Prospects of the sPHENIX Cold-QCD Physics Program at RHIC

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The 11th Circum-Pan-Pacific Symposium on High Energy Spin Physics
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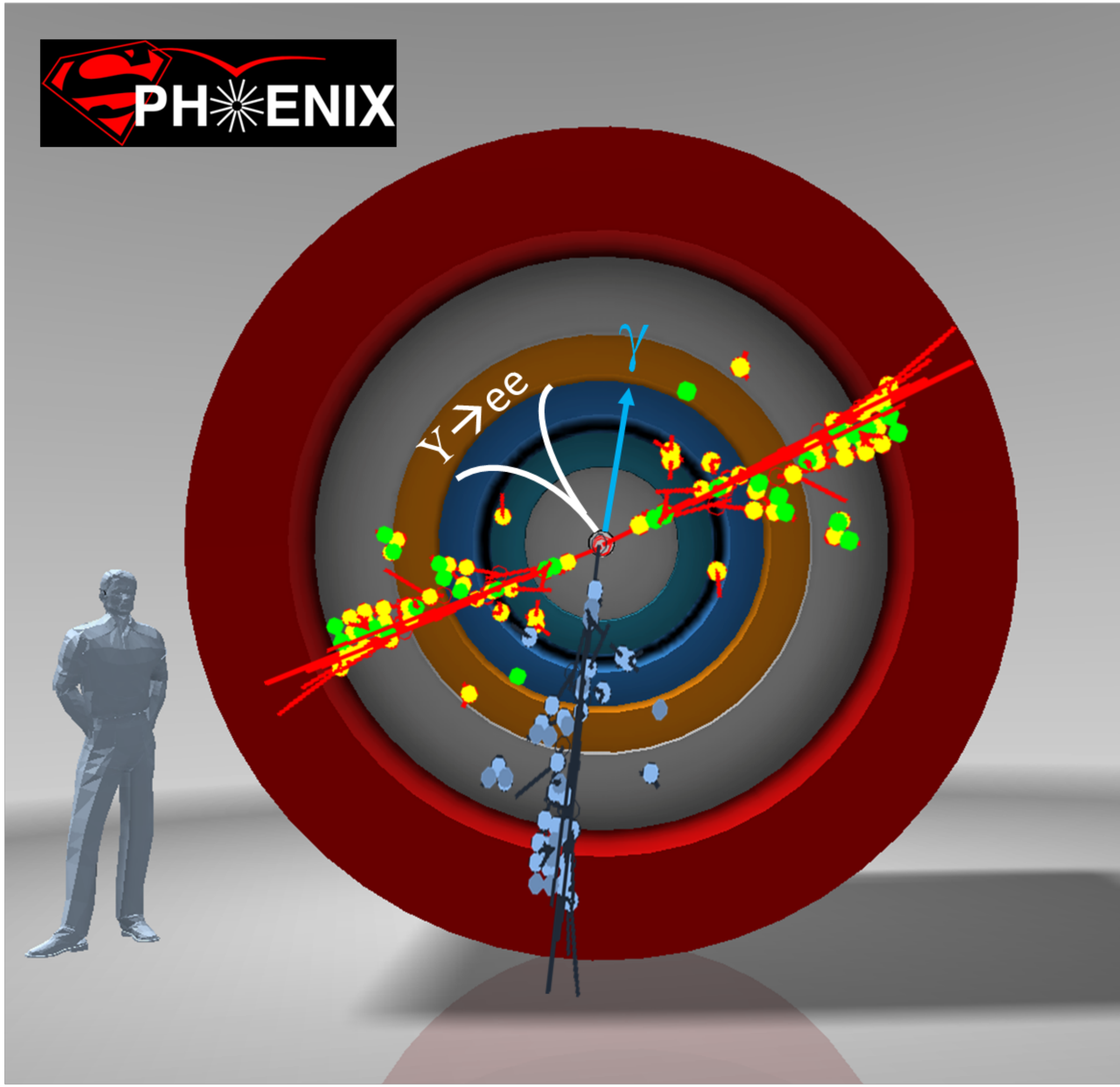
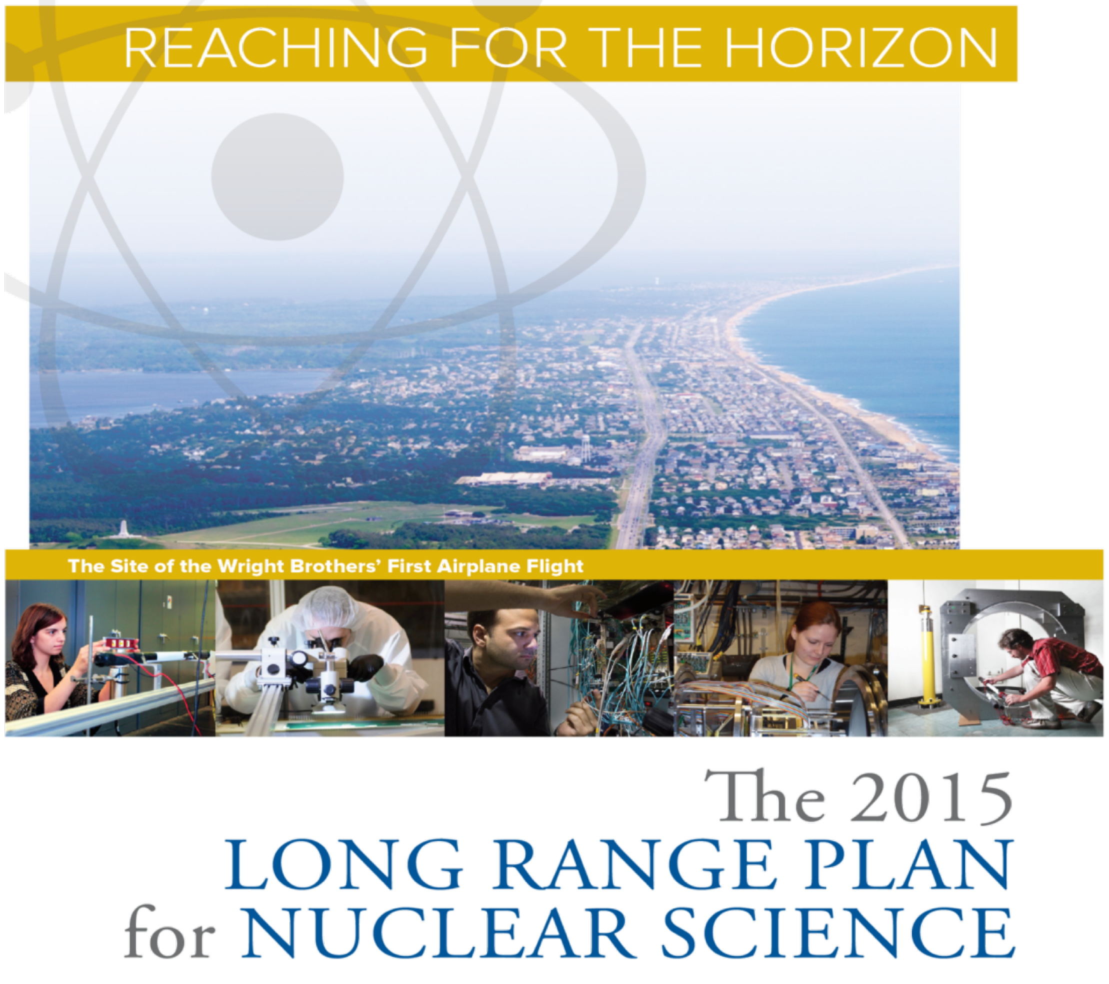
Outline

- sPHENIX physics and detectors
  - Quark-Gluon-Plasma
- A new Cold-QCD physics opportunity
  - Nucleon spin, TMD
  - Small-x, nuclear PDF
  - Forward upgrade
- Outlook
  - Forward upgrade
  - EIC



US Nuclear Physics Long Range Plan (2015)

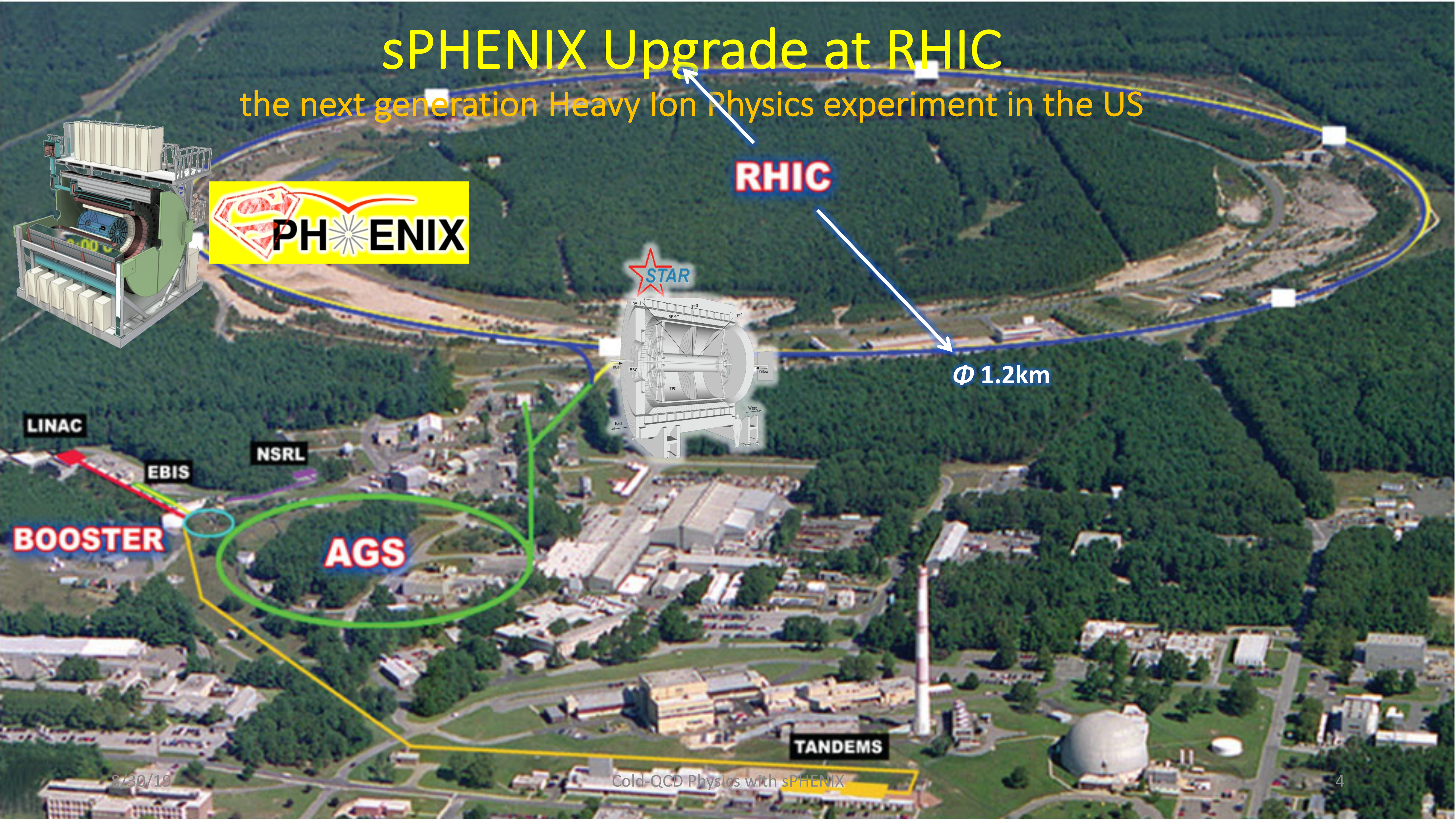
sPHENIX – to understand "Inner Workings of QGP"



"To understand the workings of the QGP, there is no substitute for microscopy. We know that if we had a sufficiently powerful microscope that could resolve the structure of QGP on length scales, say a thousand times smaller than the size of a proton, what we would see are quarks and gluons interacting only weakly with each other. **The grand challenge for this field in the decade to come is to understand how these quarks and gluons conspire to form a nearly perfect liquid."**

sPHENIX Upgrade at RHIC

the next generation Heavy Ion Physics experiment in the US



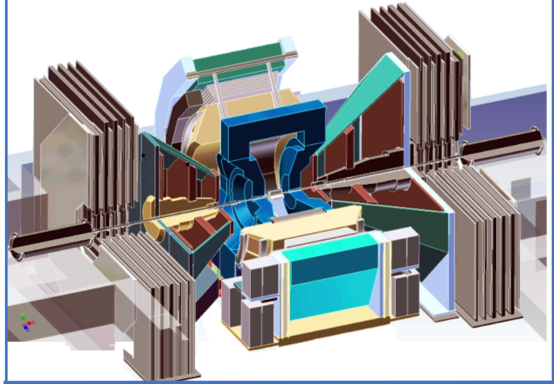
Evolution of the PHENIX Interaction Region at RHIC

sPHENIX

PHENIX experiment

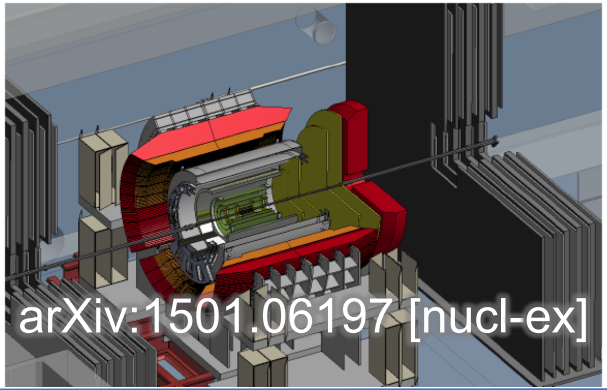
- 16y+ operation
- Broad spectrum of physics

