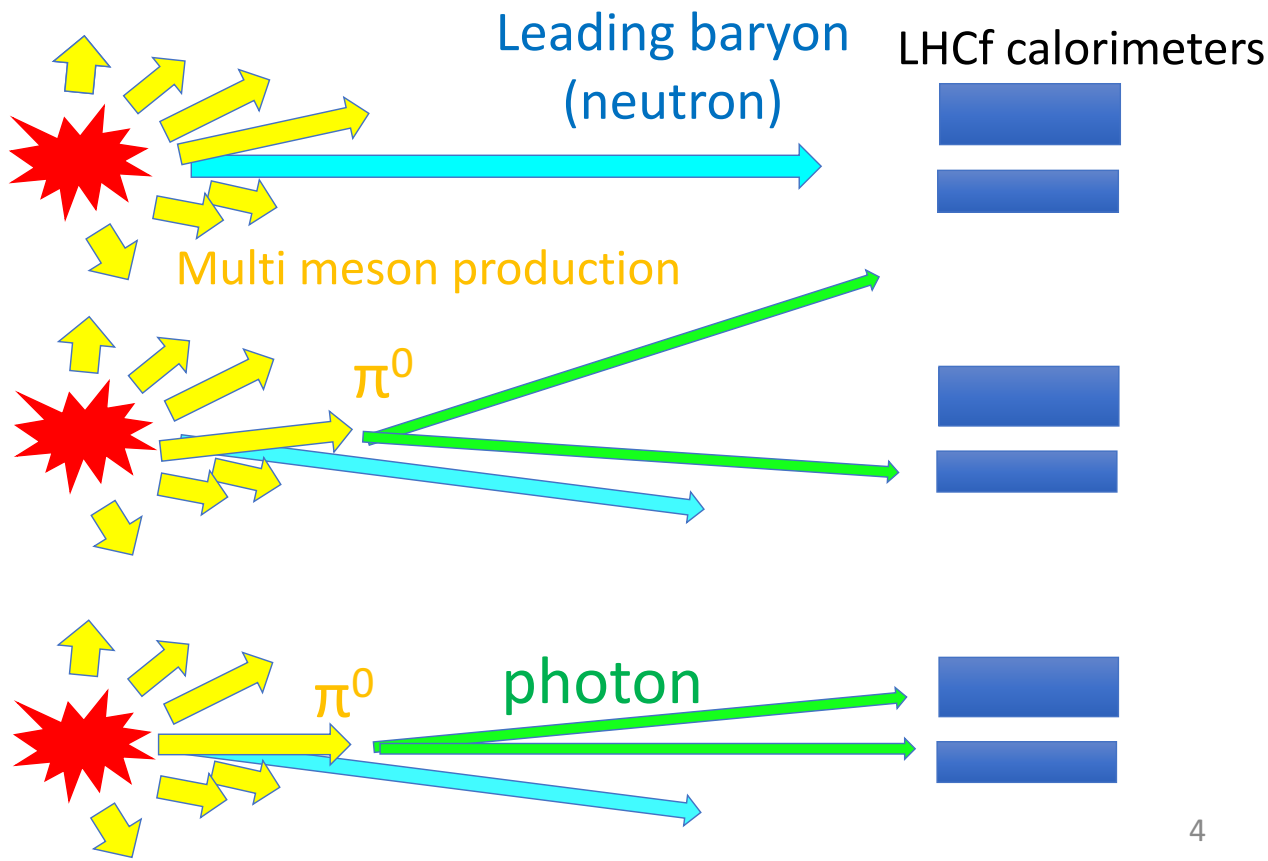




- 20mmx20mm, 40mmx40mm
- 44 r.l., 1.6 interaction length of tungsten
- 16 sampling scintillator layers
- 4 X-Y pairs of position sensitive layers
- (former LHCf Arm1 detector)

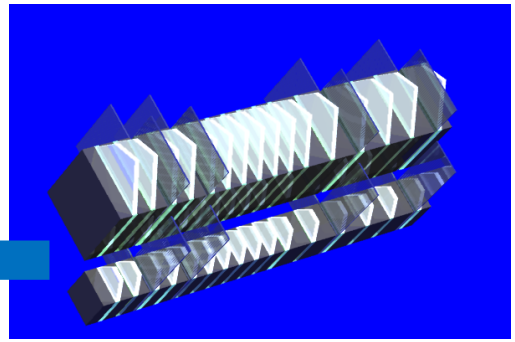
Events to be measured by RHICf

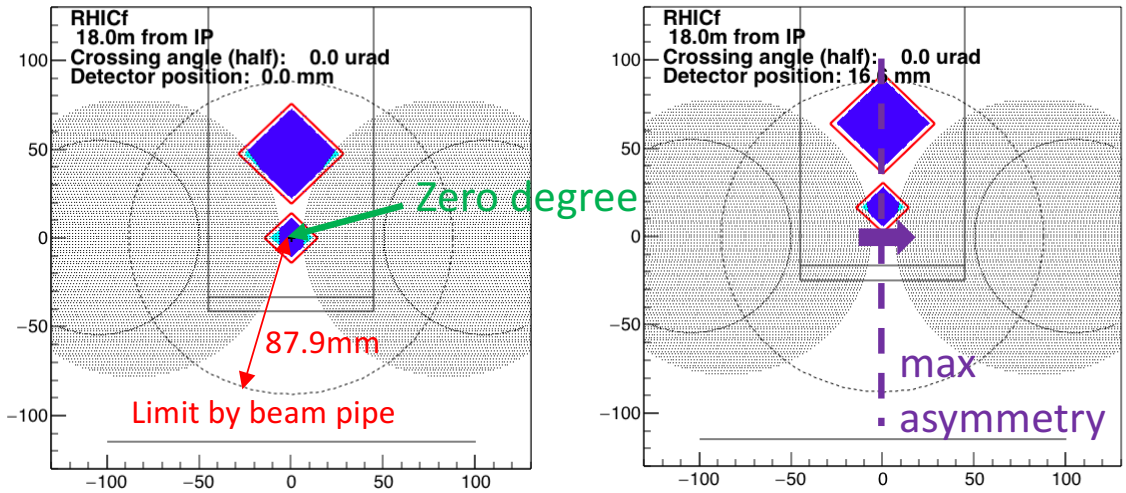


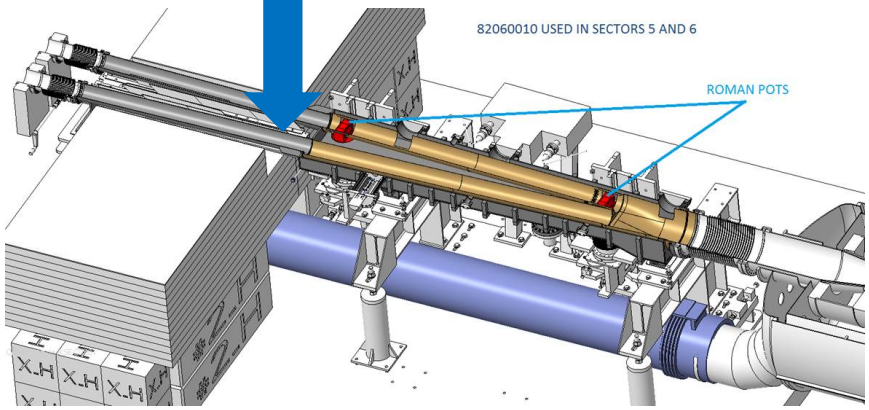


Compact double calorimeters
(20mmx20mm and 40mmx40mm)

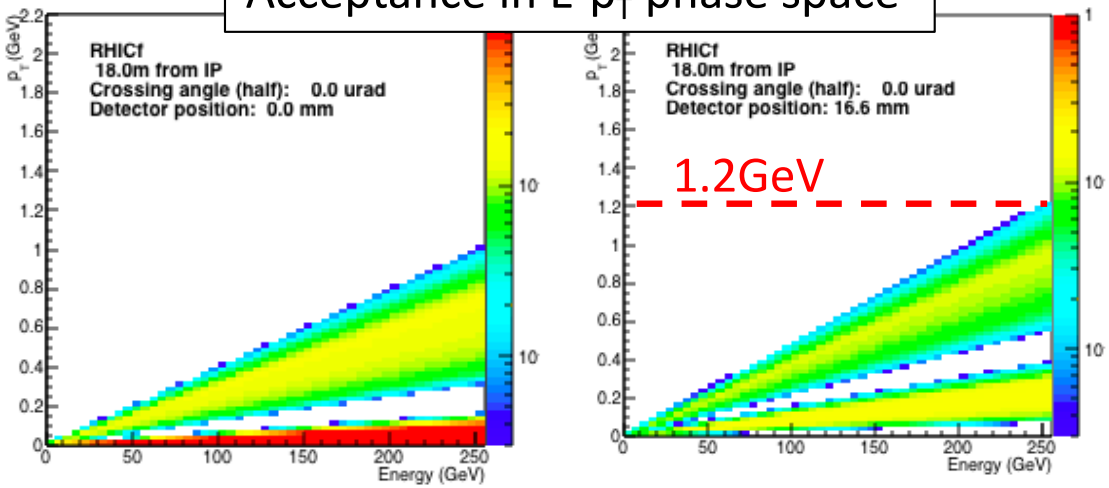
RHICf detector acceptance







Acceptance in E-p_T phase space



Widest and gapless p_T coverage is realized by moving the vertical detector position.

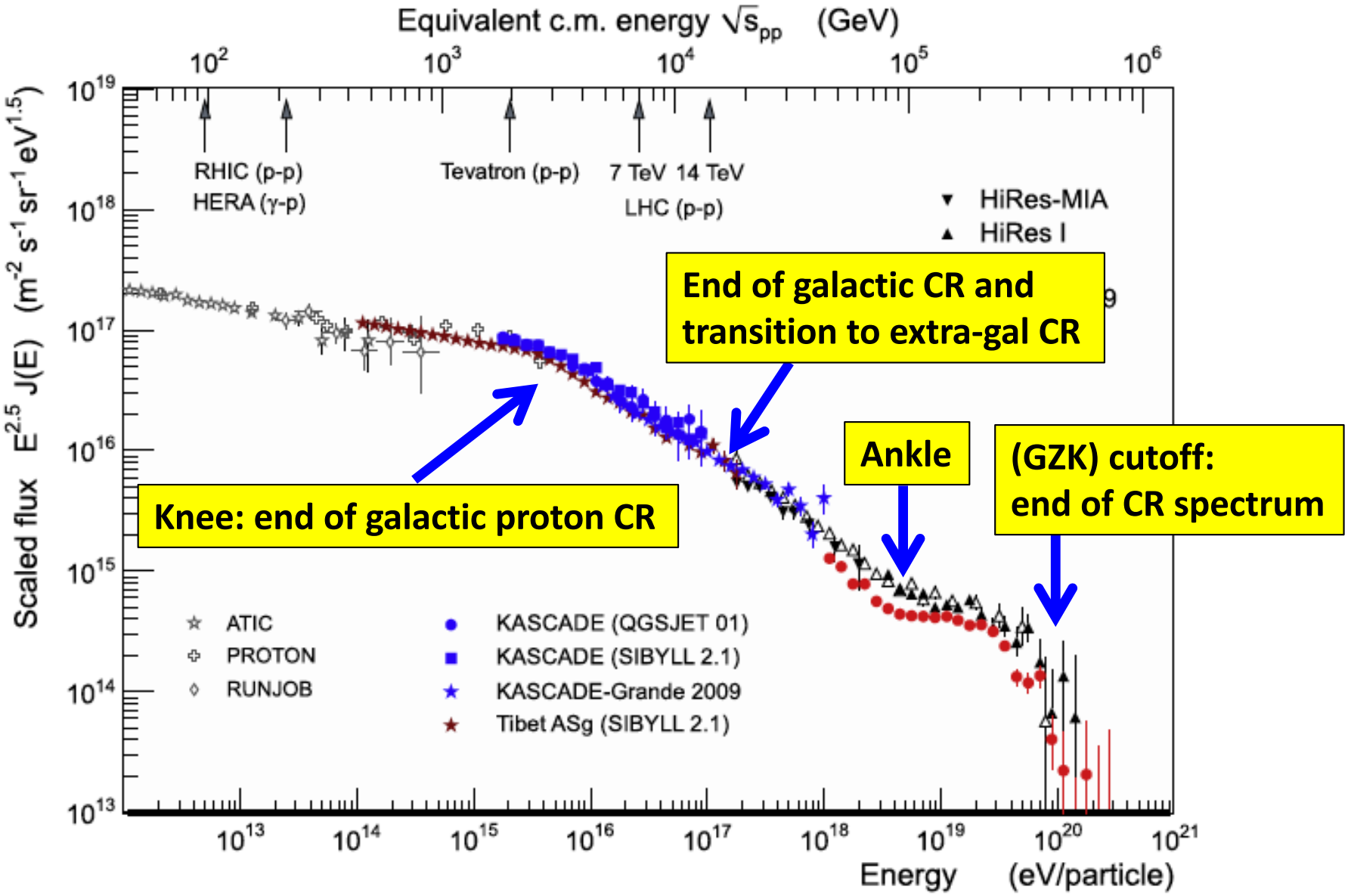
<u>Radial polarization (vertical asymmetry) maximizes the advantage of this wide p_T coverage</u>

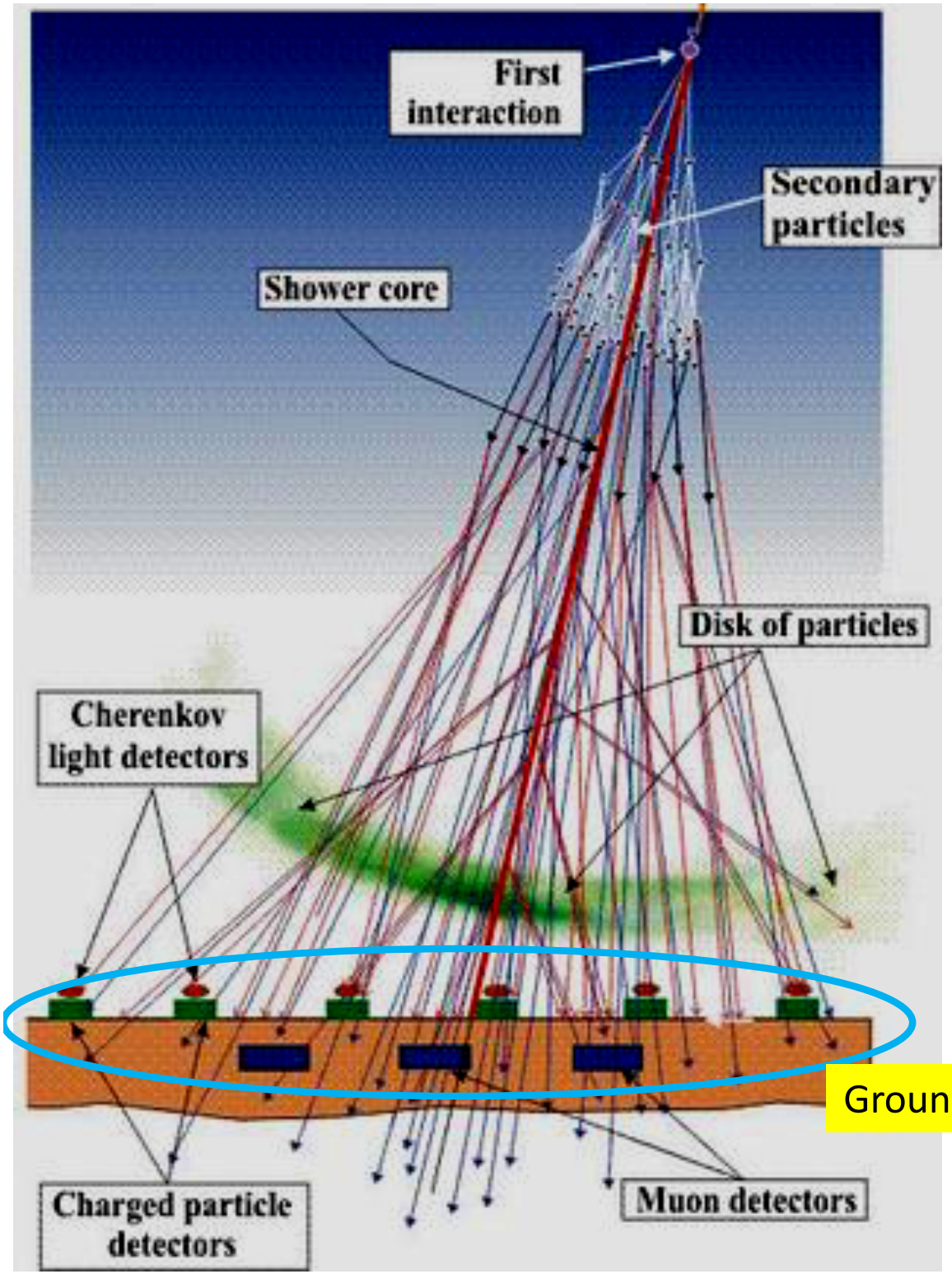
Two Physics Targets

- Cross section of neutral particle production
  - Forward particles carrying a large fraction of collisions energy are important to determine the cosmic-ray air shower structure
  - Scaling (or its break) can be studied by comparing with the data at LHC
- Single-Spin Asymmetry of forward particles in transversely polarized proton beams
  - Strong asymmetry of neutron measured by the former RHIC experiments can be studied with wider p_T coverage

Cross section measurements for Cosmic-Ray physics

Cosmic rays

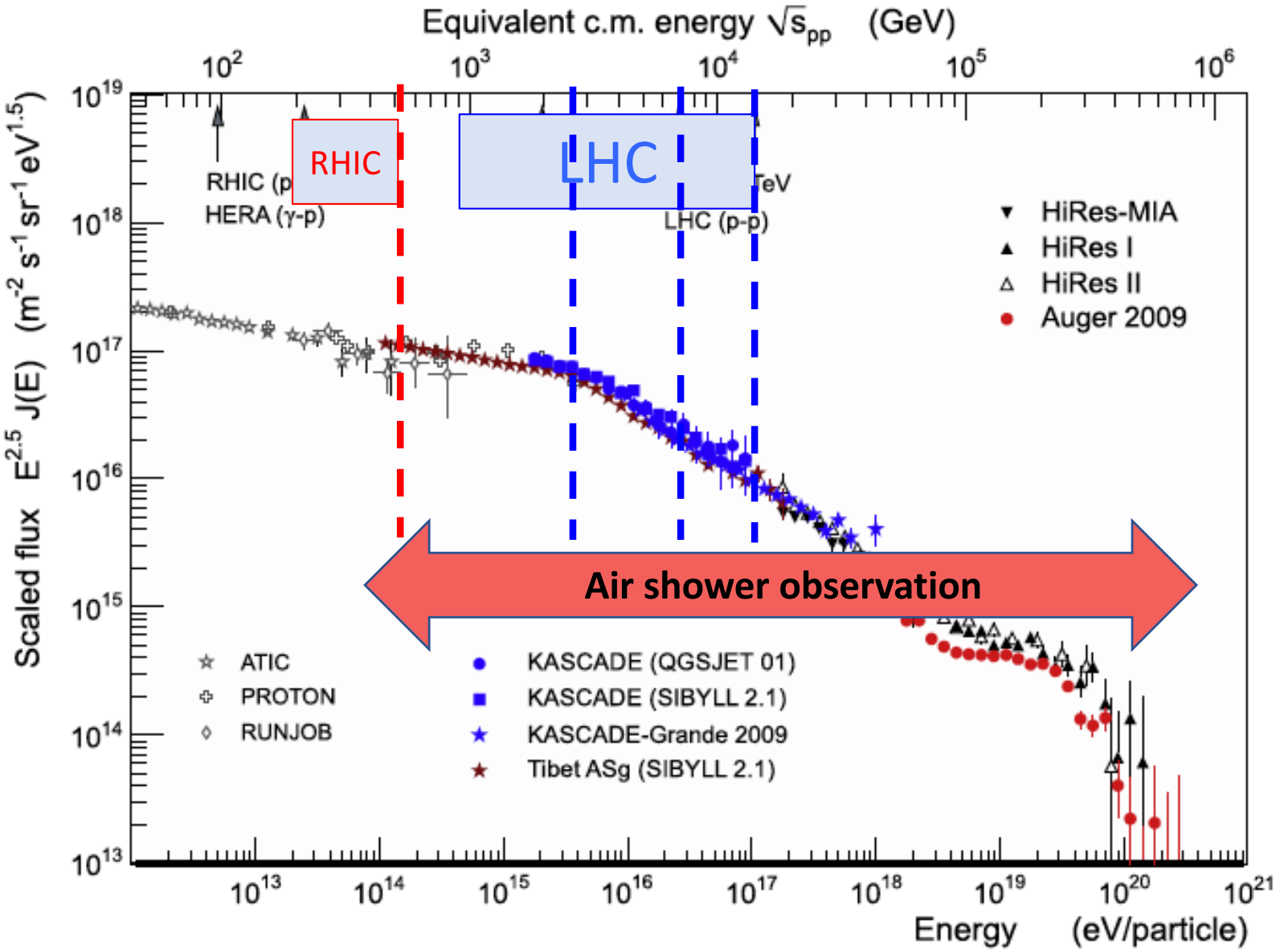

Equivalent c.m. energy $\sqrt{s_{pp}}$ (GeV)
10^2
10^3
10^4
10^5
10^6
RHIC (p-p)
HERA (γ-p)
Tevatron (p-p)
7 TeV 14 TeV
LHC (p-p)
HiRes-MIA
HiRes I
End of galactic CR and transition to extra-gal CR
Ankle
(GZK) cutoff: end of CR spectrum
Knee: end of galactic proton CR
ATIC
PROTON
RUNJOB
KASCADE (QGSJET 01)
KASCADE (SIBYLL 2.1)
KASCADE-Grande 2009
Tibet ASg (SIBYLL 2.1)
Scaled flux $E^{2.5}$ J(E) (m^{-2} s^{-1} sr^{-1} $eV^{1.5}$)
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
10^{21}
Energy (eV/particle)



Air shower and hadronic interaction

- ✓ Cosmic rays with $E>10^{14}$ eV are observed through atmospheric air shower
- ✓ Energy and mass of 1ry particles are determined from the ground observations
- ✓ Interpretation relies on the MC simulation of air showers
- ✓ **Hadronic interaction, especially forward particle production**, is a key of the MC simulation

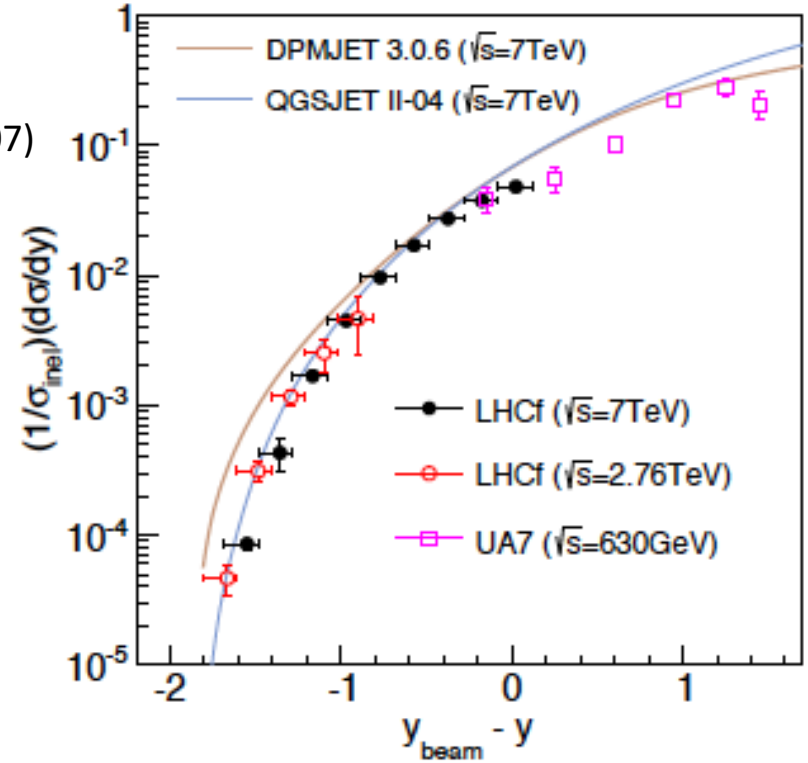
Cosmic rays

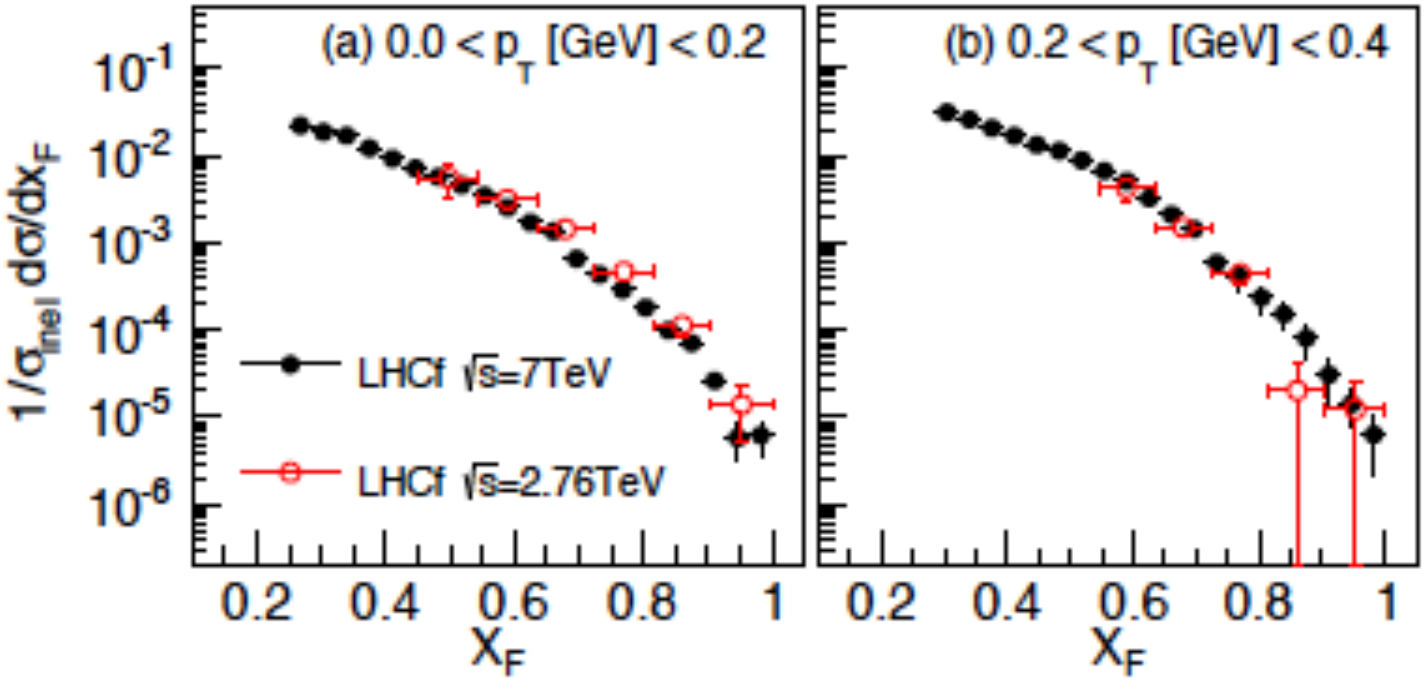


We must rely on the Monte Carlo simulation to determine energy and particle type

√s scaling ; π^0 (LHCf, PRD, 94 (2016) 032007)