  (QGP, Hadron Physics, Dark Matter)
- 170+ physics papers with 24k citations
- Last run in this form 2016



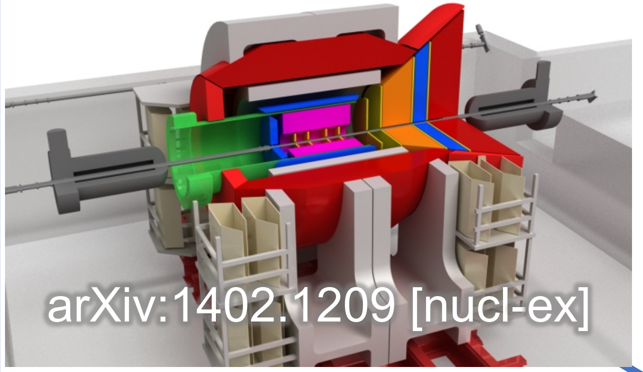
sPHENIX

- Comprehensive central upgrade base on BaBar magnet
- Jet, heavy flavor and beauty quarkonia physics program → nature of QGP
- Possible forward tracking and calorimeter upgrade → Spin,



An EIC detector

- Path of PHENIX upgrade leads to a capable EIC detector
- Large coverage of tracking, calorimetry and PID
- Open for new collaboration/new ideas

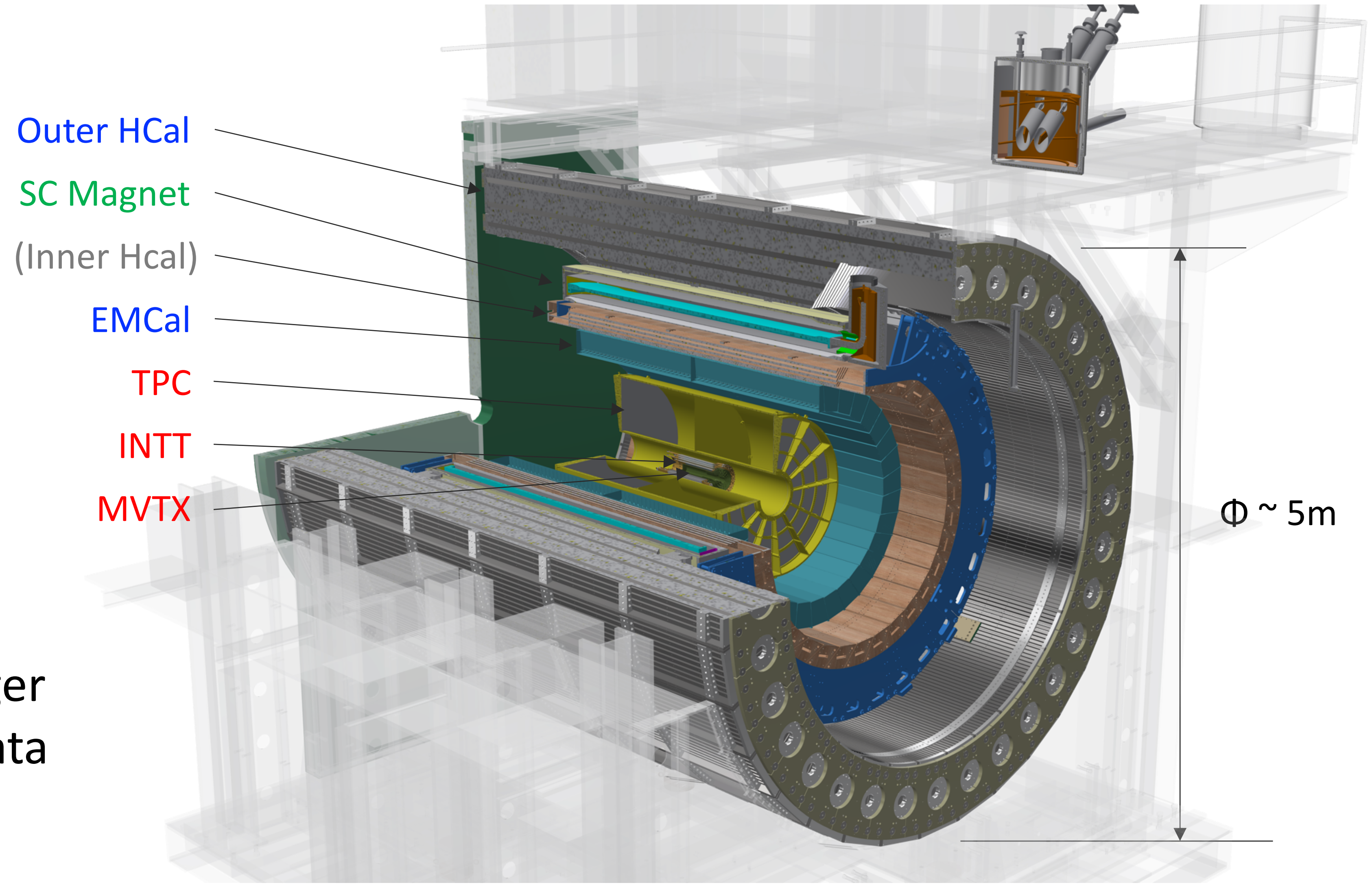


2000-2016 | 2017→2022; Physics: 2023+ | >2025+ | Time

RHIC: A+A, spin-polarized p+p, spin-polarized p+A

EIC: e+p, e+A

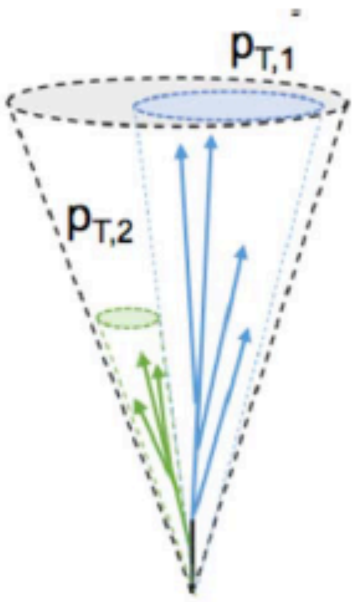
The sPHENIX Detectors



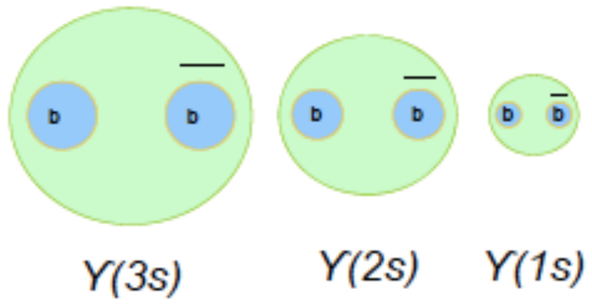
- |eta| < 1.1
- B: 1.4 T
- 15 kHz trigger
- >10 GB/s data

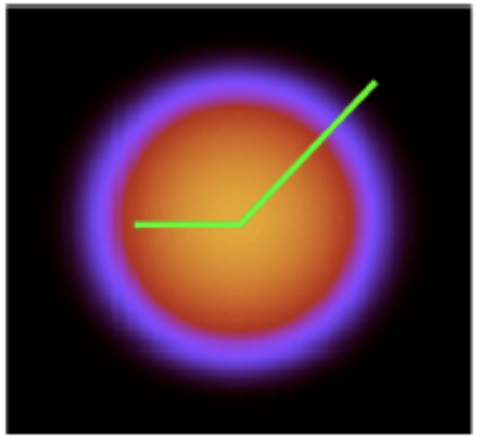
Probing the Inner Workings of QGP in sPHENIX
- Key Capabilities

Jet structure
vary momentum/angular scale of probe

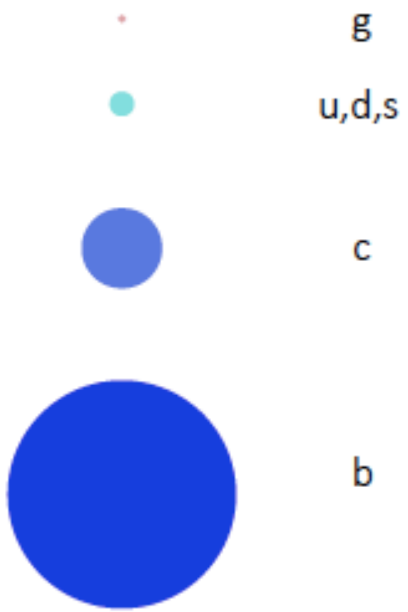


Quarkonium spectroscopy
vary size of probe



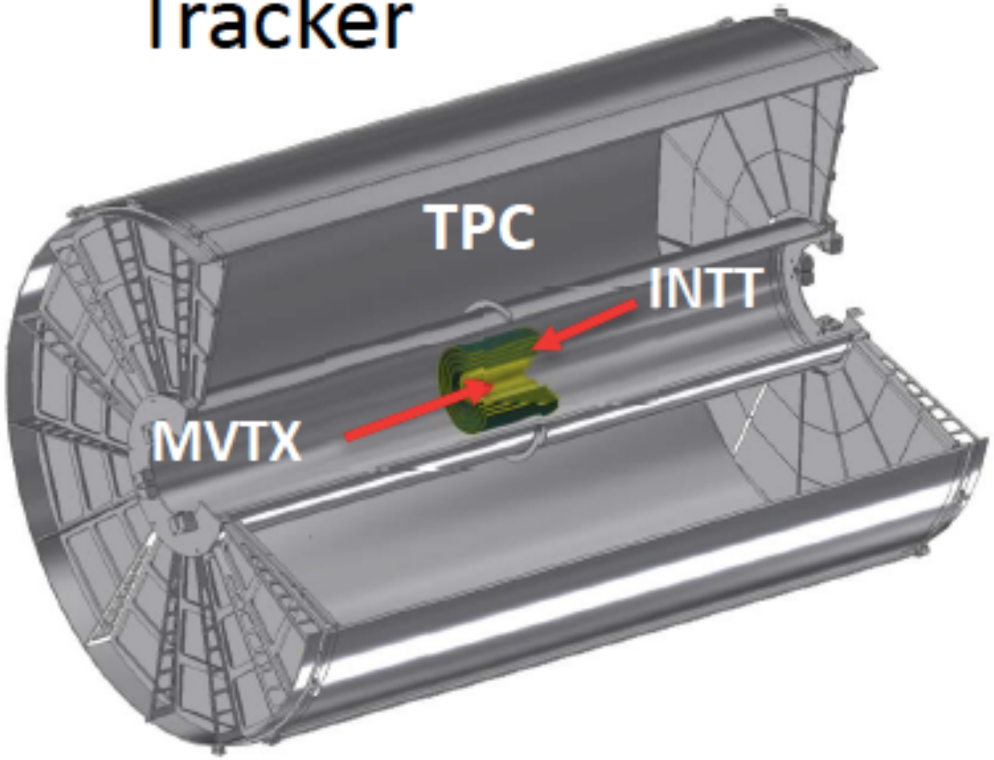


Parton energy loss
vary mass/momentum of probe



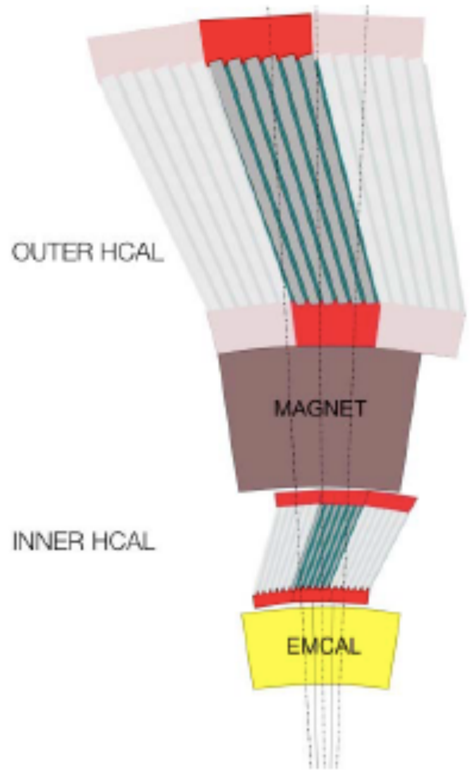
sPHENIX Detector Sub-Systems

Tracker



Continuous readout TPC
Si strip intermediate tracker
3-layer MAPS-based μ vertex

Calorimeter stack

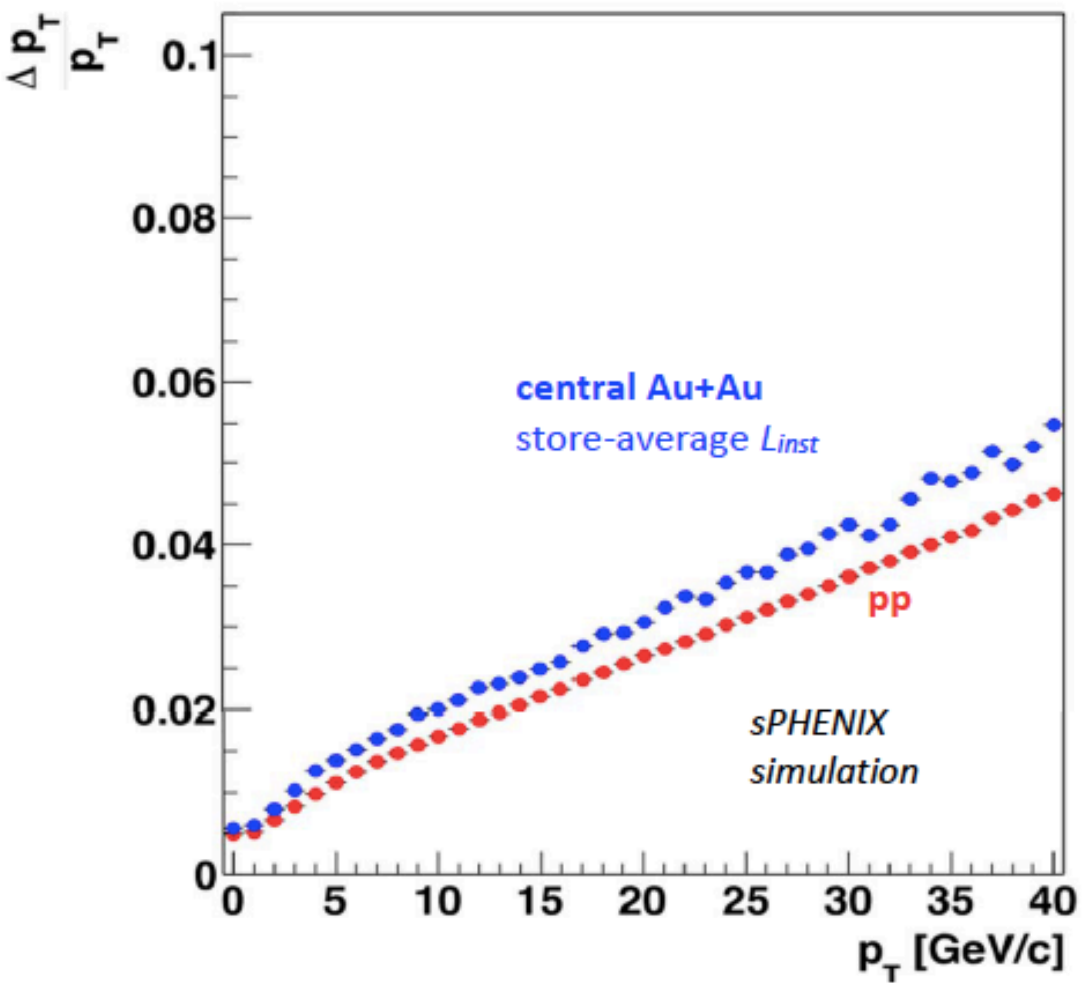


Tungsten/SciFi EMCal
Steel/plastic scintillator HCAL
SiPM readout

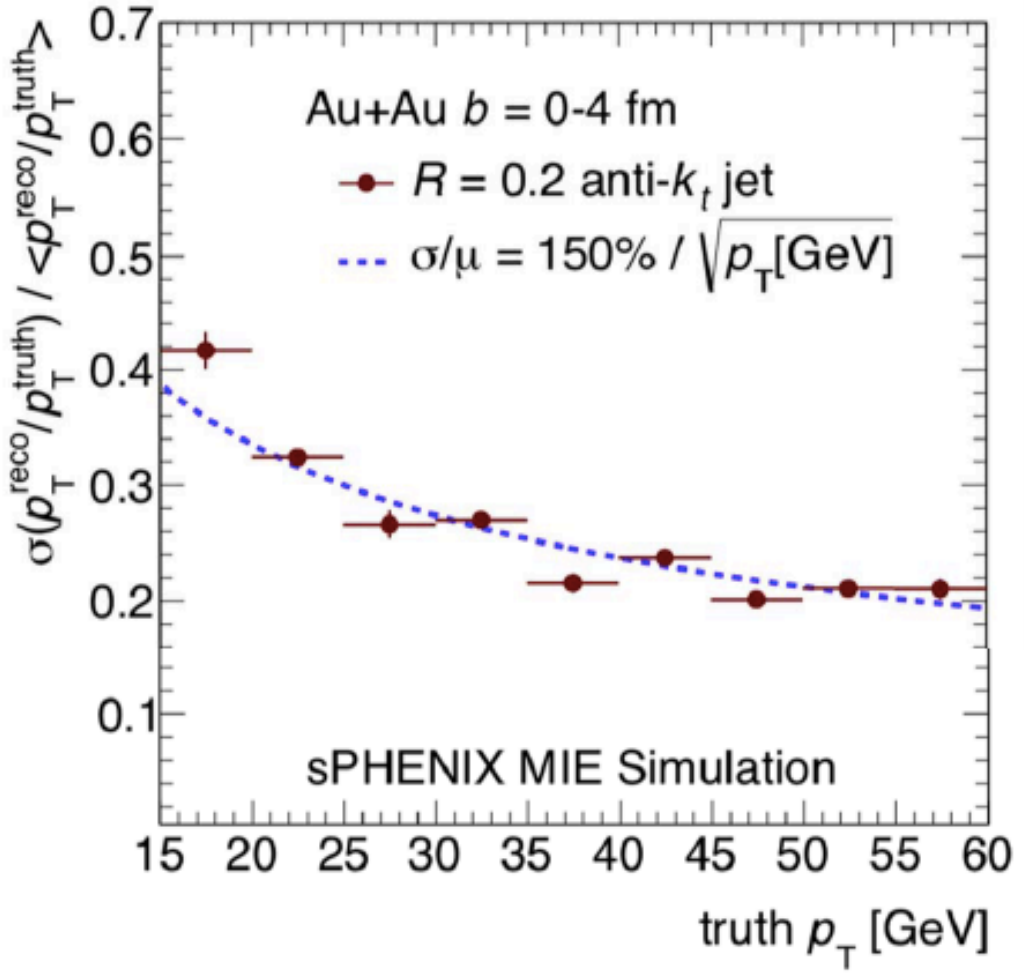
Detector Performance: Tracking and Jets

GEANT simulations verified with test beam data

Track pT resolution (central Au+Au)

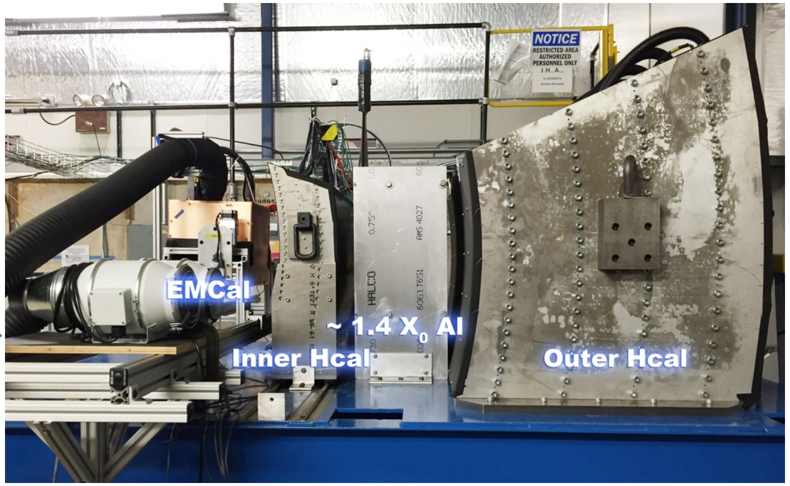


Single jet resolution (central Au+Au)