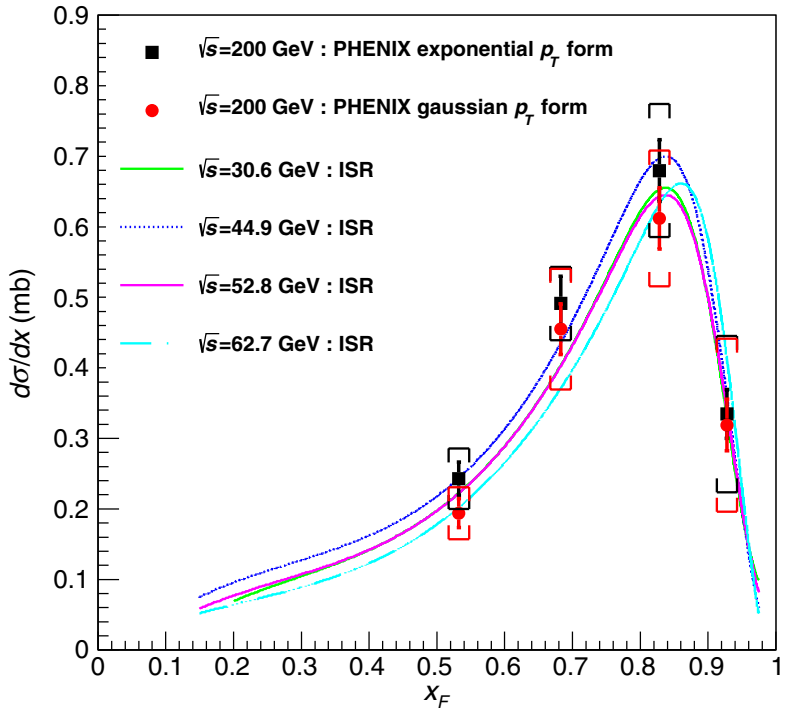
- ✓ Scaling is essential to extrapolate beyond LHC
- ✓ (630GeV –) 2.76TeV – 7TeV
  good scaling within uncertainties
- ✓ Wider coverage in y and p_T with 13TeV data
- ✓ Wider √s coverage with RHICf experiment at √s=510GeV





Feynman x;
$x_F = 2p_z/\sqrt{s}$

√s scaling; Neutron @ zero degree

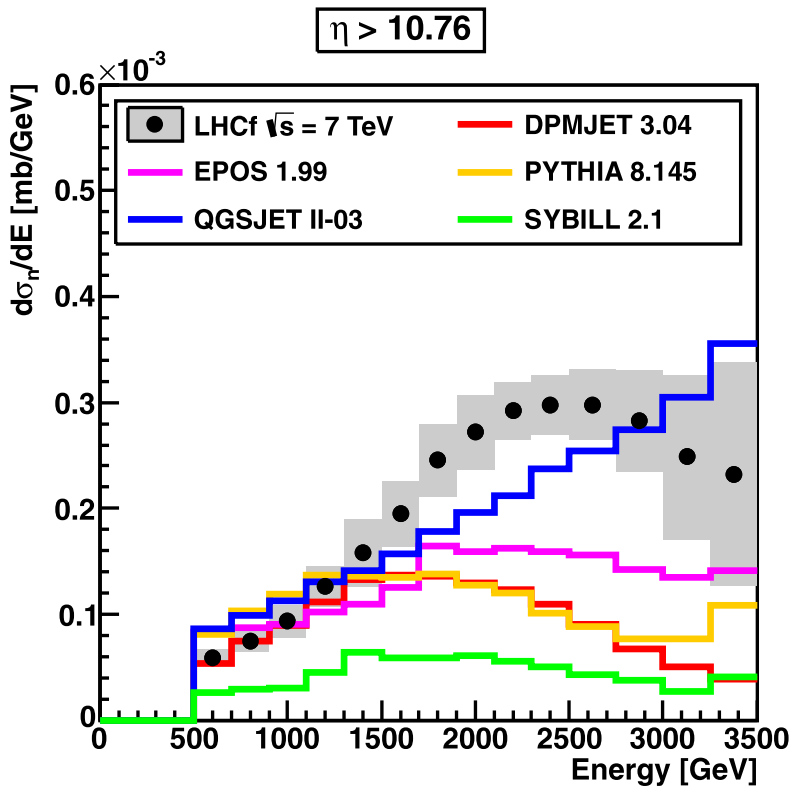


PHENIX, PRD, 88, 032006 (2013)

$p_T < 0.11\ x_F$ GeV/c

√s = 30-60 GeV @ISR

√s = 200 GeV @RHIC



LHCf

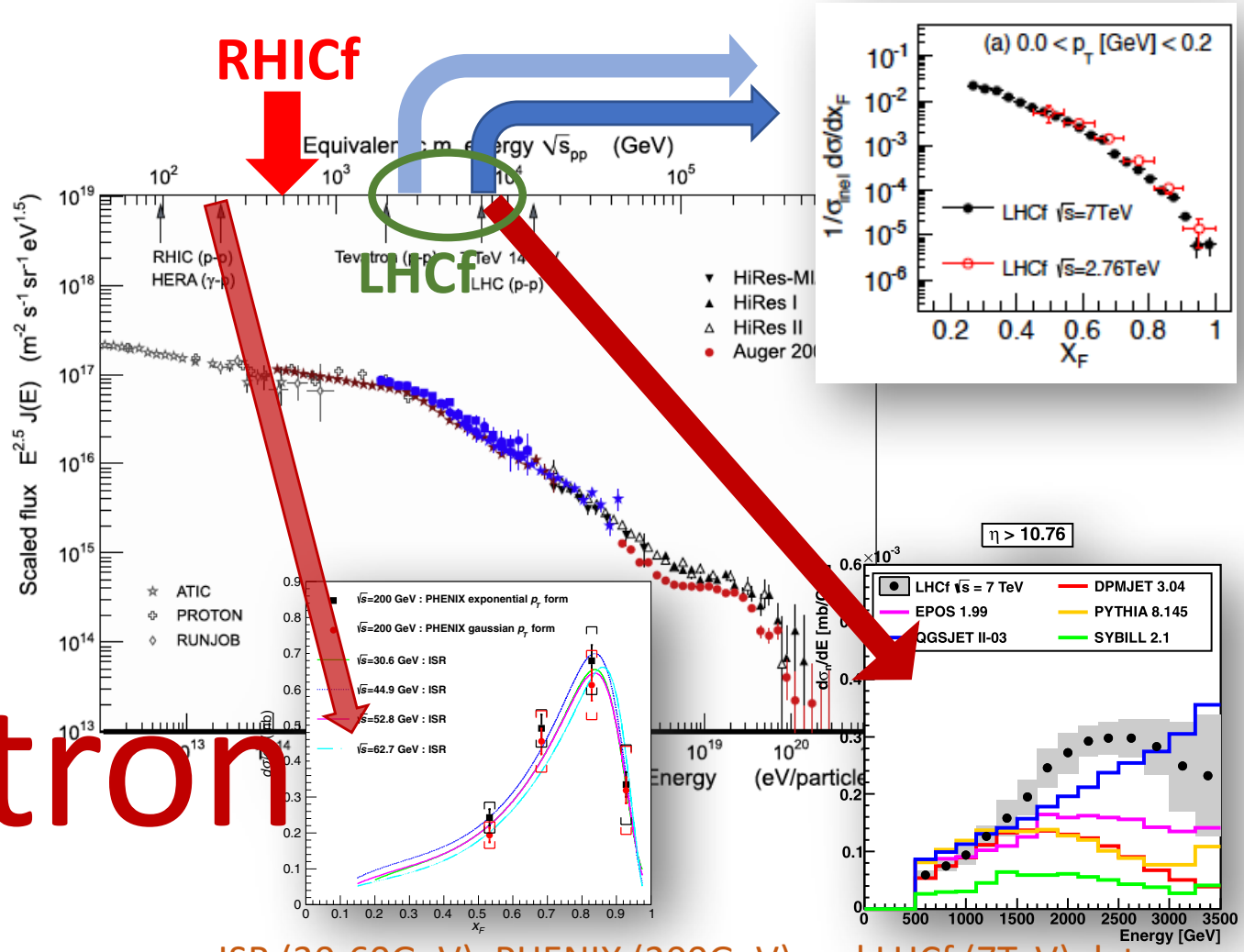
$p_T < 0.15\ x_F$ GeV/c

√s = 7000 GeV @LHC

- ✓ PHENIX explains the result by 1 pion exchange
- ✓ More complicated exchanges at >TeV?
- ✓ LHCf data at 900GeV, 2.76TeV to be analyzed
- ✓ RHICf data at 510GeV will be added soon

√s scaling, or breaking?

LHCf 2.76TeV and 7TeV data shows Feynman scaling of forward π^0



π^0

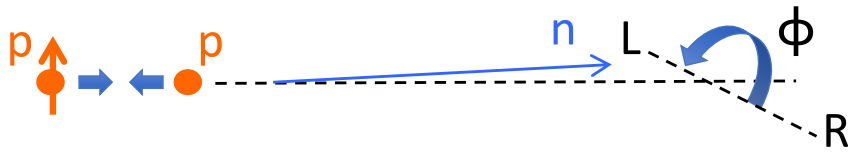
neutron

ISR (30-60GeV), PHENIX (200GeV) and LHCf (7TeV) data indicate Feynman scaling ***braking*** of forward neutrons

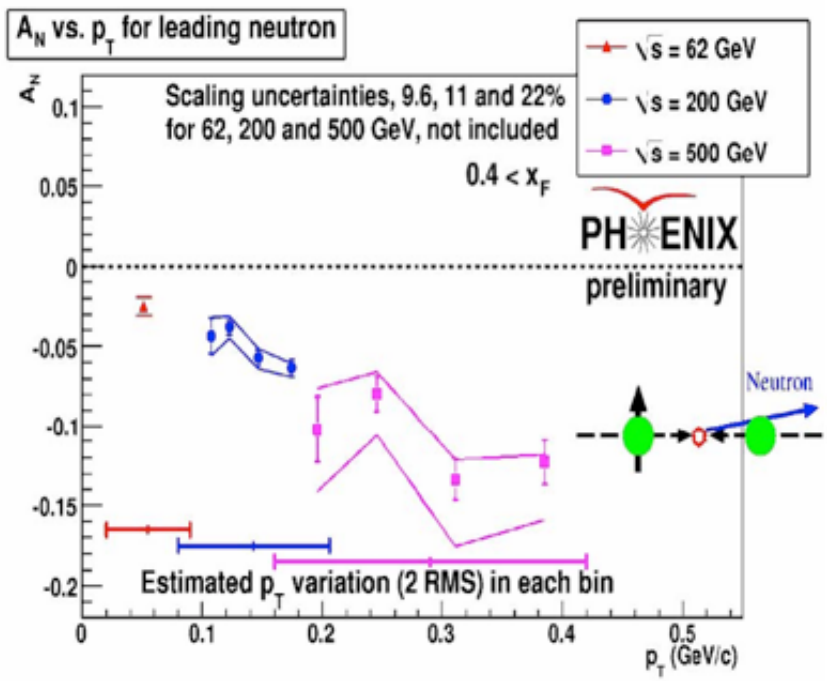
Single-spin asymmetry measurements with high spatial resolution

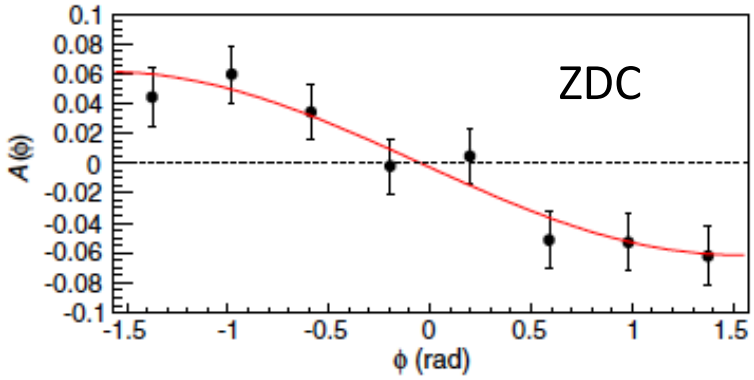
Single-spin asymmetry by PHENIX

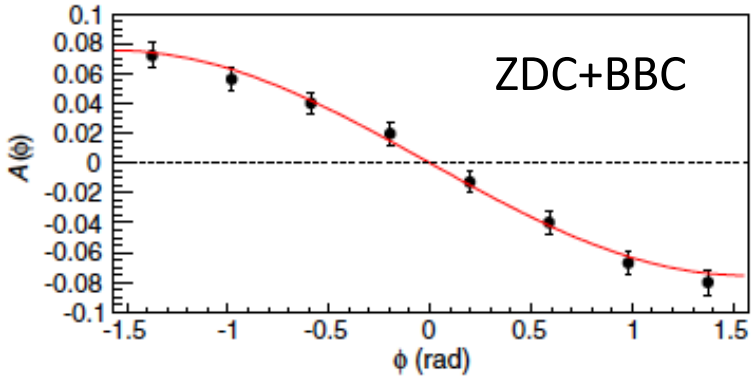
(PRD, 88, 032006, 2013)



- ✓ strong asymmetry in forward neutrons was discovered at RHIC
- ✓ scaled with pT at √s = 62, 200, 500 GeV?