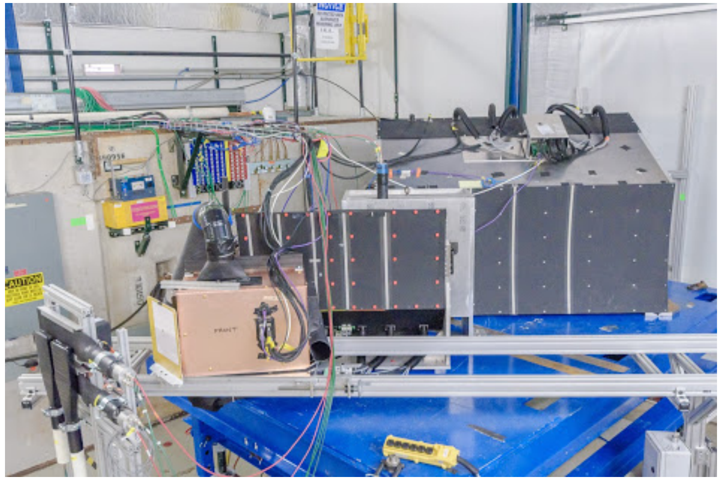


Calorimeters Beam Tests

February 2014
Proof of principle

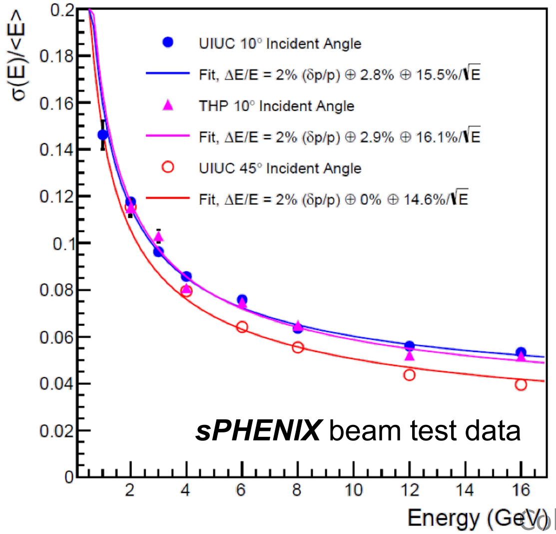


February 2016: η~0 prototype

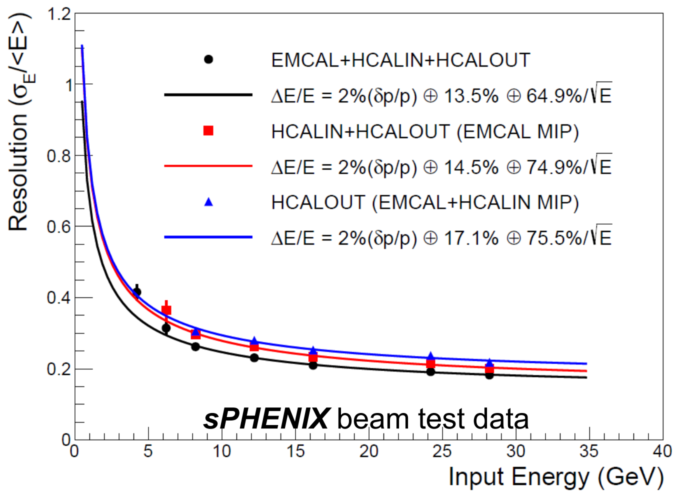


February 2017: η~0.9 prototype

Electron
Energy resolution
arXiv:1704.01461

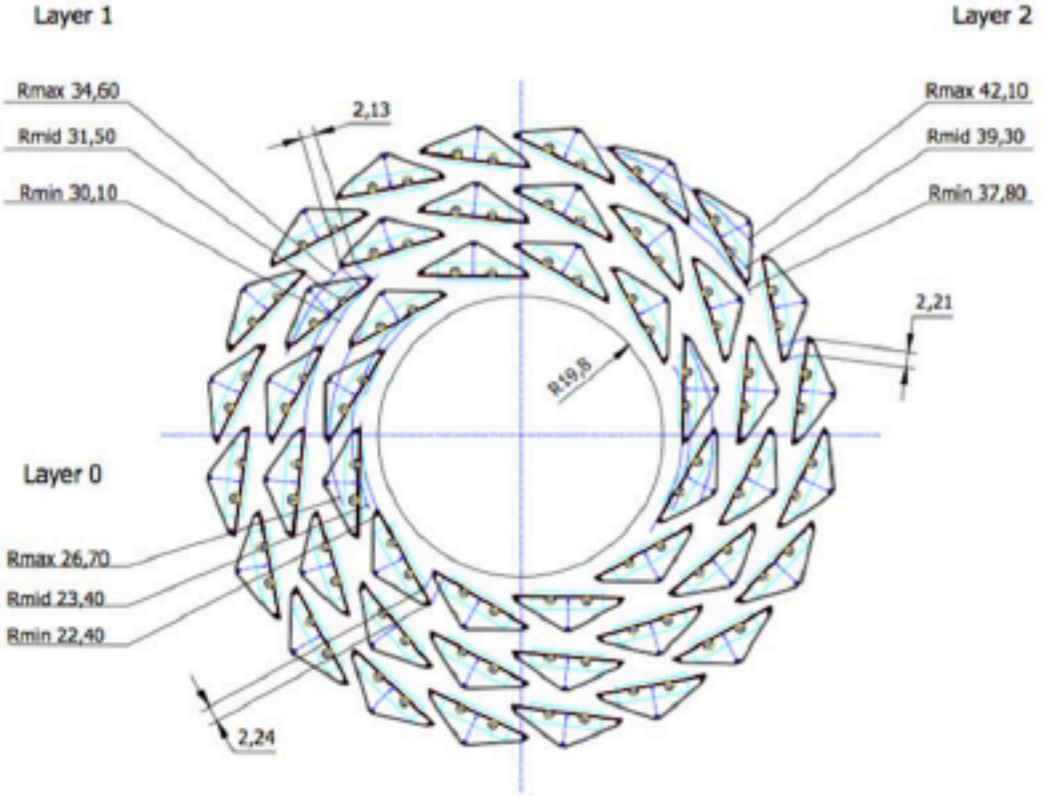


Pion
Energy resolution
arXiv:1704.01461

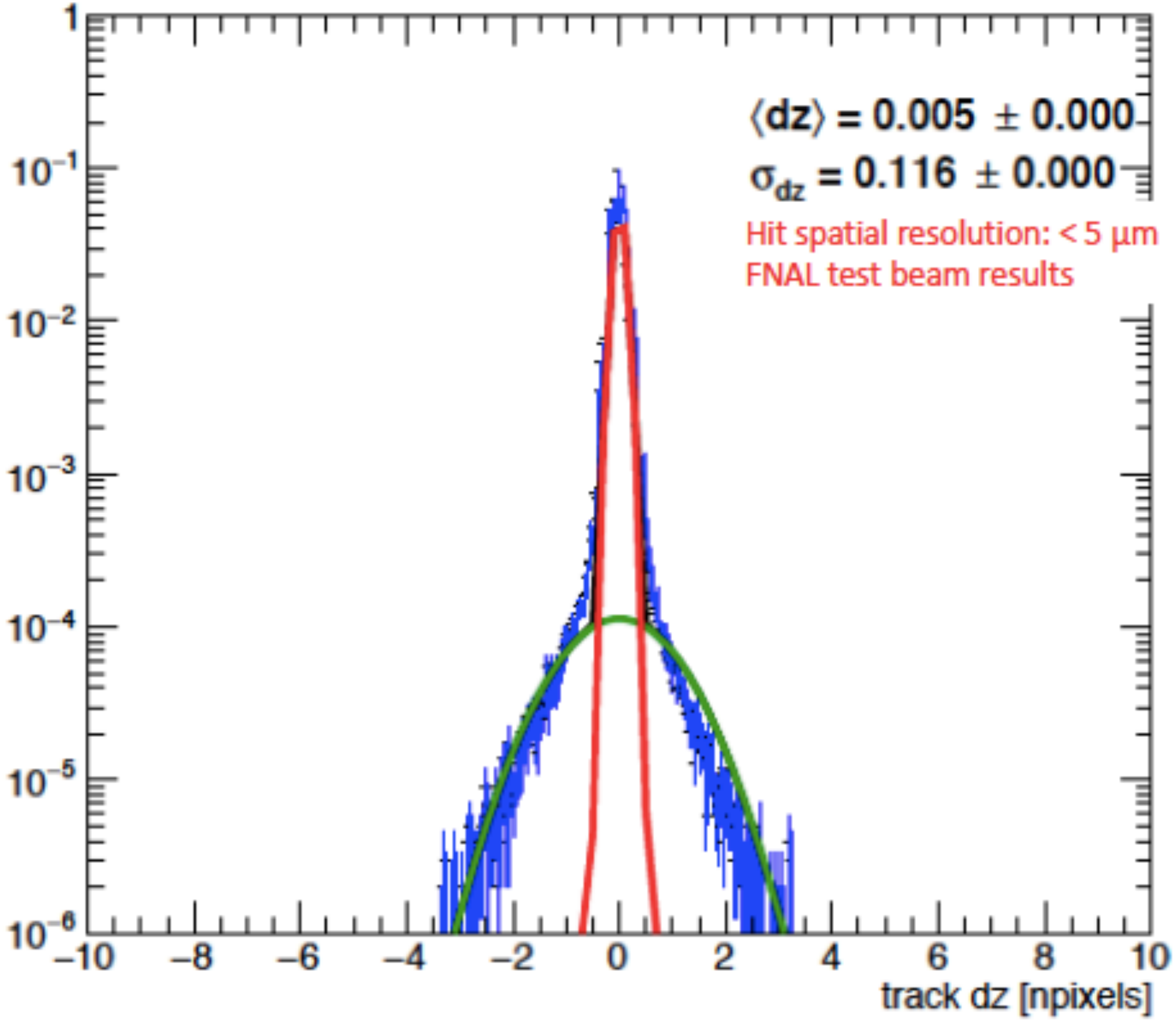


Monolithic-Active-Pixel-Sensor based Precision Vertex Detector
-- for Open Heavy Quark Measurements

Stave layout beam view



MVTX spatial resolution



MVTX based on copy of ALICE staves with support structure modified for sPHENIX

Evolving sPHENIX Run Plan

Champaign -2, Champaign-1

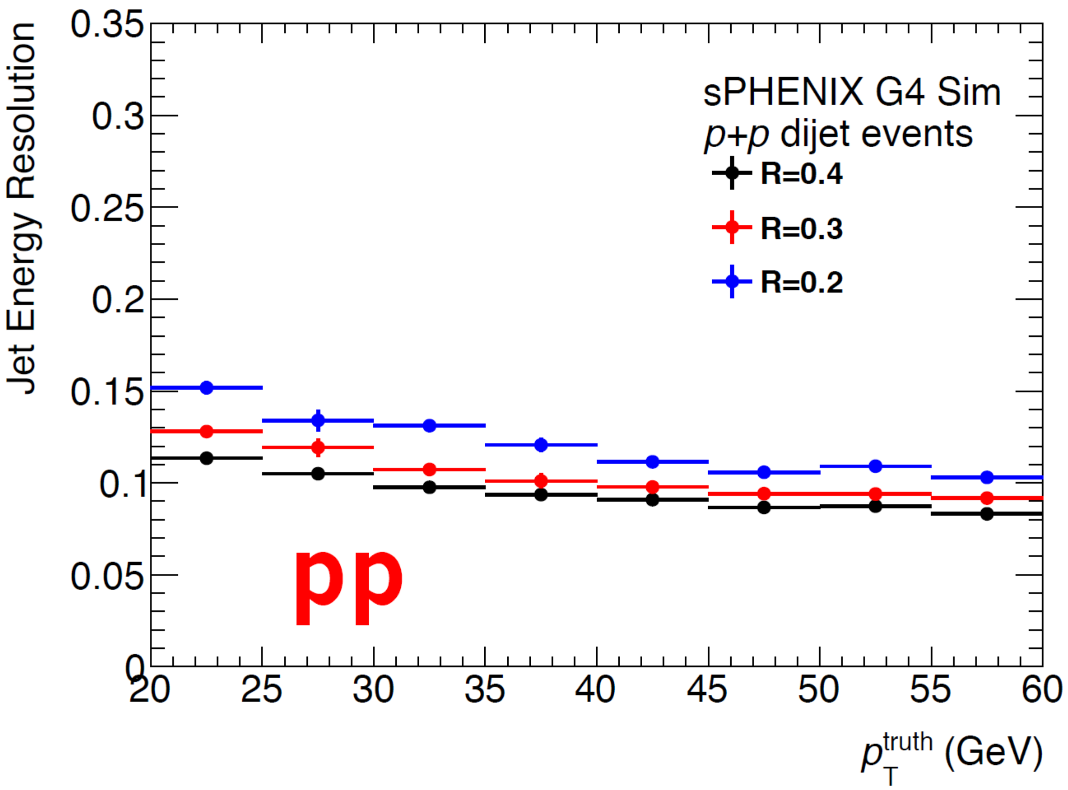
Year	Species	Energy [GeV]	Phys. Wks	Rec. Lum.	Samp. Lum.	Samp. Lum. All-Z
Year-1	Au+Au	200	16.0	7 nb^{-1}	8.7 nb^{-1}	34 nb^{-1}
Year-2	p+p	200	11.5	—	48 pb^{-1}	267 pb^{-1}
Year-2	p+Au	200	11.5	—	0.33 pb^{-1}	1.46 pb^{-1}
Year-3	Au+Au	200	23.5	14 nb^{-1}	26 nb^{-1}	88 nb^{-1}
Year-4	p+p	200	23.5	—	149 pb^{-1}	783 pb^{-1}
Year-5	Au+Au	200	23.5	14 nb^{-1}	48 nb^{-1}	92 nb^{-1}

- Consistent with DOE CD-0 “mission need” document
- Incorporates BNL C-AD guidance on luminosity evolution
- Incorporates commissioning time in first year

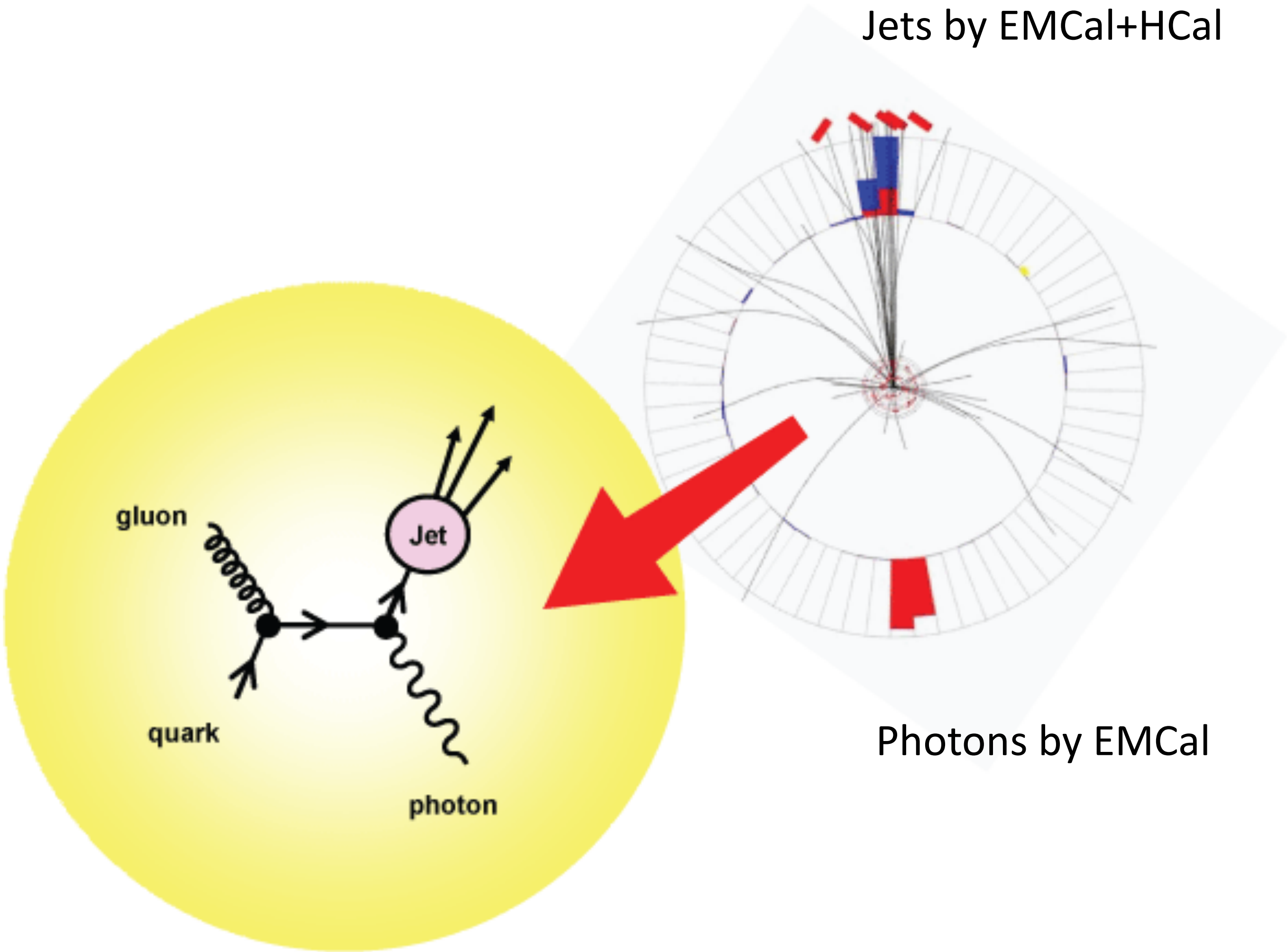
Minimum bias Au+Au at 15 kHz for $|z| < 10$ cm:

Precision Calorimetry for Jets and Photons

Excellent jet resolution in both p+p and A+A



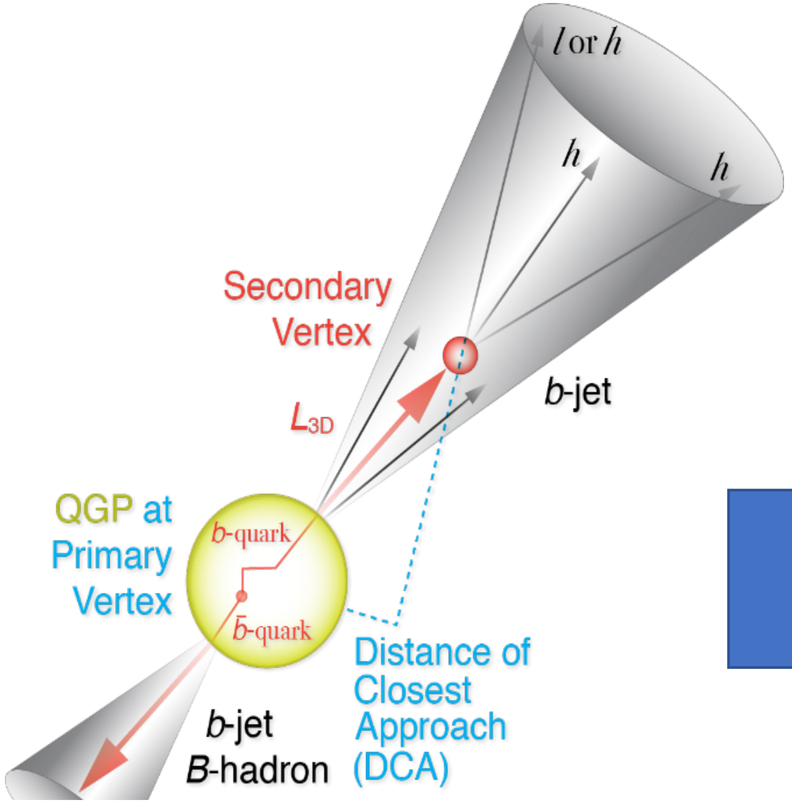
Jets by EMCal+HCal

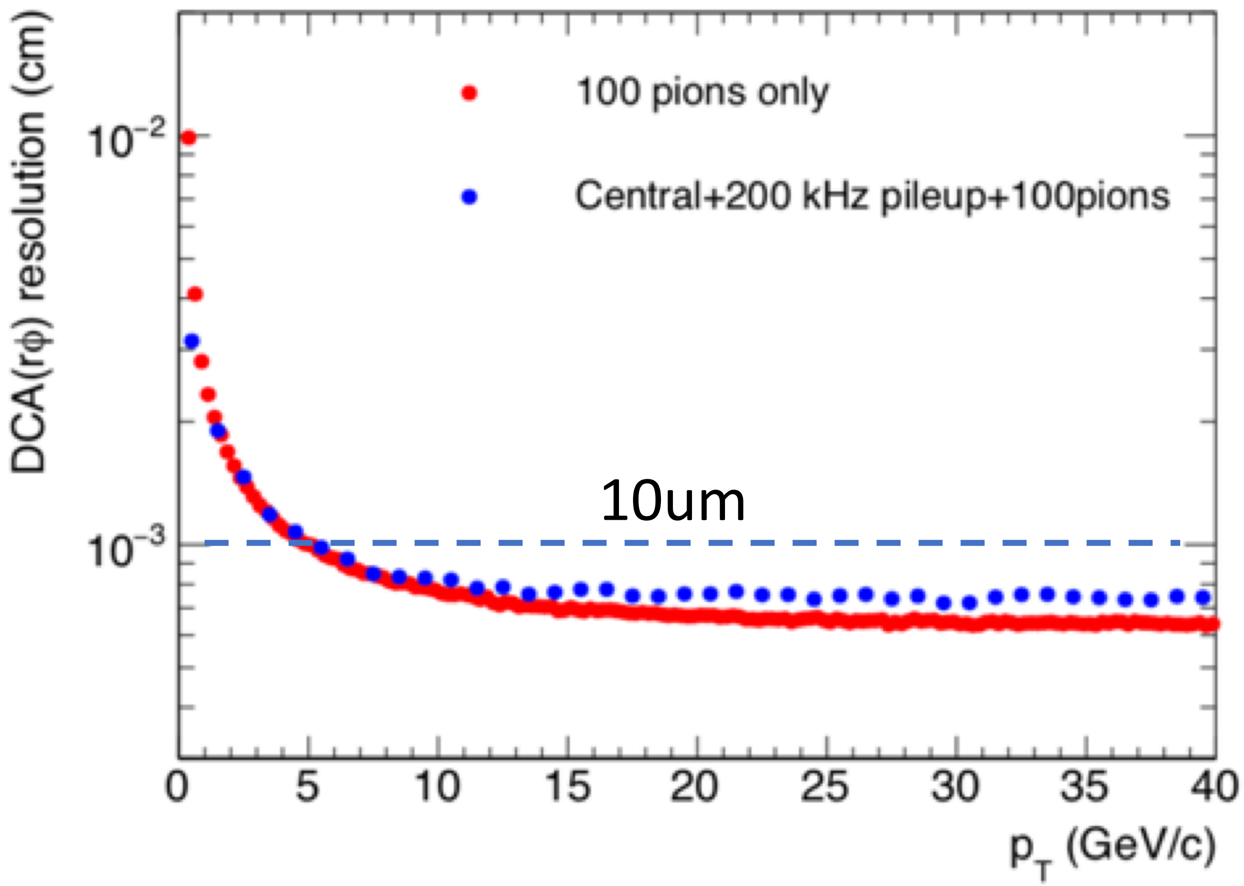


Photons by EMCal

Precision Vertex and Open HF Observables

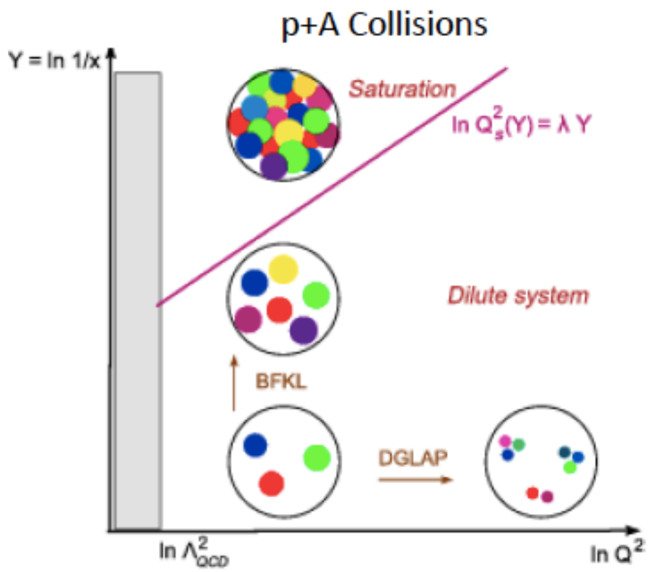
- Precision vertex tracker + high rate capability
  → Precision open charm and bottom over wide scales



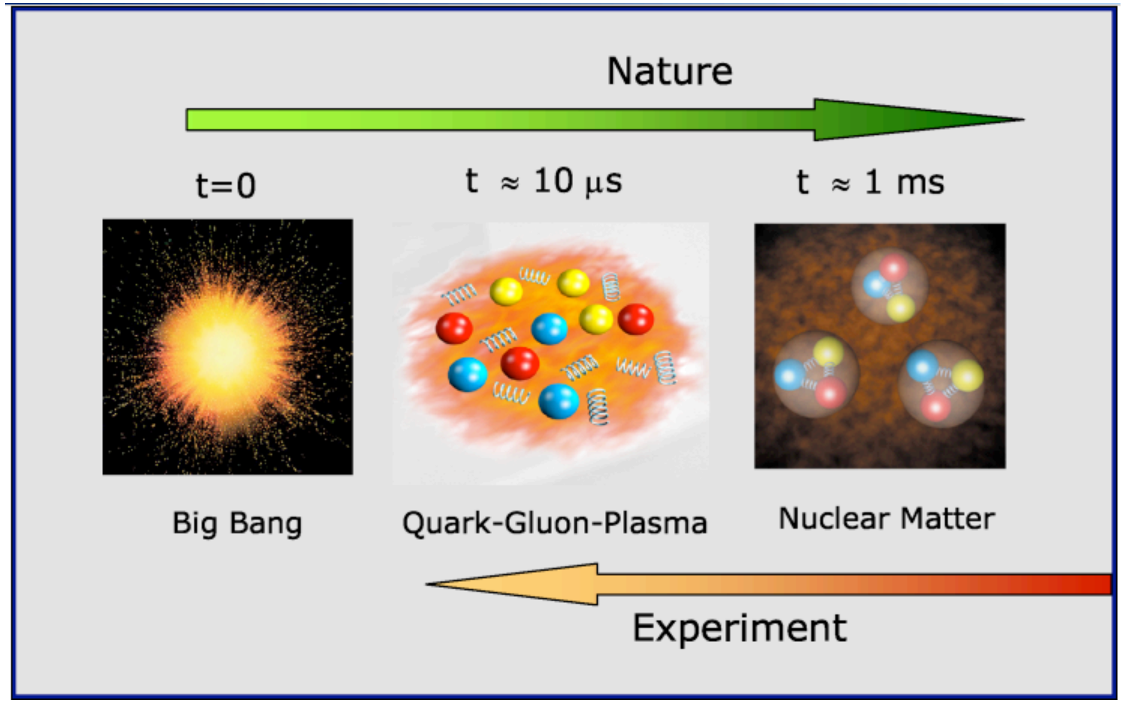


A Broad Physics Program with sPHENIX

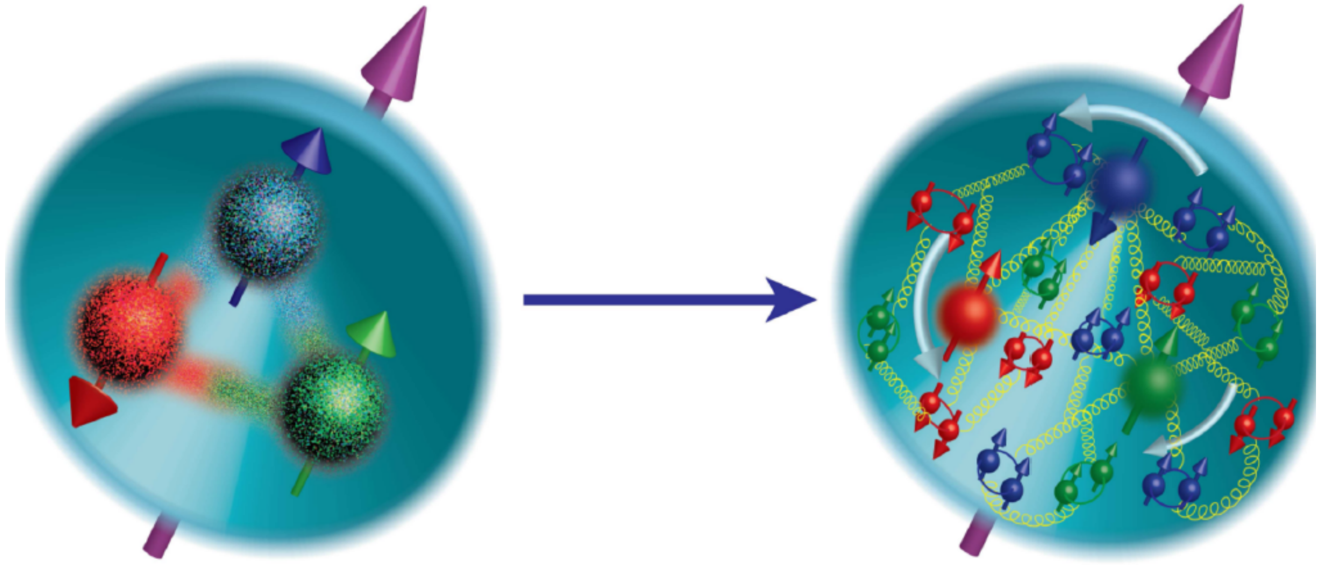
- Nuclear matter under extreme condition, “QGP”
- Nucleon and nuclear structures, QCD evolution, “Cold QCD”



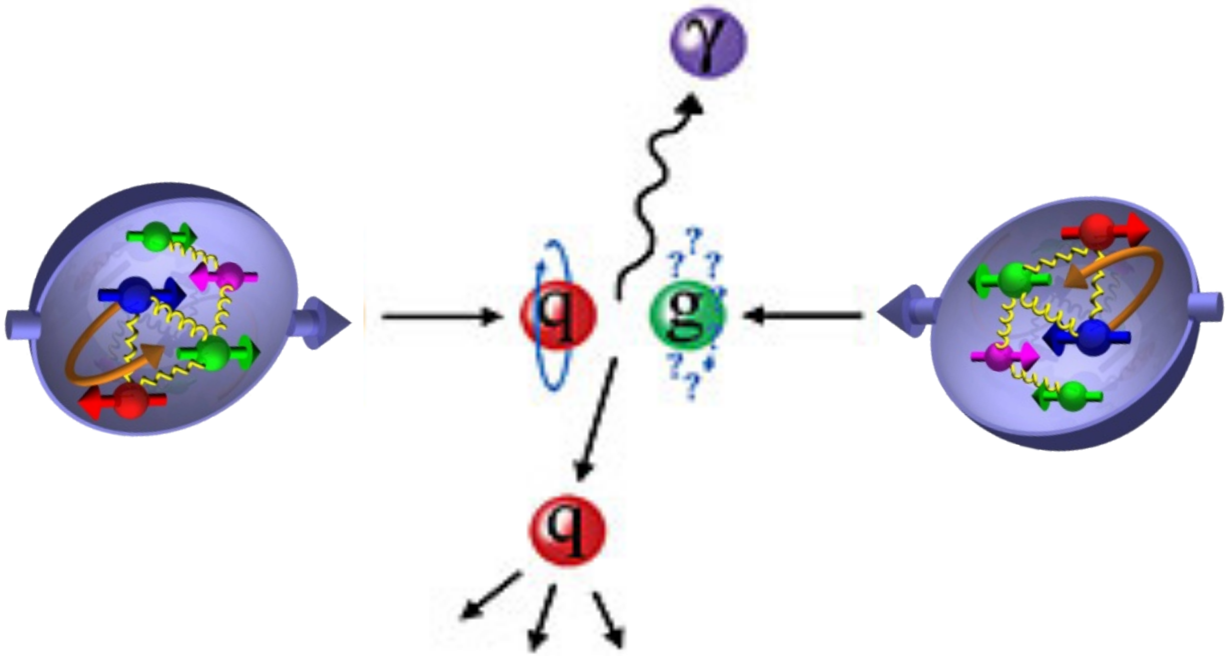
“Hot” QGP physics



“Cold” QCD physics



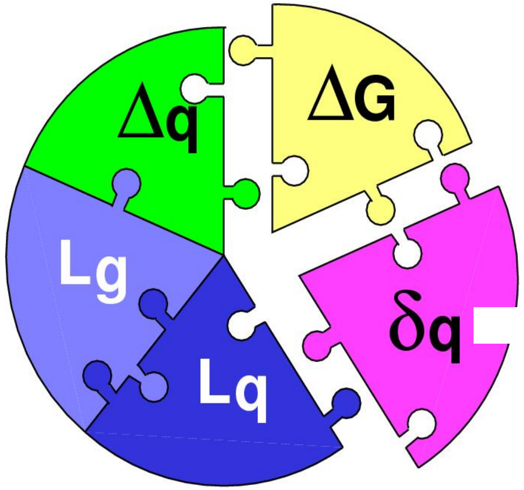
Gluon Polarization



Three Decades of the Proton Spin Puzzle

sPHENIX

- Early expectation: large gluon polarization



$$\Delta\Sigma' = \Delta\Sigma - \frac{\alpha_s}{2\pi}\cdot\Delta G$$

$$\frac{\alpha_s}{2\pi}\cdot\Delta G = 0.3 \pm 0.1$$

Axial anomaly
Cheng & Li, PRL (1989)

EMC, 1980s

$$\frac{1}{2} = \frac{1}{2}\Delta q + L_q^z + \Delta G + L_g^z$$

$$\Delta q \sim 30\% \quad (SIDIS/DIS)$$

$$\Delta G \sim 40\% \quad (RHIC)$$

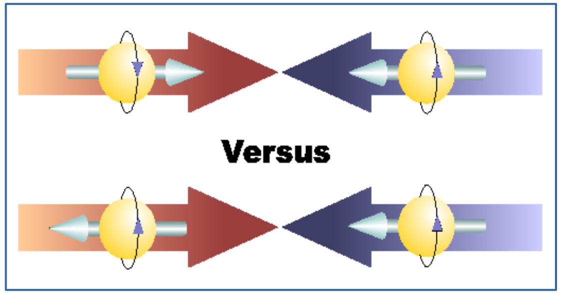
$$L \sim ? \quad (RHIC, FNAL?)$$

	Quark Spin	Gluon Spin
SLAC -> 2000	(E80 – E155)	
CERN ongoing	(EMC), (SMC), COMPASS	
DESY ->2007	(HERMES)	
JLab ongoing	Hall A,B,C	
RHIC ongoing	(BRAHMS), (PHENIX), STAR	

SIDIS/DIS

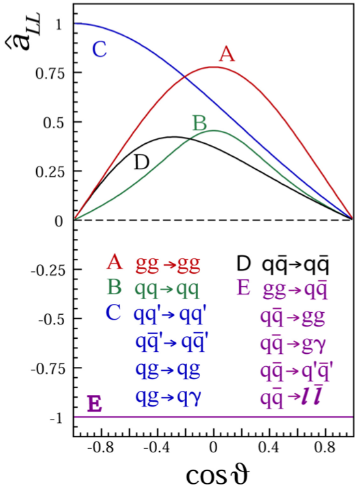
Polarized p+p /hadrons

Gluon Polarization and π^0 (or jet) A_{LL}



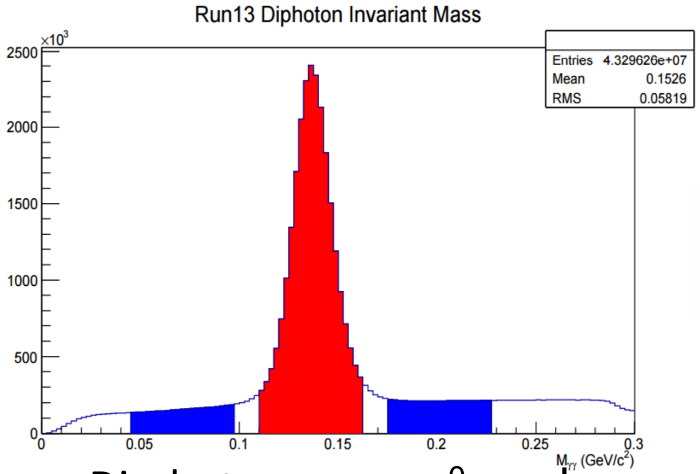
$A_{LL}=(N^{++}-N^{+-})/(N^{++}+N^{+-})$

-- Parton distribution functions
-- Partonic hard scattering rates
-- Fragmentation functions



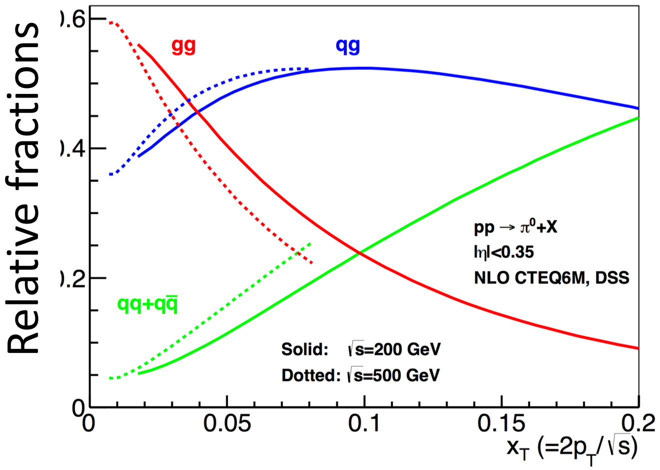
$$\Delta\sigma(pp\rightarrow\pi^0X)\approx\Delta q(x_1)\otimes\Delta g(x_2)\otimes\Delta\hat{\sigma}^{qg\rightarrow qg}(\hat{s})\otimes D_q^{\pi^0}(z)...$$

DIS ? pQCD e+e-



Di-photon mass: π^0 peak

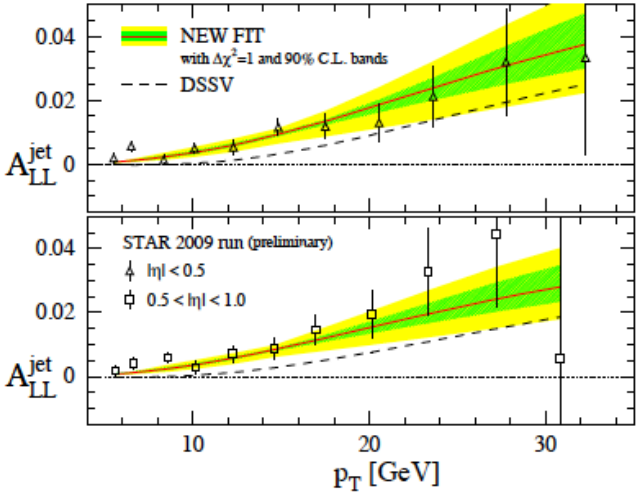
$$A_{LL}^{\pi0}=\frac{A_{LL}^{\pi0+BG}-w_{BG}A_{LL}^{BG}}{1-w_{BG}}$$



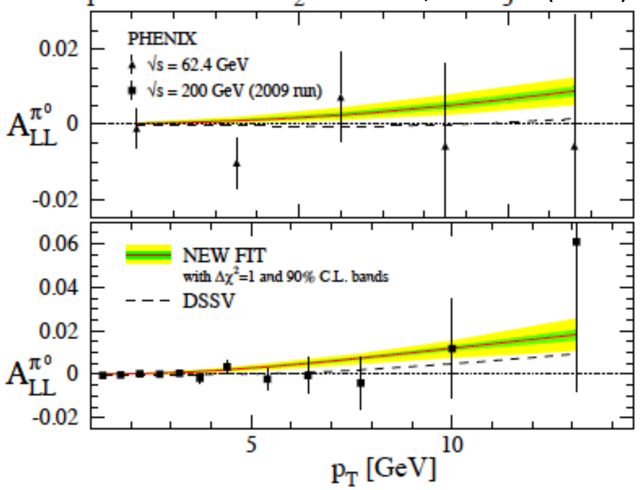
First Hint of Non-zero Gluon Polarization from RHIC

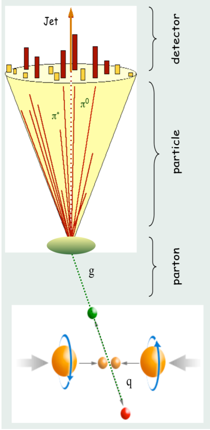
- PHENIX and STAR A_{LL} data

STAR: PRL 115, 092002 (2015)

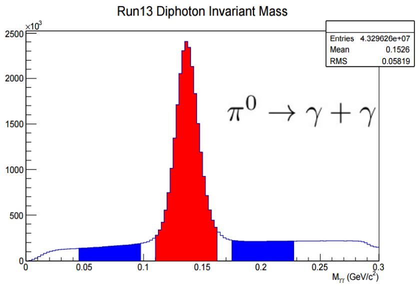


PHENIX: PRD 90, 012007 (2014)





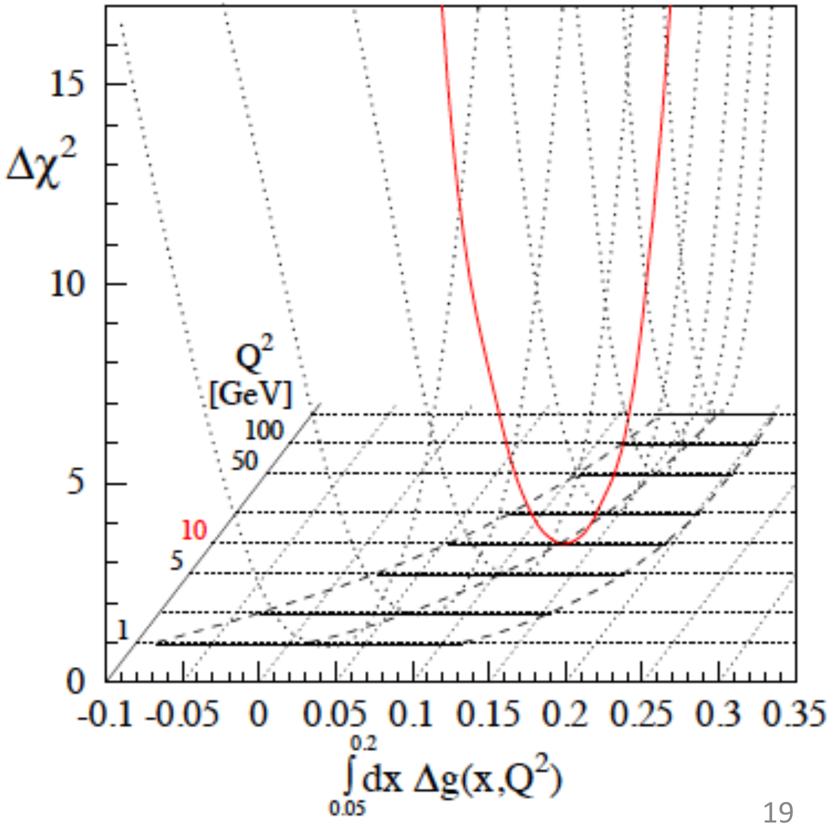
Run 2009
p+p@200GeV



$$\int_{0.05}^{1} \Delta g(x, Q^2)dx = 0.2^{+0.06}_{-0.07}$$

@ Q^2 = 10 GeV^2

PRL 113, 012001 (2014), DSSV

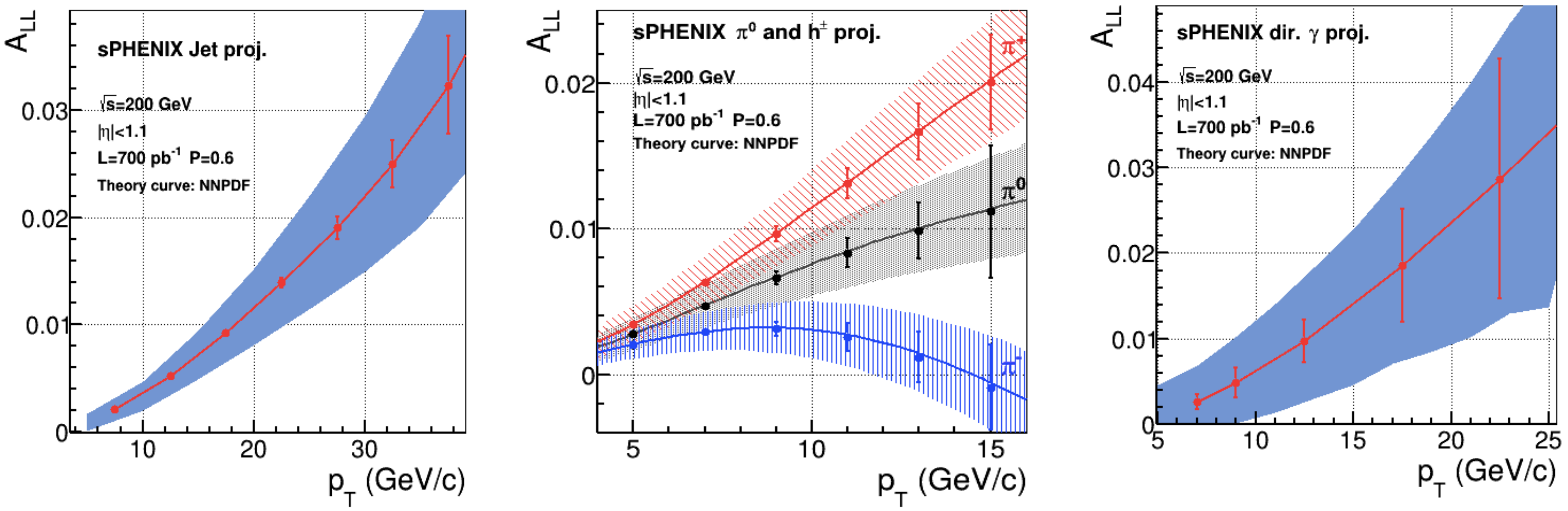


RHIC Multi-Year Plan: sPHENIX 2023-2027+

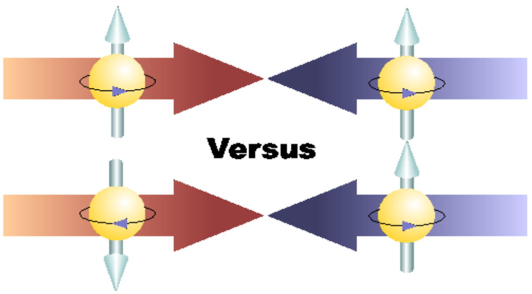
(Cold QCD plan under development now)