PHENIX results at 200GeV

Theoretical explanation

- Pion-a_1 interference: results
  - The data agree well with independence of energy
- The asymmetry has a sensitivity to presence of different mechanisms, e.g. Reggeon exchanges with spin-non-flip amplitude, even if they are small amplitudes

$$A_N \approx \frac{2\,\mathrm{Im}\left(fg^*\right)}{|f|^2 + |g|^2}$$

f : spin non-flip amplitude
g : spin flip amplitude

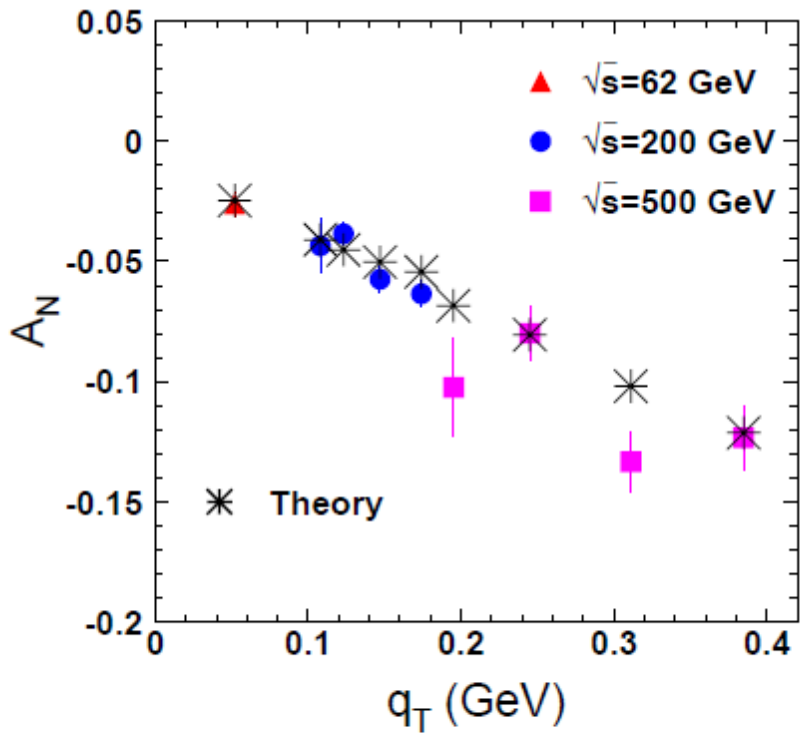
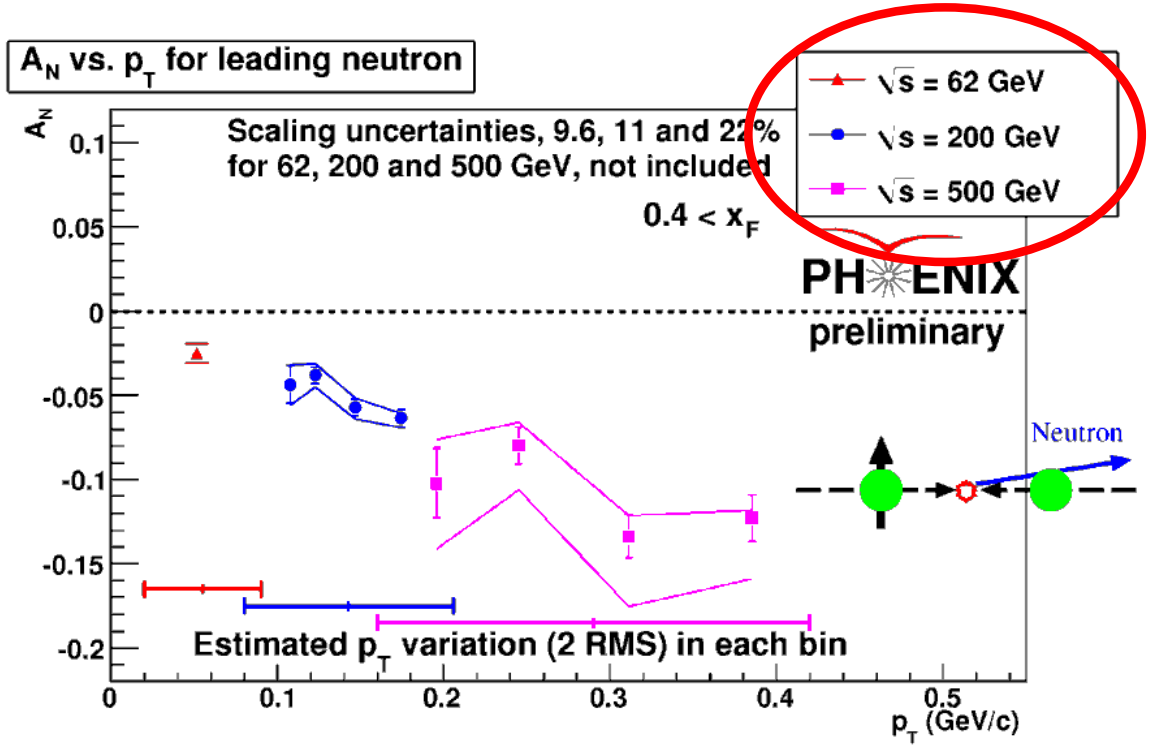


FIG. 1: (Color online) Single transverse spin asymmetry A_N in the reaction $pp \to nX$, measured at $\sqrt{s} = 62,\ 200,\ 500$ GeV [1] (preliminary data). The asterisks show the result of our calculation, Eq. (38), which was done point by point, since each experimental point has a specific value of z (see Table I).

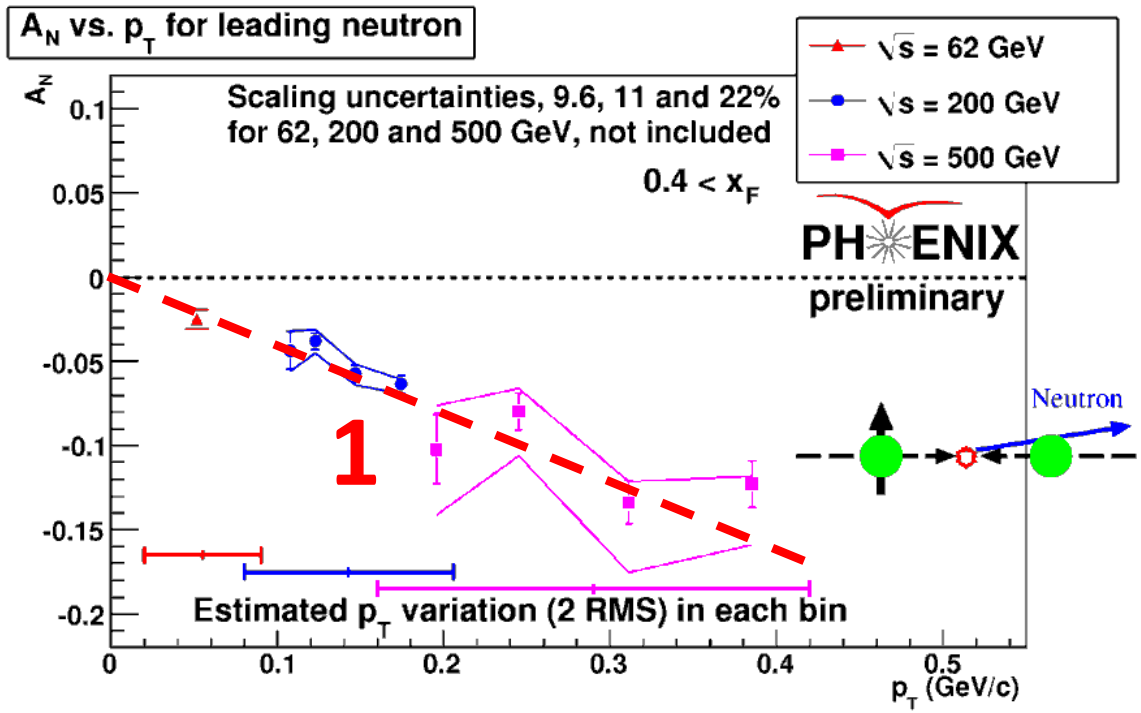
Kopeliovich, Potashnikova, Schmidt, Soffer: Phys. Rev. D 84 (2011) 114012.

SSA of forward neutron production



1. Measurement at p_T<0.3GeV in a single √s
   - possible by RHICf because of its 1mm position resolution for neutrons
2. Measurement at p_T>0.3GeV to know A_N evolution
   - possible by RHICf because of its wide p_T coverage required for cross section measurements

SSA of forward neutron production



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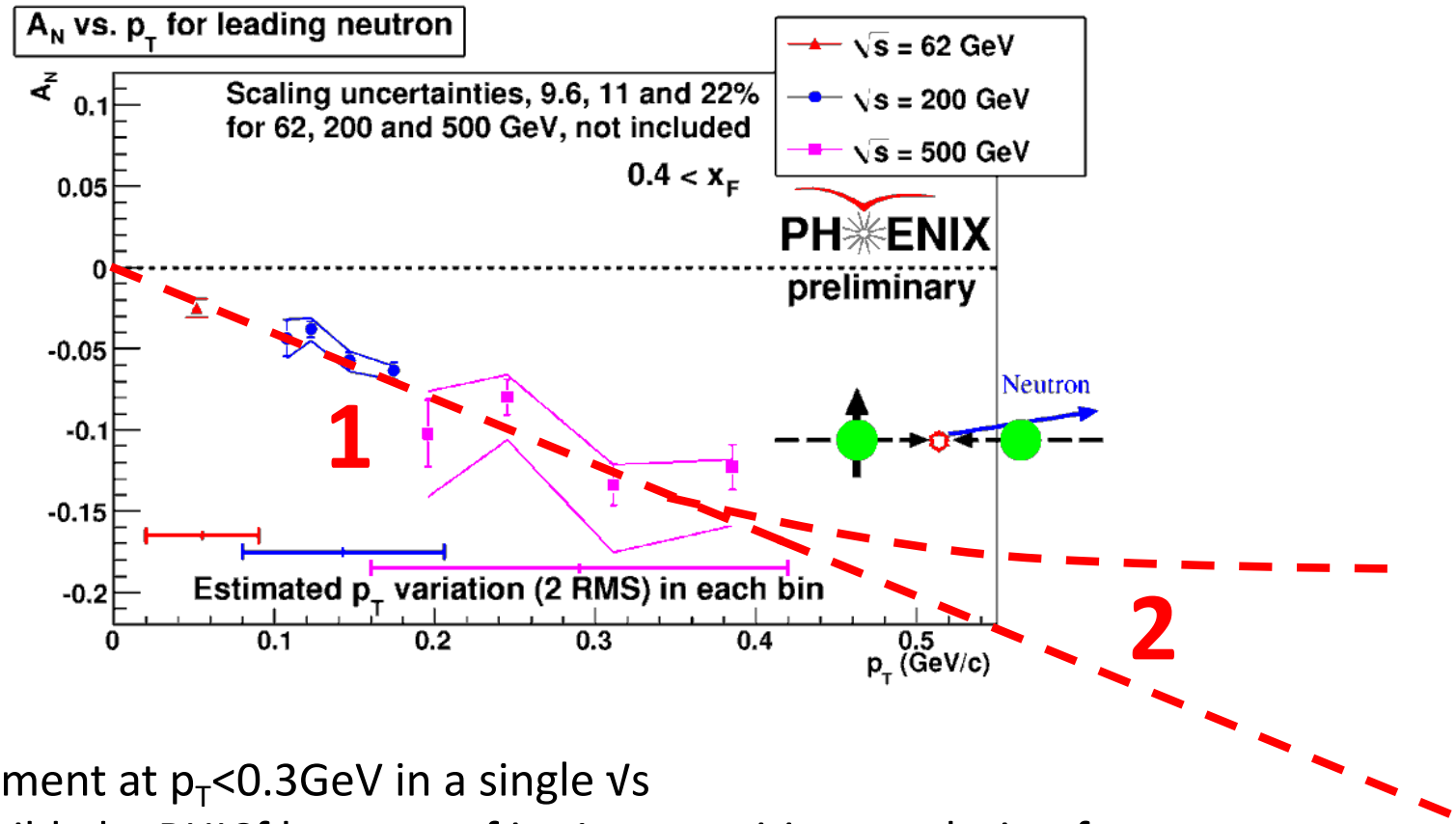

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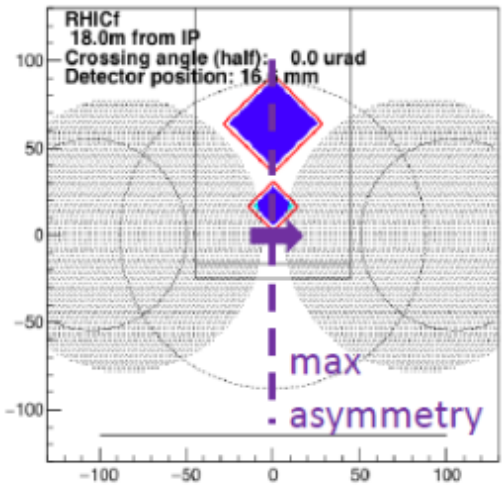
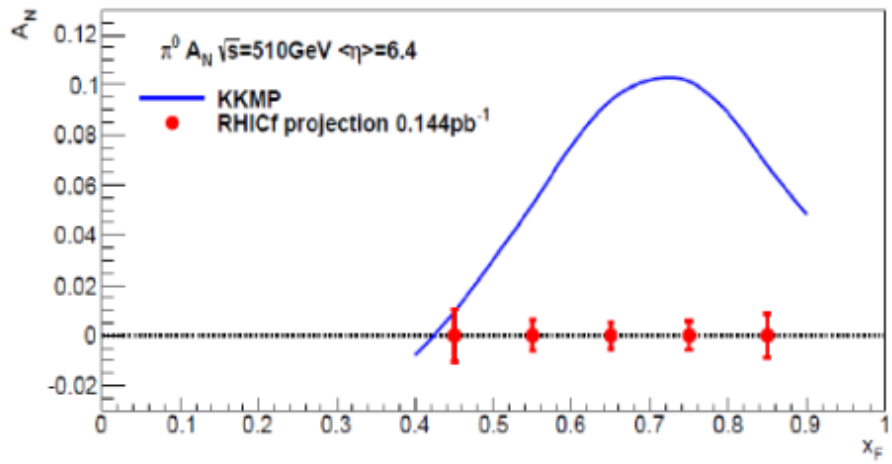
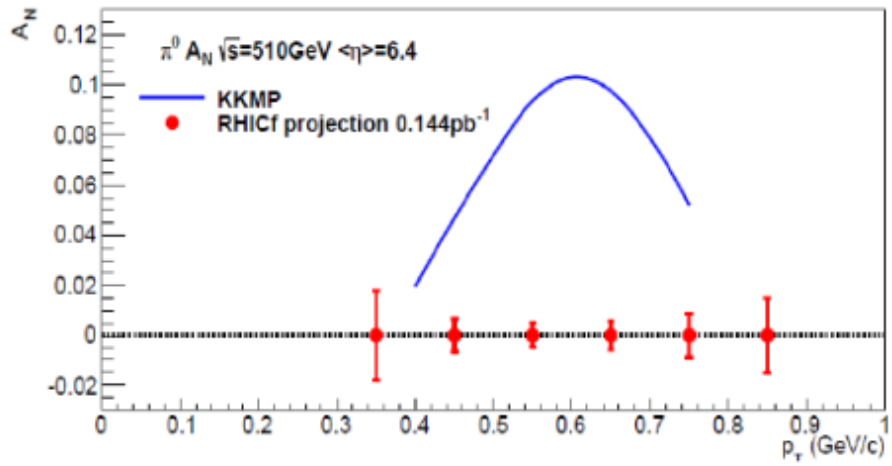
π^0 asymmetry measurement