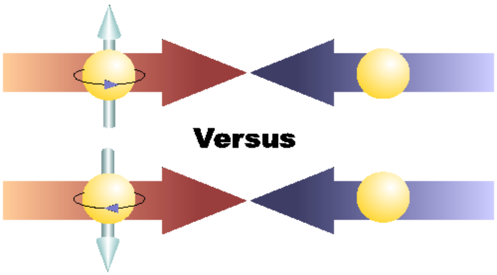
- Jets, hadrons, direct photons and more
- Study gluon polarization

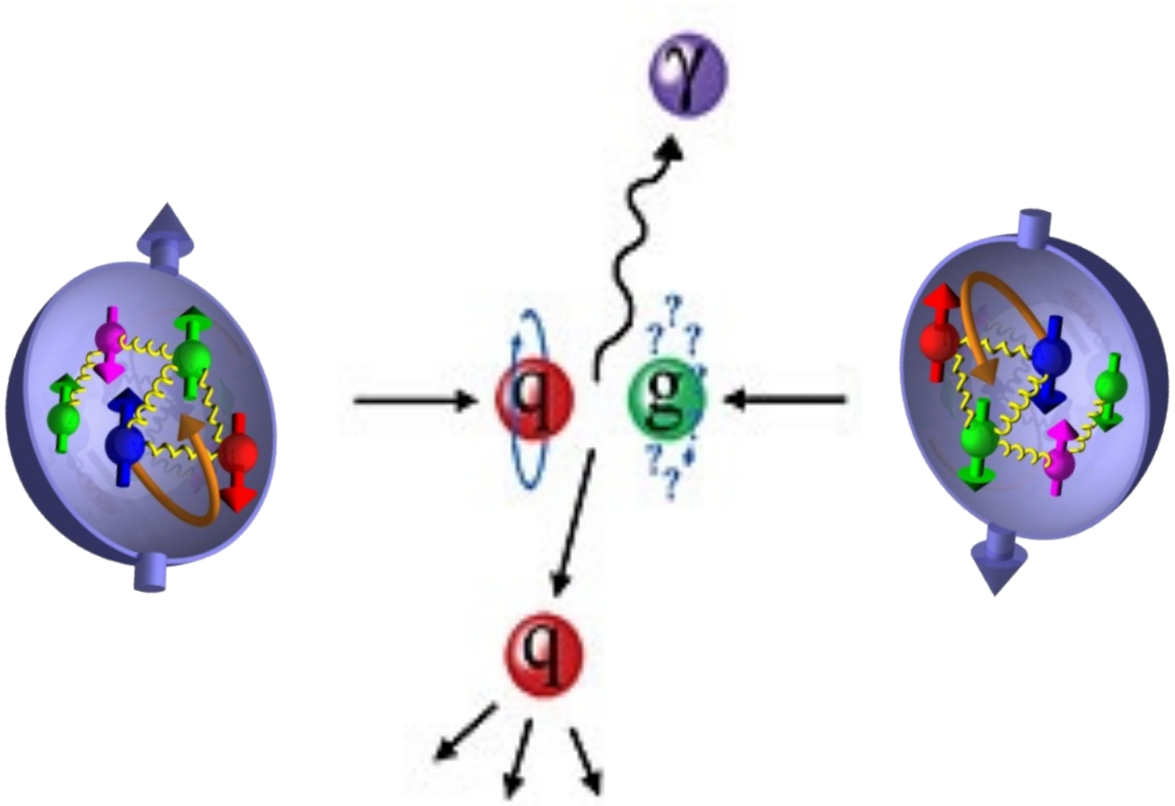
Ref: RHIC 2015 pp200
Recorded lumi ~50pb^{-1}



Physics with Transversely Polarized p+p Collisions at RHIC



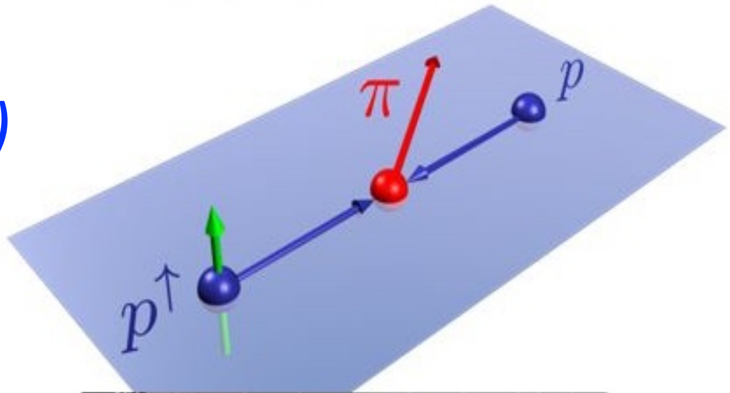




“TMD” phenomena: The Challenge of “Too Large”

Large Transverse Single Spin Asymmetry (TSSA) in forward hadron production persists up to top RHIC energy

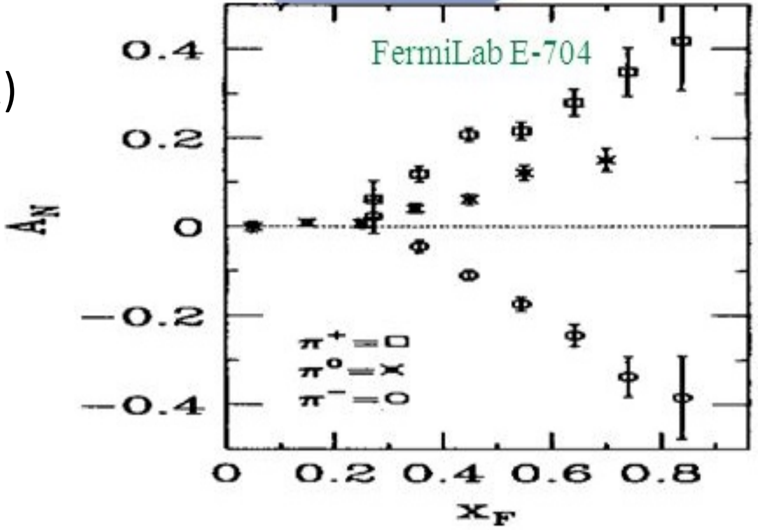
$A_N \sim O(10\%)$

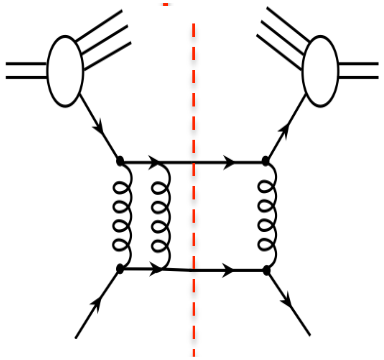


Kane, Pumplin, Repko (1978)

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

Fermilab
E704 (1991)





$$\propto \alpha_s \frac{m_q}{p_T}$$

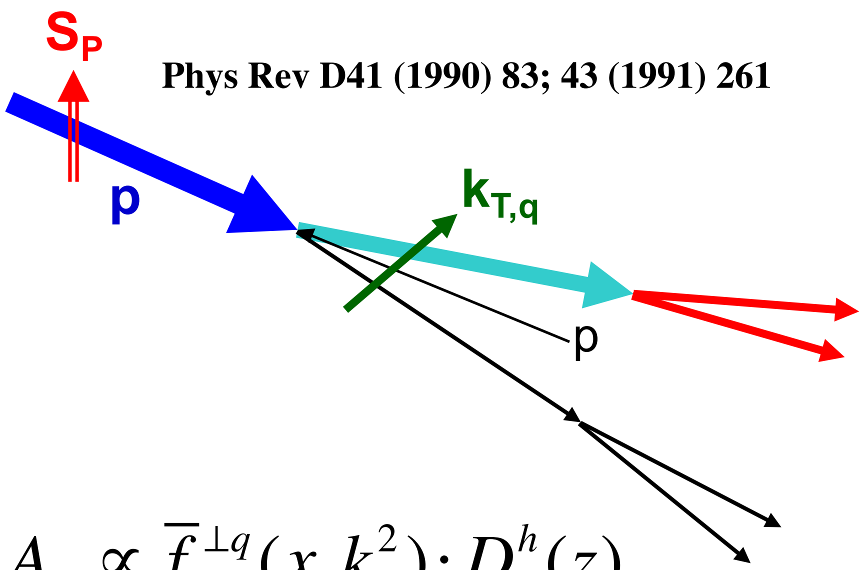
$$A_N^{(pred.)} \sim 0$$

Probe the Underlying Physics via Hard Scatterings TMD, Collinear Twist-3 Factorizations

(i) Sivers mechanism:
correlation proton spin & parton k_T

SIDIS:

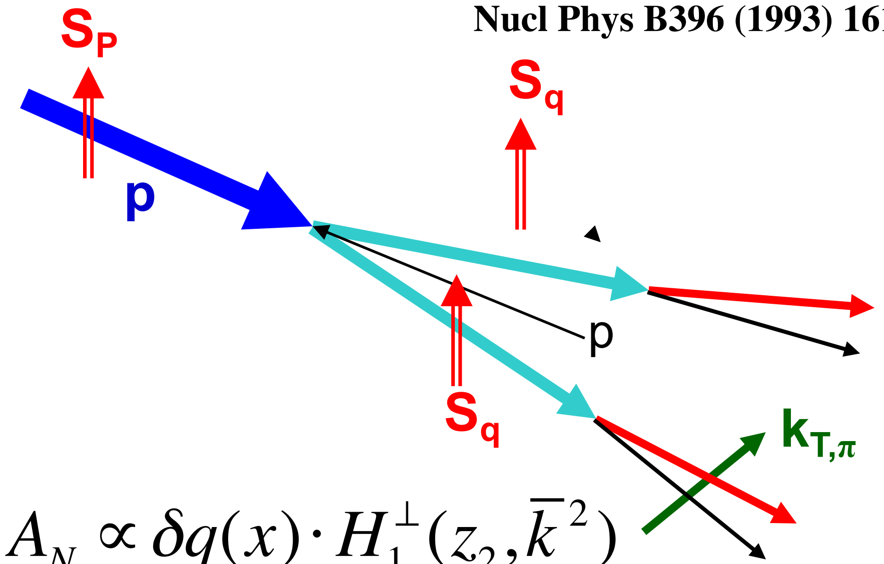
Phys Rev D41 (1990) 83; 43 (1991) 261



$$A_N \propto \bar{f}_{1T}^{\perp q}(x, k_\perp^2) \cdot D_q^h(z)$$

(ii) Collins mechanism:
Transversity × spin-dep fragmentation

Nucl Phys B396 (1993) 161



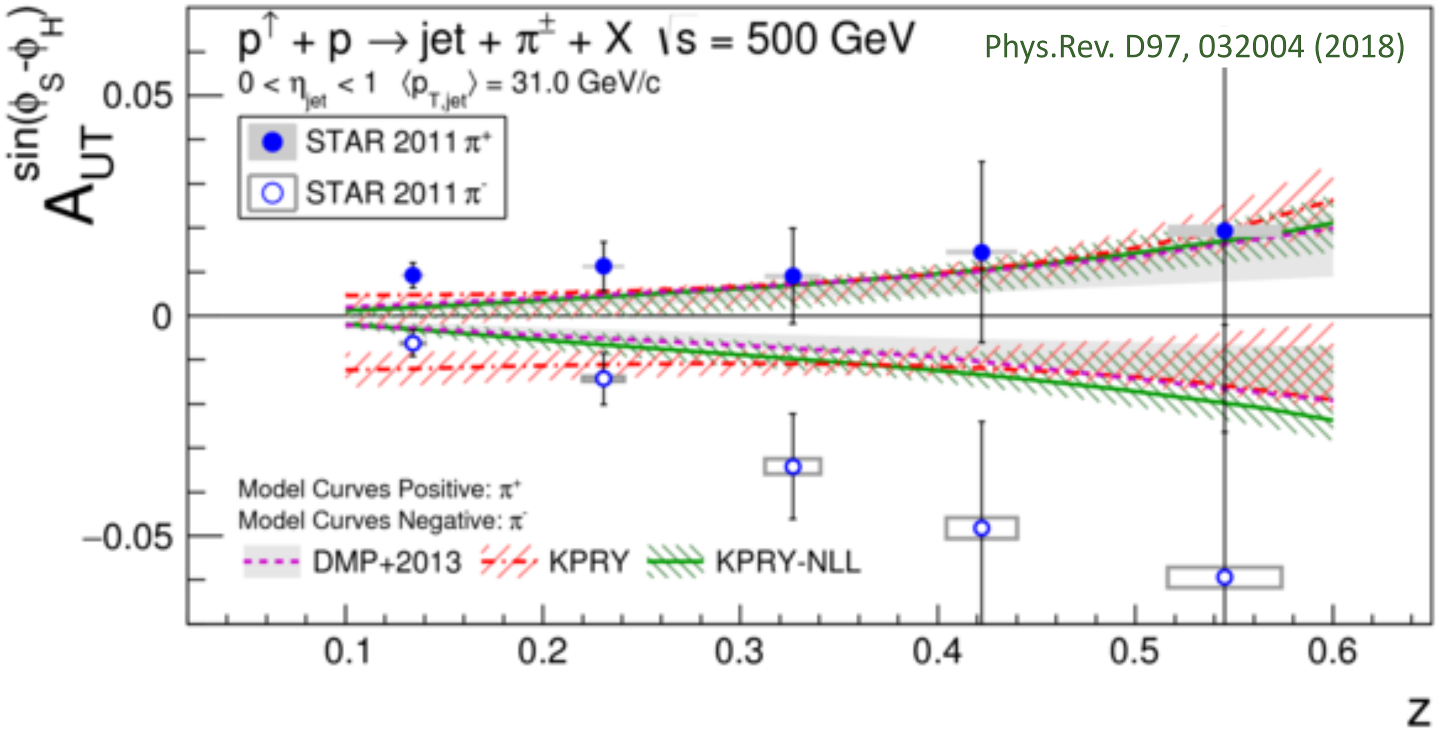
$$A_N \propto \delta q(x) \cdot H_1^\perp(z_2, \bar{k}_\perp^2)$$