- π^0 A_N measurement using TL at +y=16.6mm, <η> = 6.4
  - 3×10^5 π^0 detected in 4-hour measurement
  - Comparison of existing η region (3–4) and RHICf low-η region (> 6)







- Theory calculation by Pitonyak
- pQCD calculation does not apply for the very low p_T values
- At p_T > 0.75 GeV/c, this mechanism cannot generate A_N since phase space vanishes

Beam Use Request for RUN17

Parameter	Value
Beam energy (GeV)	255
Beam intensity (protons per bunch)	2×10^{11}
Number of colliding bunch	111
Number of non-colliding bunch	9
Beam emittance (mm mrad)	20
β^* (m)	10
Luminosity ($cm^{-2}s^{-1}$)	2.0×10^{31}
Polarization direction	radial
Polarization amplitude	0.4–0.5
β^* setup time	1 day
Radial polarization setup time	1 day
Data taking time	2 days

- Beam setup 2 days
  - β^*=10m to keep the beams parallel (σ=1.5mm at detector) 1day
  - Radial polarization to access p_T>0.3GeV in SSA measurement 0.3-1 day [not more than 24 hours in case of any difficulty]
- Physics operation 2 days
  - 12 hours data taking for minimum success both in cross section and SSA measurements **in parallel**
- Backup
  - we hope 24 hours data taking is assured only when we have (recoverable) trouble
- Timing
  - To be discussed, but not very early phase
  - Hope around May 2017

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Parameter	Value
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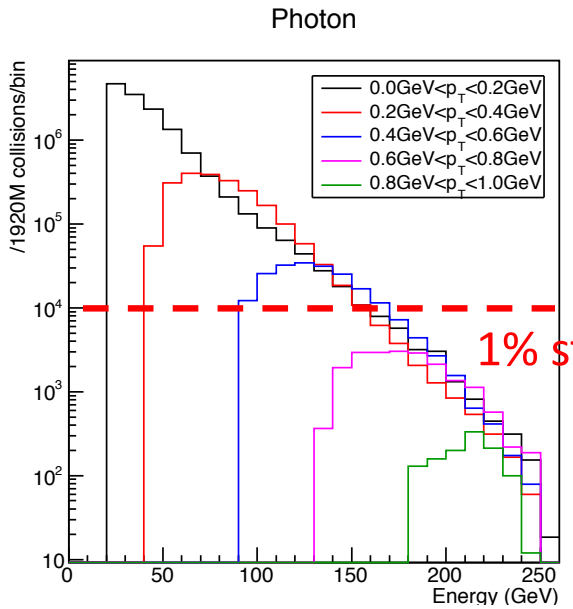
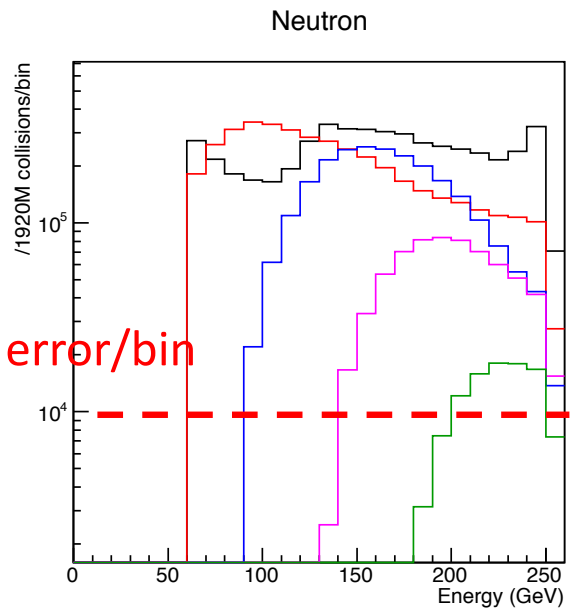
Number of colliding bunch	111
Number of non-colliding bunch	9
Beam emittance (mm mrad)	20
β^* (m)	10 -> 8
Luminosity ($cm^{-2}s^{-1}$)	2.0×10^{31}
Polarization direction	radial
Polarization amplitude	0.4–0.5
β^* setup time	1 day
Radial polarization setup time	1 day
Data taking time	2 days

- Beam setup 2 days => 1day
  - β^*=10m to keep the beams parallel (σ=1.5mm at detector) 1day
  - Radial polarization to access p_T>0.3GeV in SSA measurement 0.3-1 day [not more than 24 hours in case of any difficulty]
- Physics operation 2 days => 3.5 days
  - 12 hours data taking for minimum success both in cross section and SSA measurements **in parallel**
- Backup
  - we hope 24 hours data taking is assured only when we have (recoverable) trouble
- Timing
  - To be discussed, but not very early phase
  - Hope around May 2017 => 21-26 June

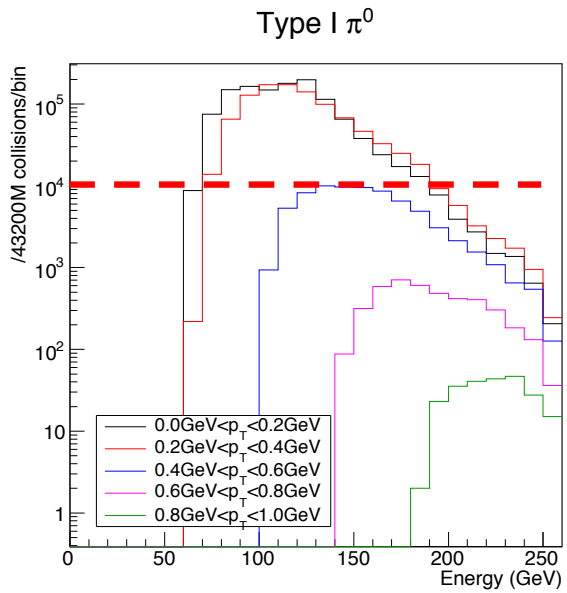
STARTING TODAY!!!

Expected statistics in 12 hours





1% stat error/bin



Neutron SSA

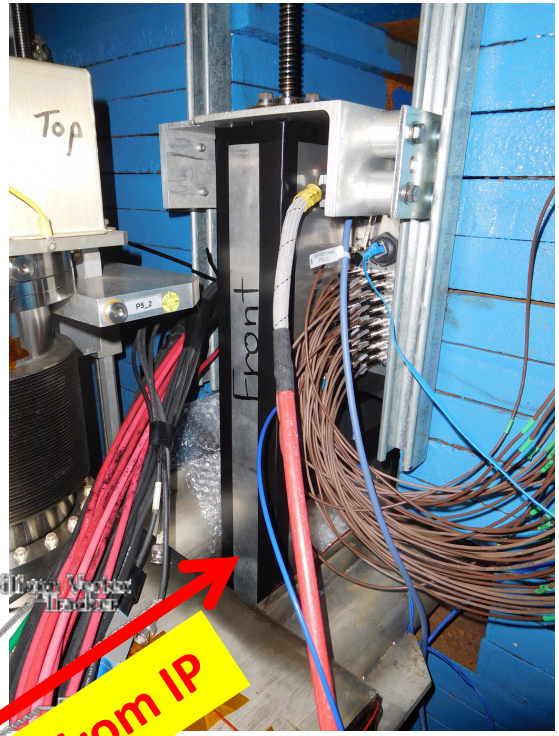
$p_T(GeV)$	N $(\times 10^3)$	δA
0.0–0.1	2,310	0.0013
0.1–0.2	2,570	0.0012
0.2–0.3	1,710	0.0015
0.3–0.4	2,190	0.0014
0.4–0.5	1,210	0.0018
0.5–0.6	1,130	0.0019
0.6–0.7	402	0.0032
0.7–0.8	260	0.0039
0.8–1.2	104	0.0062

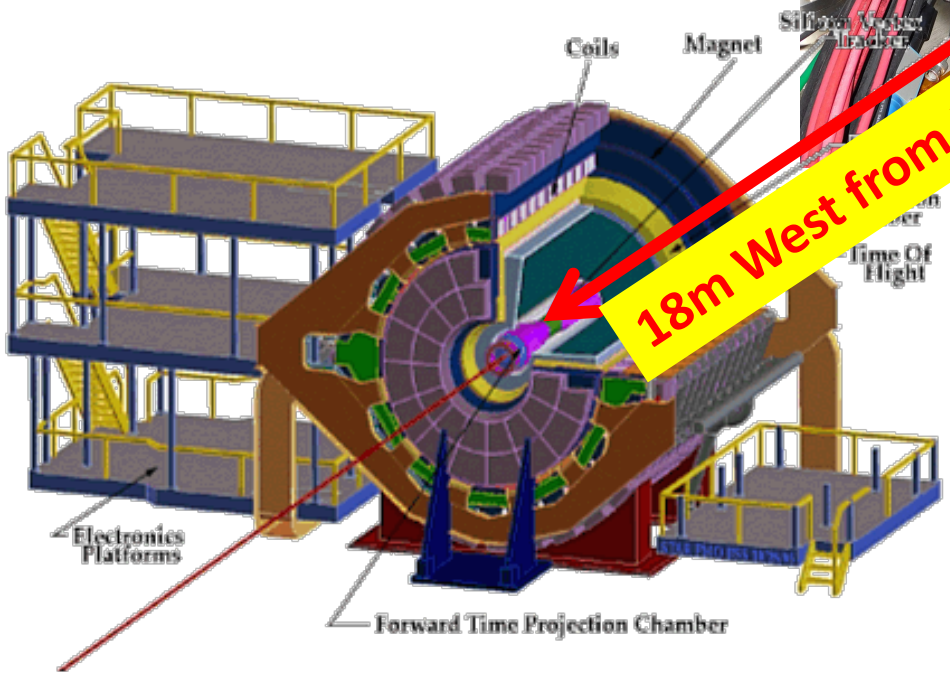
- After 12 hours, high threshold energy and EM enhanced trigger to increase statistics in high energy photons and π^0

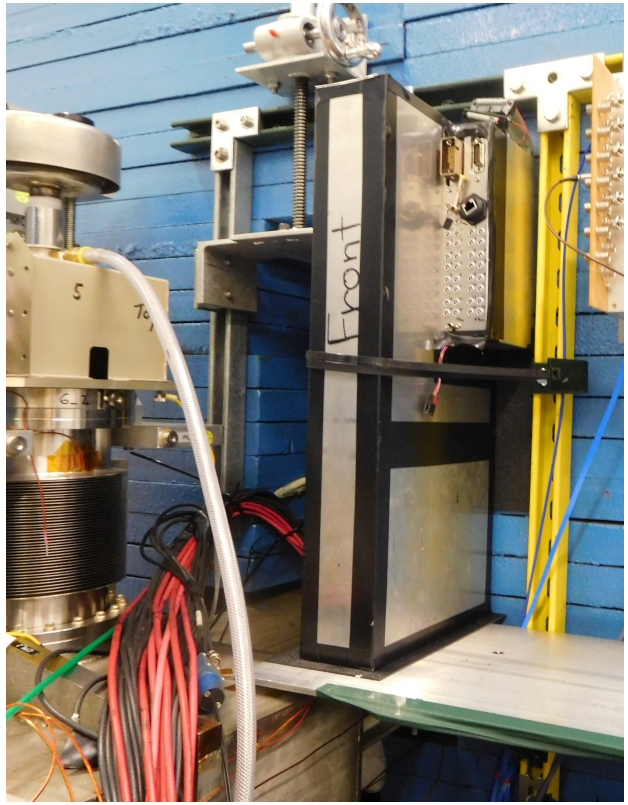
Status of RHICf

RHICf Installation @STAR interaction point

Test in October-December

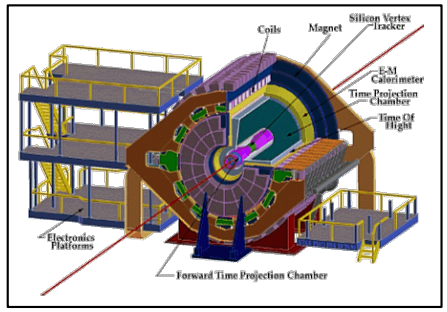


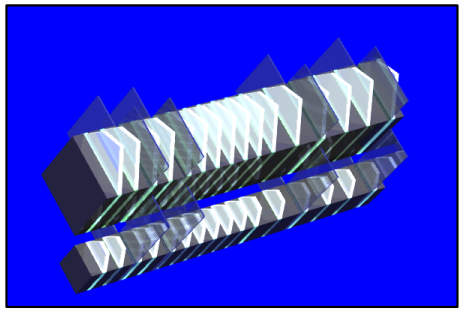




Off-axis since January to observe collision without interfering ZDC

STAR-RHICf common data taking





Trigger generation

Trig signal

Trigger generation

Token number

Token receipt

Data

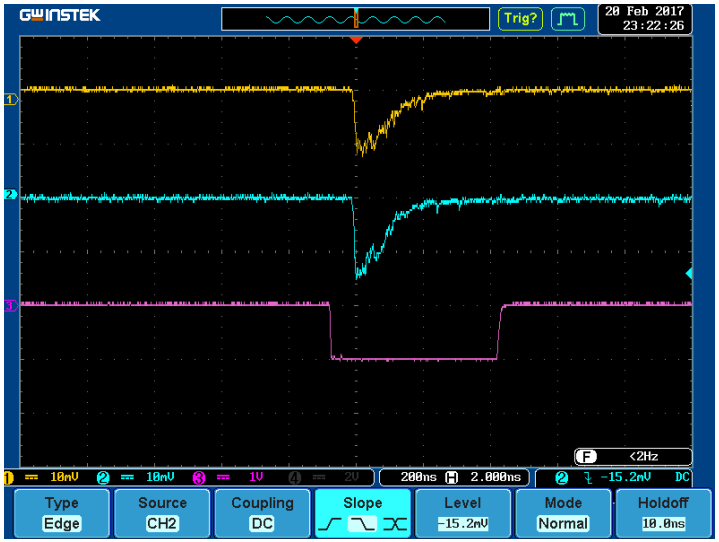
Event build

Common data storage

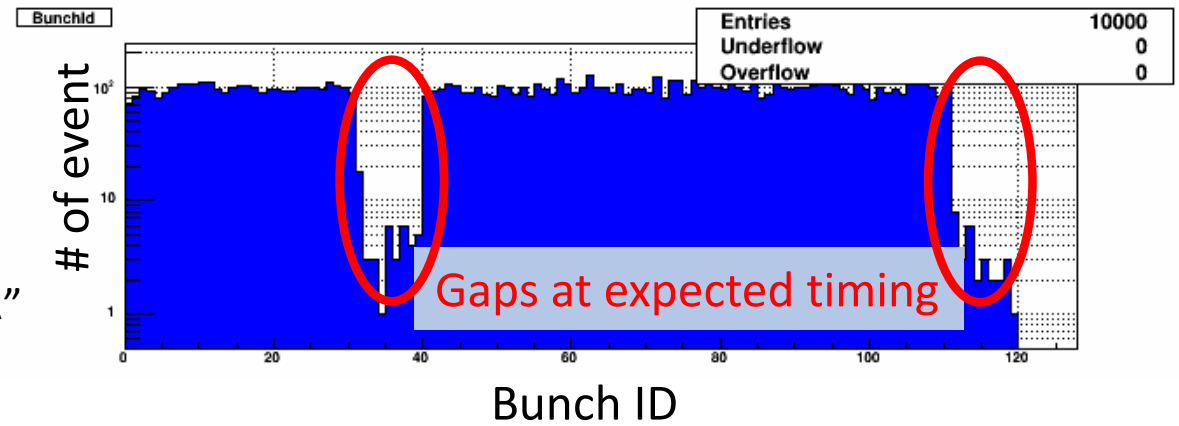
Stand alone data storage

Test with Collisions

- RHIC starts first RUN2017 collision on 20-Feb
- RHICf observed shower signal (PMT coincidence) and tuned timing
- Common operation (RHICf triggers STAR) tested and common data successfully recorded at STAR (analysis of physics correlation on going)

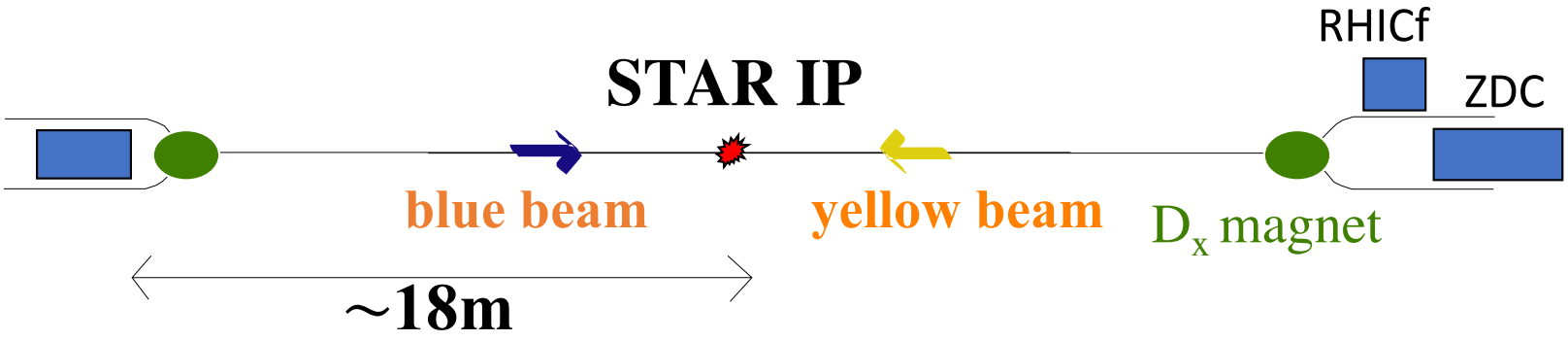


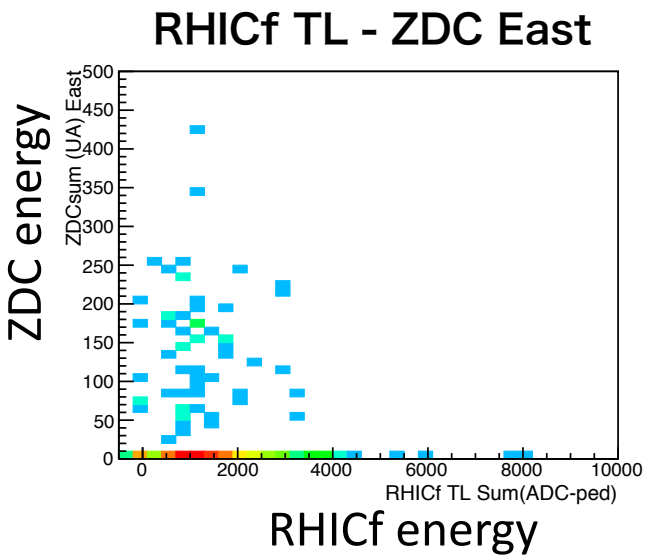
RHICf calorimeter PMT signals and ADC Gate after timing tuned

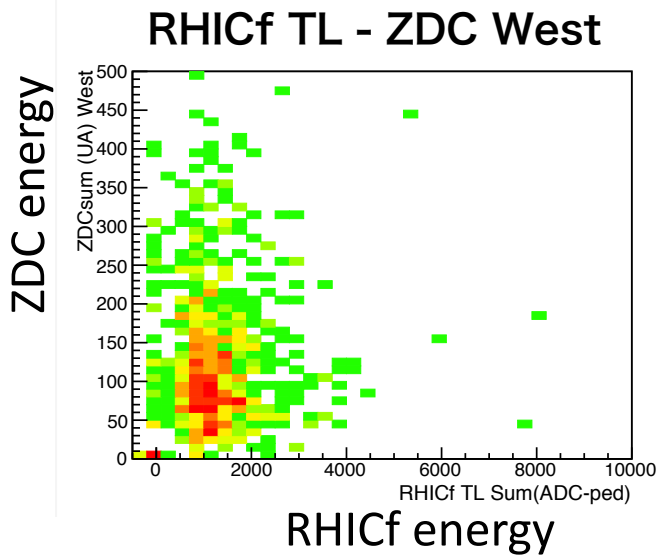


Bunch ID of RHICf trigger recorded at "STAR"
Two abort gaps correctly identified

Common run in Au-Au collisions

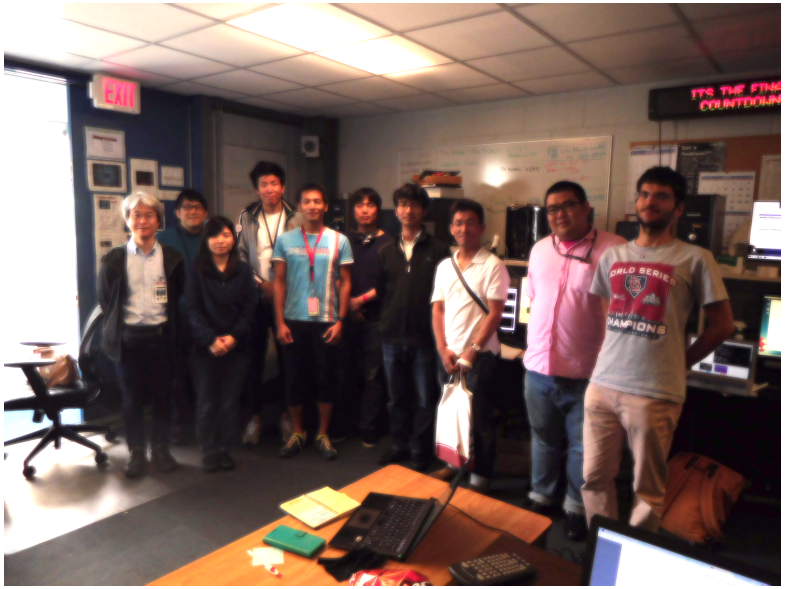






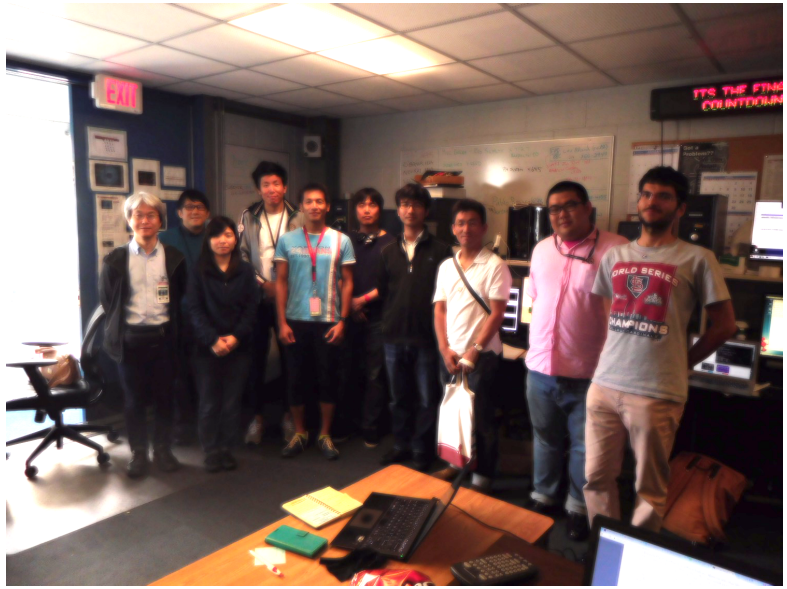
- We are measuring same collision!!

Summary



- RHICf is
  - Forward (zero degree) calorimeters at STAR to measure
    - Neutral particle production to understand cosmic-ray air shower developments
    - Single-spin asymmetry of neutral particles with wide p_T coverage
  - Ready to operate with STAR
  - Preparing for physics operation from TODAY!!!

Summary



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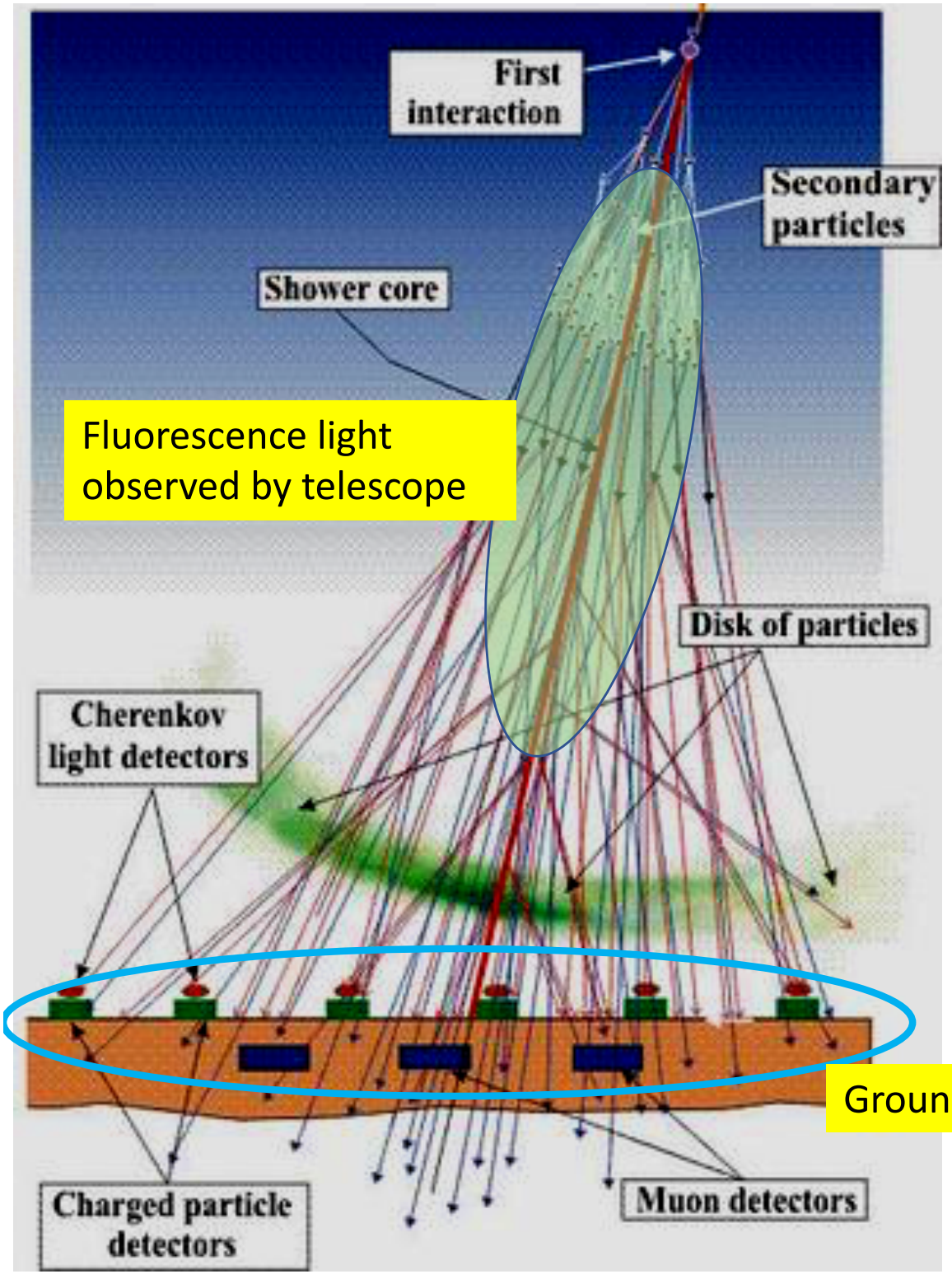
RHICf thanks all RHIC community especially PAC, C-AD, STAR and PHENIX teams for supporting our activity

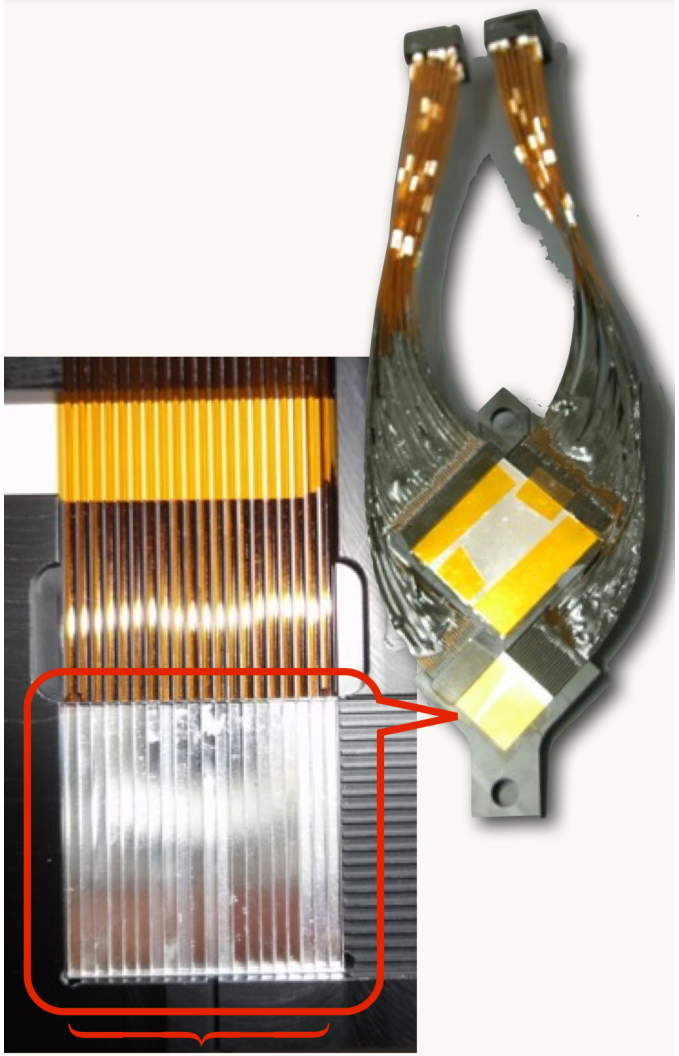
Backup



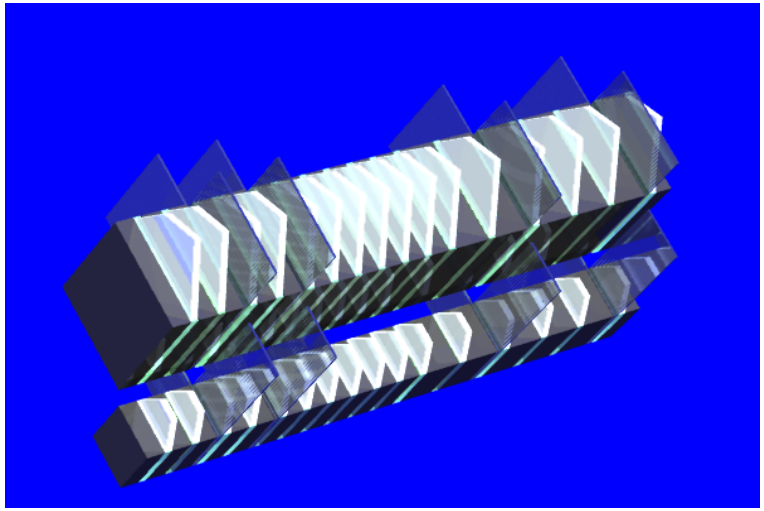
Air shower and hadronic interaction

- ✓ Cosmic rays with $E>10^{14}$ eV are observed through atmospheric air shower
- ✓ Energy and mass of 1ry particles are determined from the ground observations
- ✓ Interpretation relies on the MC simulation of air showers
- ✓ **Hadronic interaction, especially forward particle production**, is a key of the MC simulation

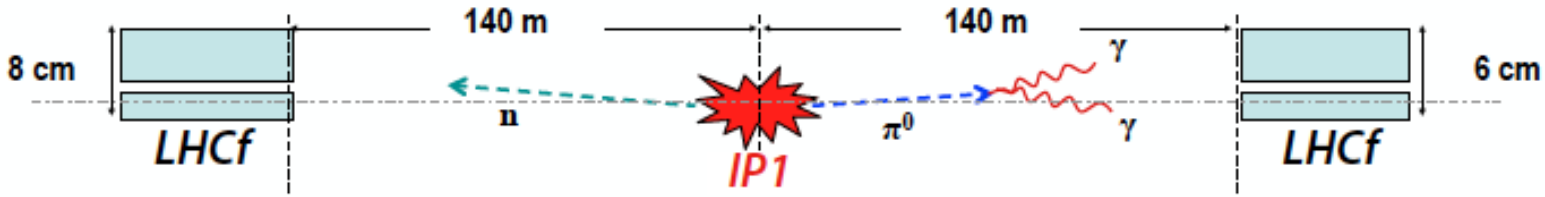
RHICf position sensitive layer



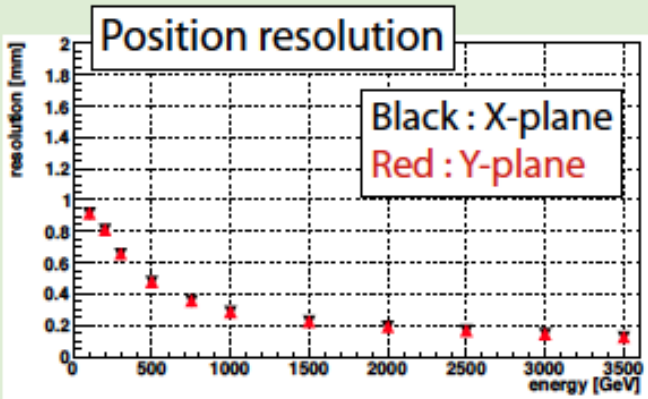
- Array of thin GSO scintillators with
  - 1mmx1mmx20mm or 40mm
- 4 XY pairs, 2 optimized for EM showers and 2 for hadronic showers
- Read out by 8x 64ch MAPMT

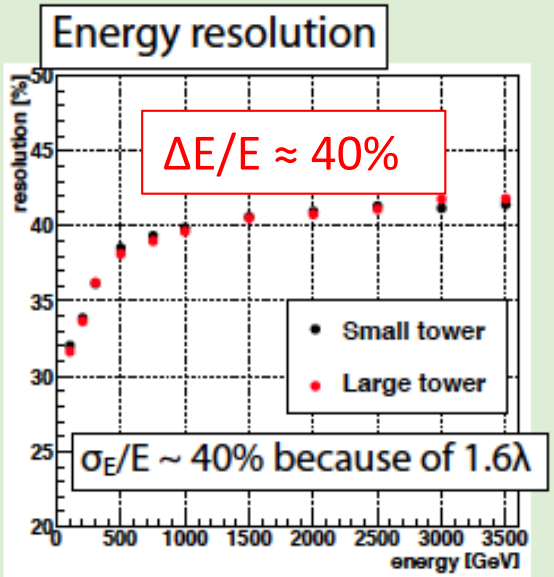


Detector performance

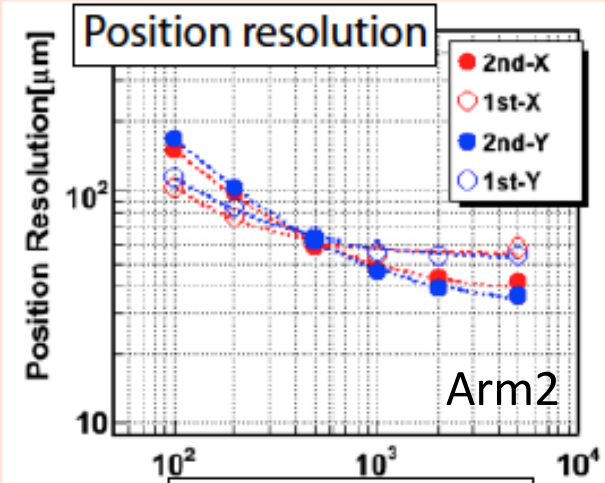


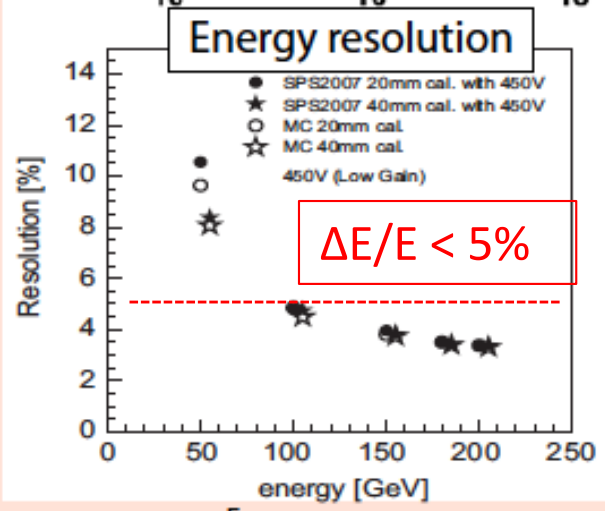
Hadronic shower (MC)





EM shower (MC)





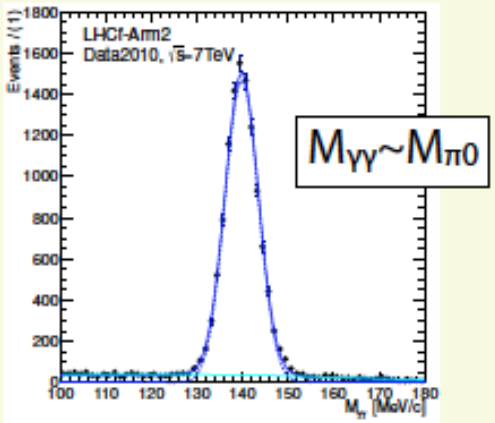
PID technique

400GeV photon

1TeV neutron

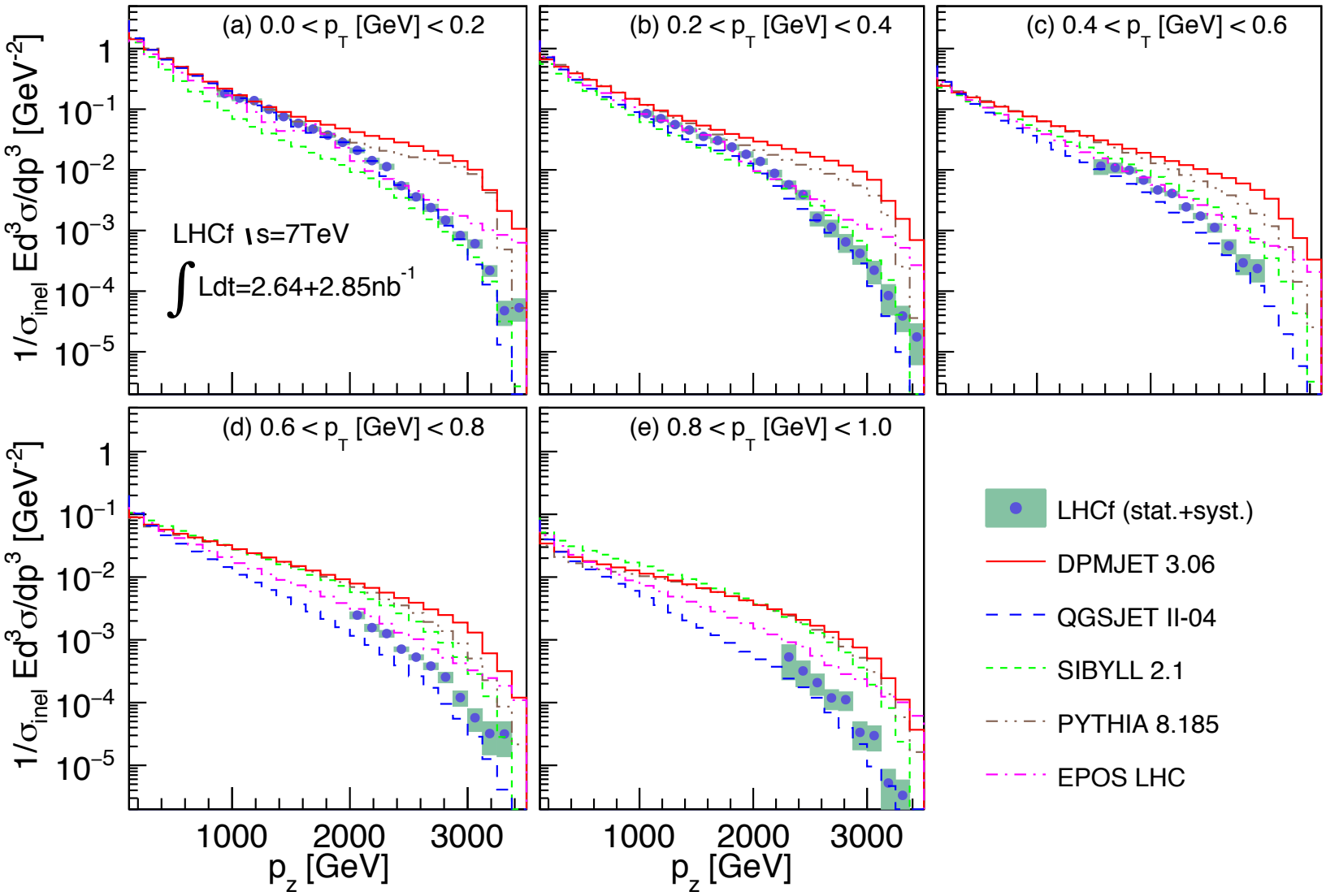
Identification of incoming particle by shower shape

π^0 reconstruction



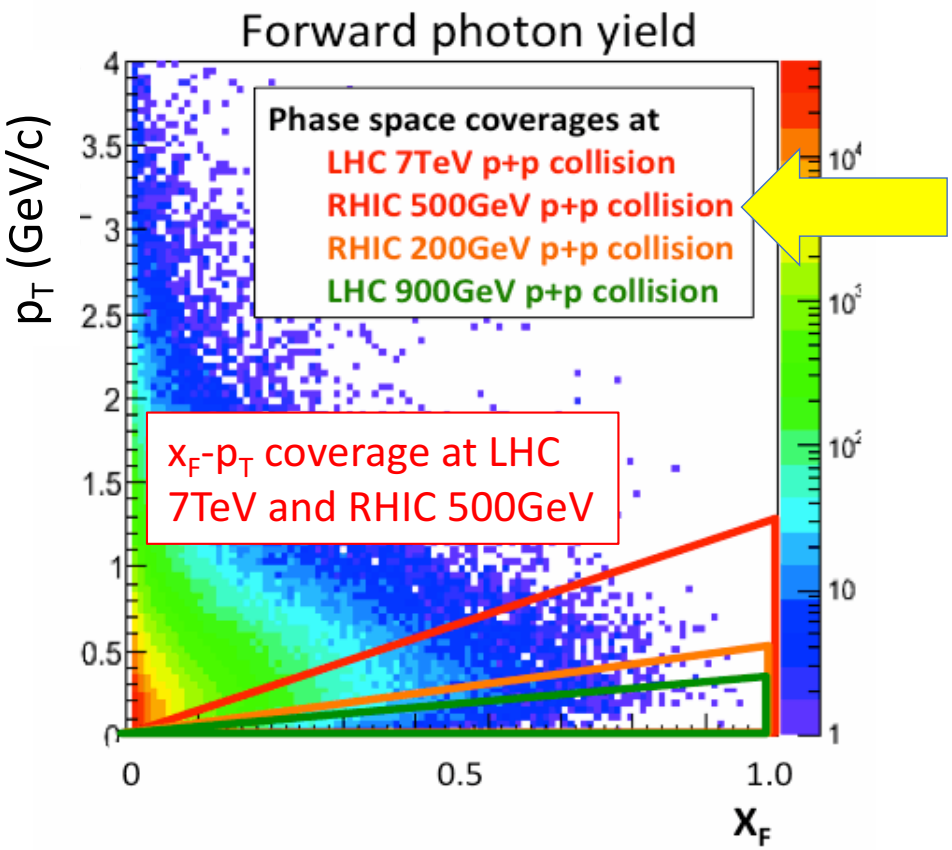
π^0 p_z spectra in 7TeV p-p collisions

(PRD, 94 (2016) 032007)



✓ DPMJET3 and PYTHIA8 overestimate over all E-p_T range

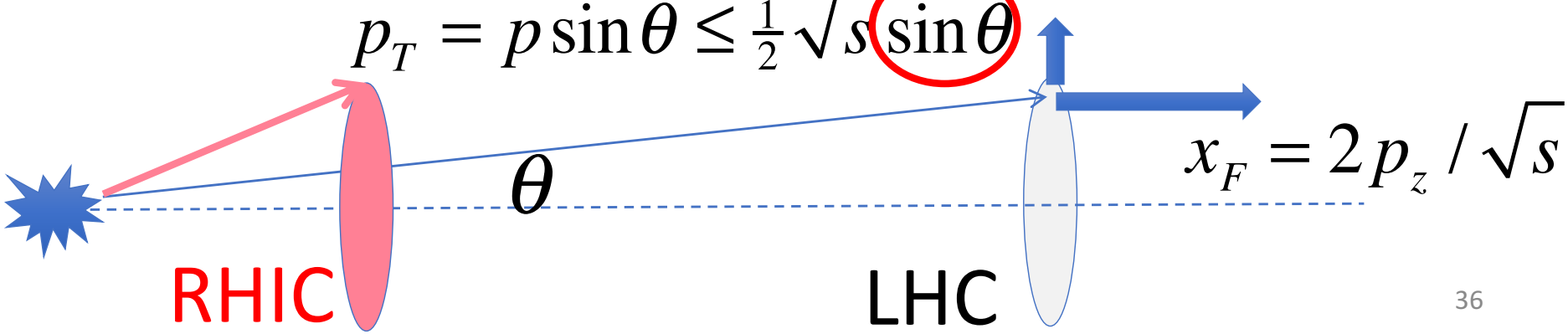
Why not LHC 900GeV?



- ✓ Wide x_F-p_T coverage is desired
- ✓ Maximum p_T coverage is proportional to $\theta\sqrt{s}$

- ✓ RHIC allows larger θ with smaller $\sqrt{s}$
- ✓ x_F-p_T coverage at LHC 7TeV and RHIC 500GeV are almost identical!!

$$p_T = p\sin\theta \le \tfrac{1}{2}\sqrt{s}\sin\theta$$



Single spin asymmetry (RHICf)

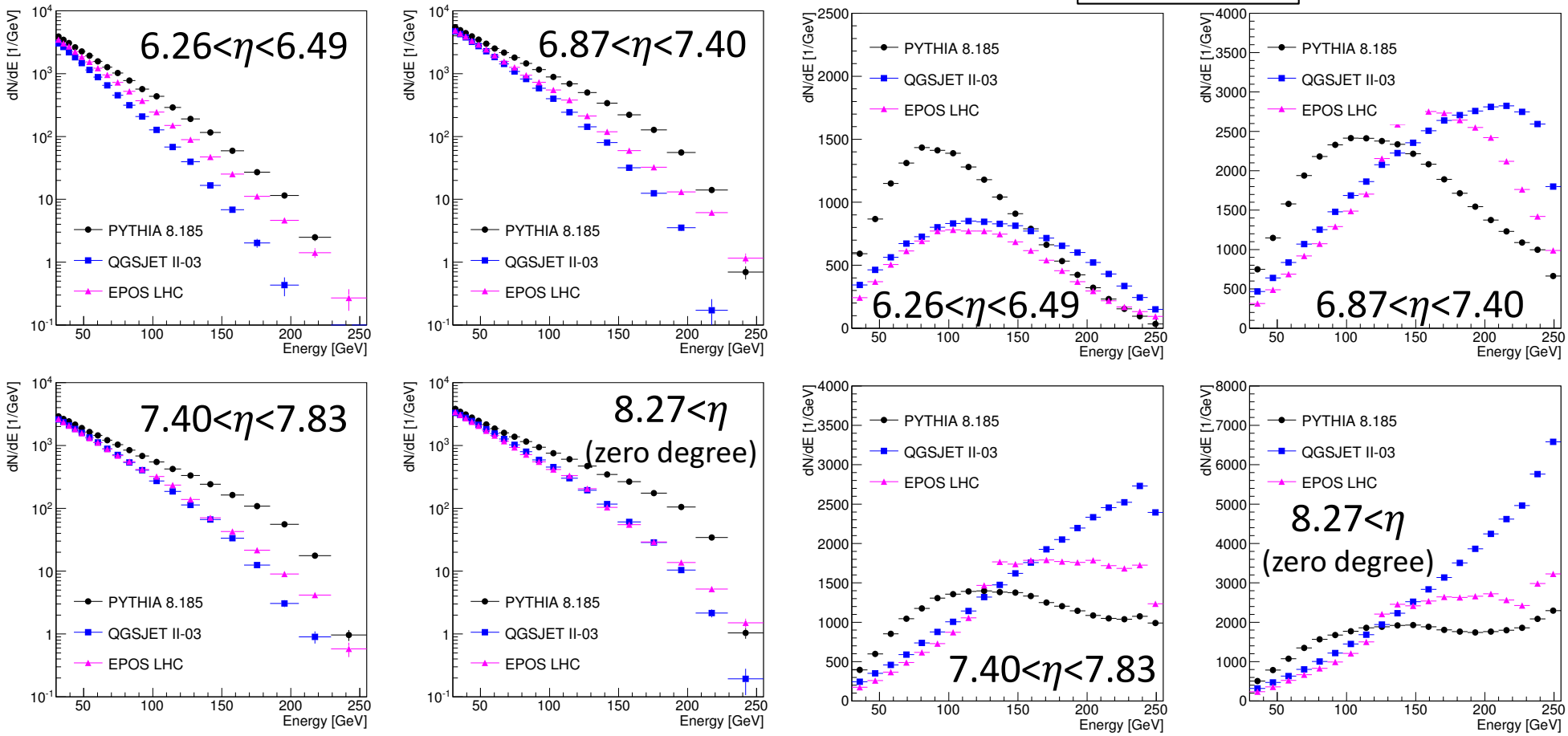
(12 (4) hours statistics for neutron/photon (π^0))

	neutron		photon		π^0	
p_T (GeV/c)	$N(\times 10^3)$	δA	$N(\times 10^3)$	δA	$N(\times 10^3)$	δA
0.0 – 0.1	660	0.0025	110	0.0060	100	0.0063
0.1 – 0.2	920	0.0021	120	0.0058	130	0.0055
0.2 – 0.3	820	0.0022	110	0.0060	89	0.0067
0.3 – 0.4	670	0.0024	79	0.0071	58	0.0083
0.4 – 0.5	450	0.0030	43	0.0096	37	0.010
0.5 – 0.6	250	0.0040	18	0.015	14	0.017
0.6 – 0.8	170	0.0049	8	0.022	8	0.022
0.8 – 1.0	29	0.012	1	0.063	1	0.063

Model to model difference and 12 hours statistics

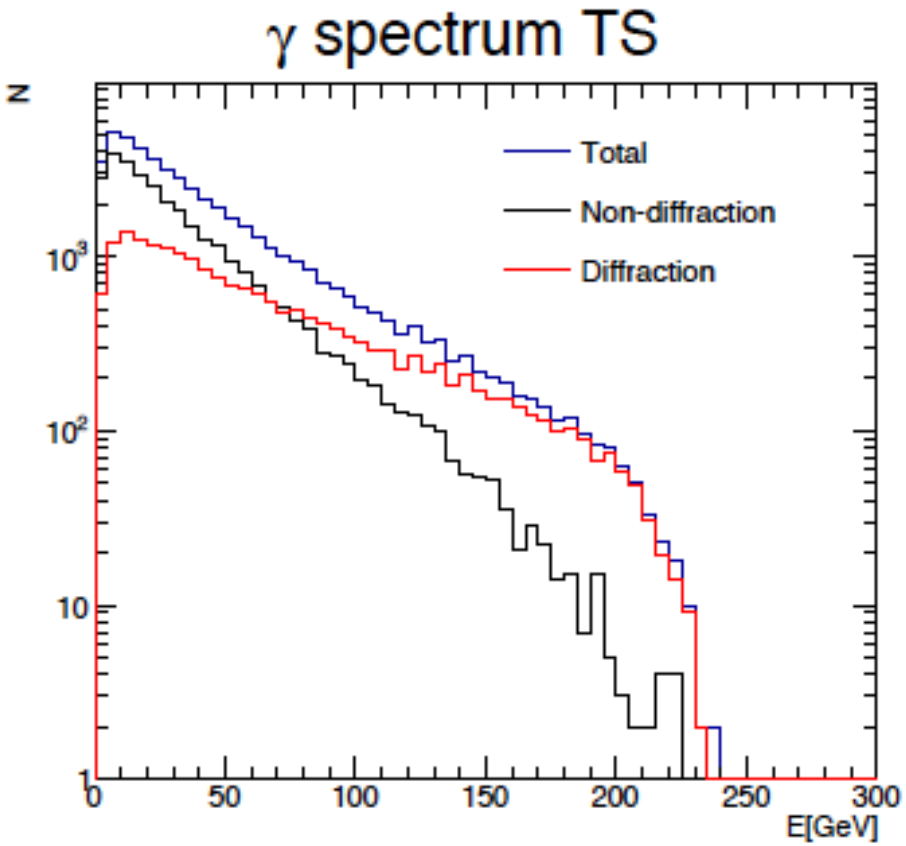
Photon

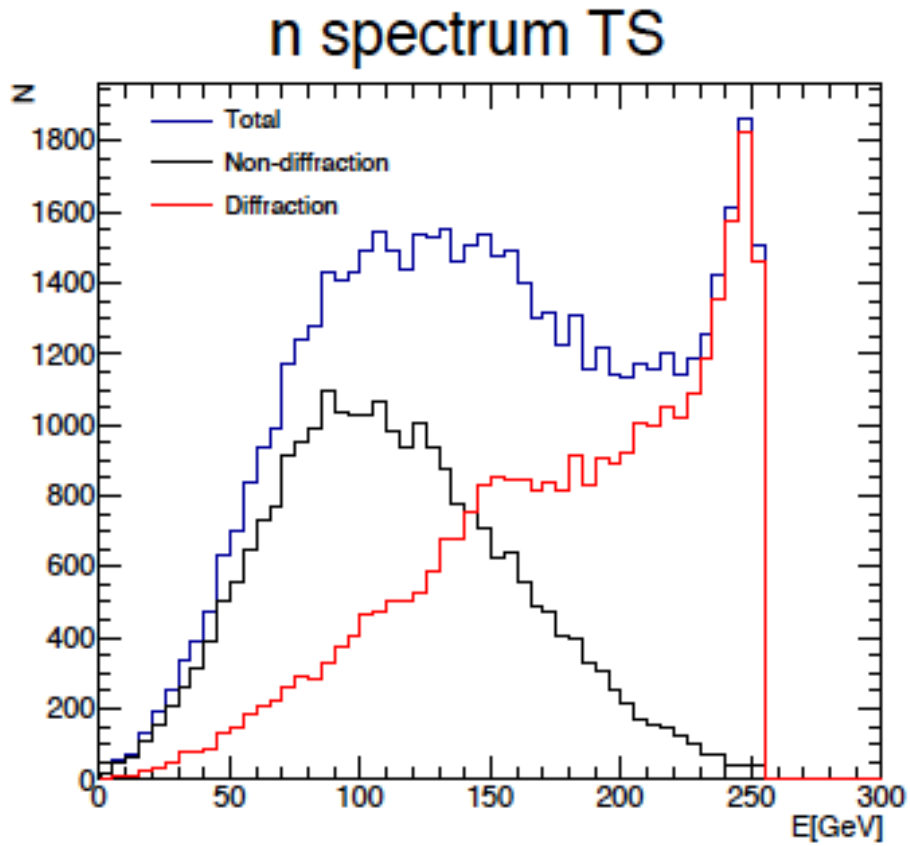
Neutron



- ✓ Behavior is very similar to the 7TeV, 13TeV cases
- ✓ Good statistics except for photon highest energy

diffractive vs. non diffractive at η>8.2 with √s=510GeV p+p collisions





PYTHIA 8 simulation

BLUE: inclusive spectra expected by RHICf only

RED: diffractive only ("RHICf + no central track in STAR" will be similar => TBC)

BLACK: non diffractive ("RHICf + >=1 central track in STAR" => TBC)