pp: **Collinear Twist-3 (RHIC):** quark-gluon/gluon-gluon correlations

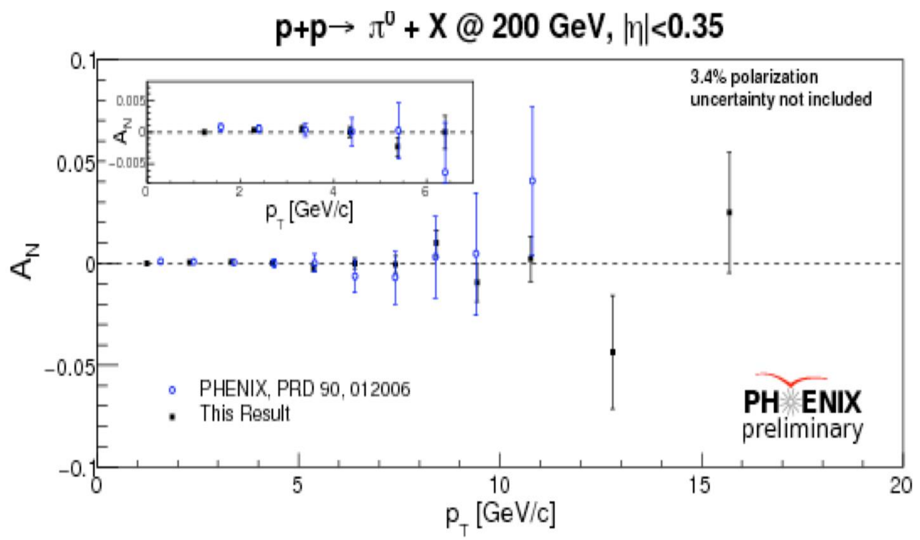
Collins-Like Asymmetry Observed in Jet in p+p Collisions

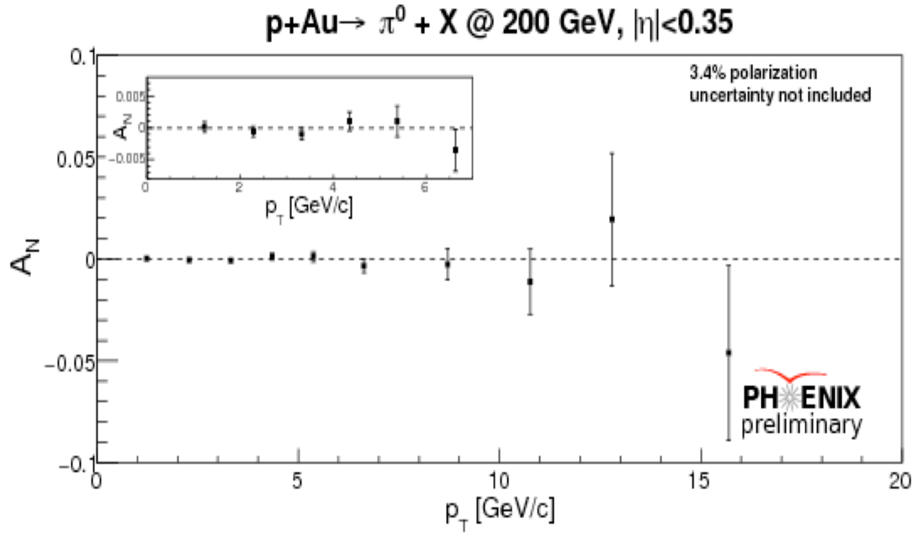
Projections for sPHENIX in progress;
-> Inclusive single hadron TSSA in p+p seems mostly from Twist-3 Collins function

None-zero "Collins-like" TSSA at central rapidity in jet!



Inclusive hadron A_N = 0 at central rapidity

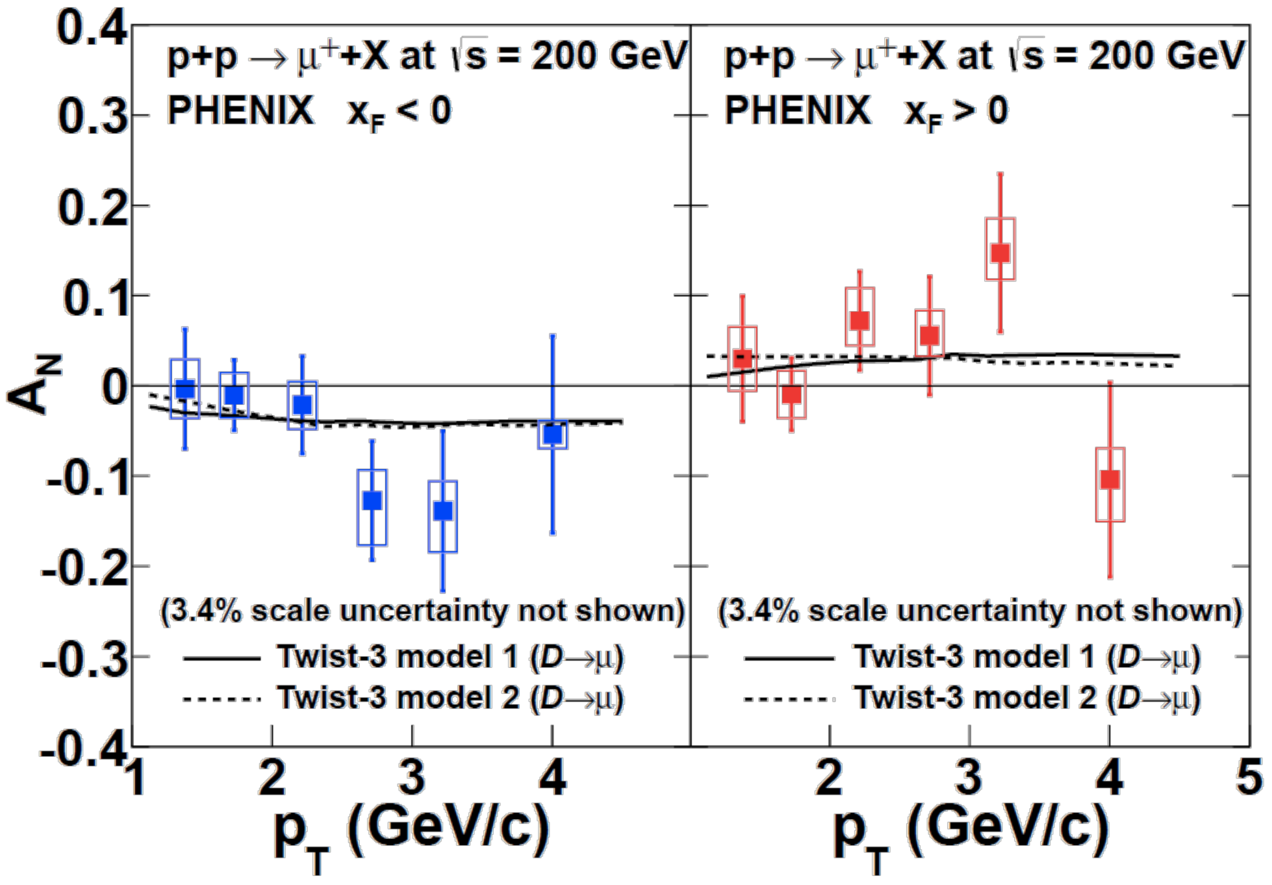




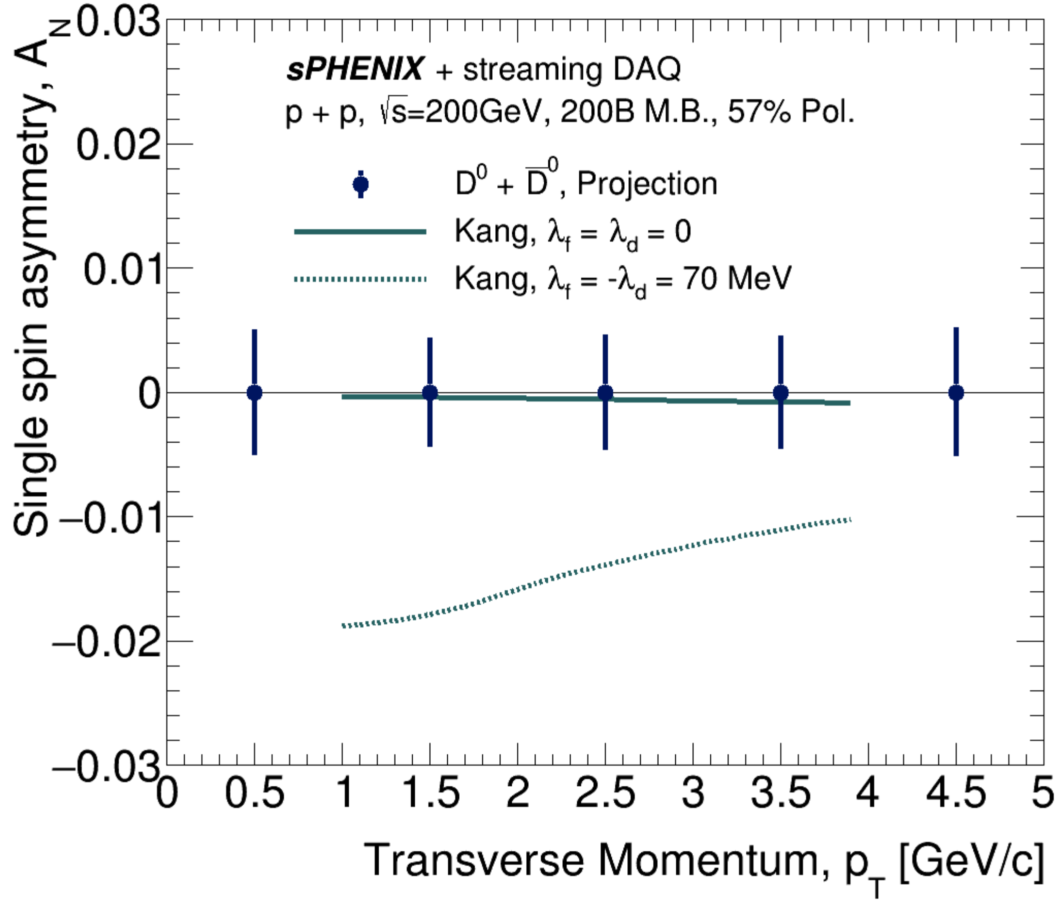
Probe Gluon TMD with D^0

Charm is unique probe of gluon TMD
D^0_AN→ Tri-gluon correlation

PHENIX, DOI:10.1103/PhysRevD.95.112001

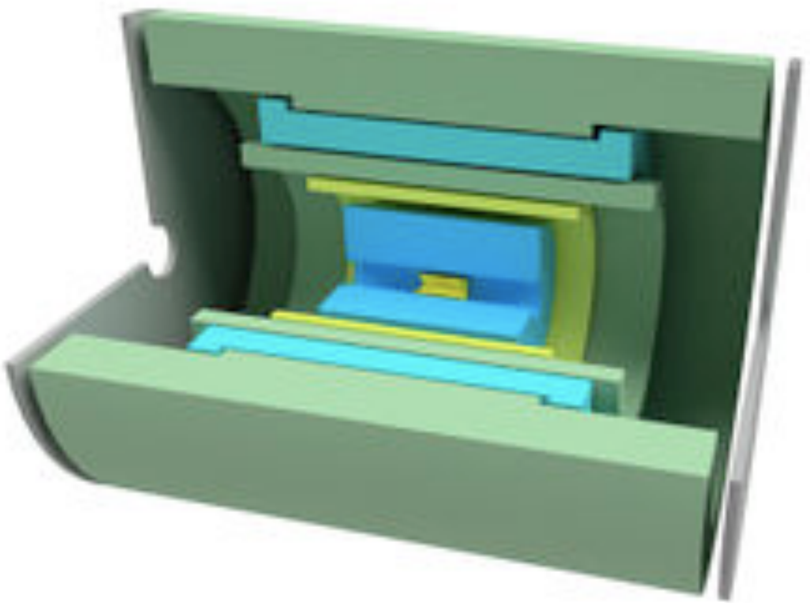


sPHENIX projection



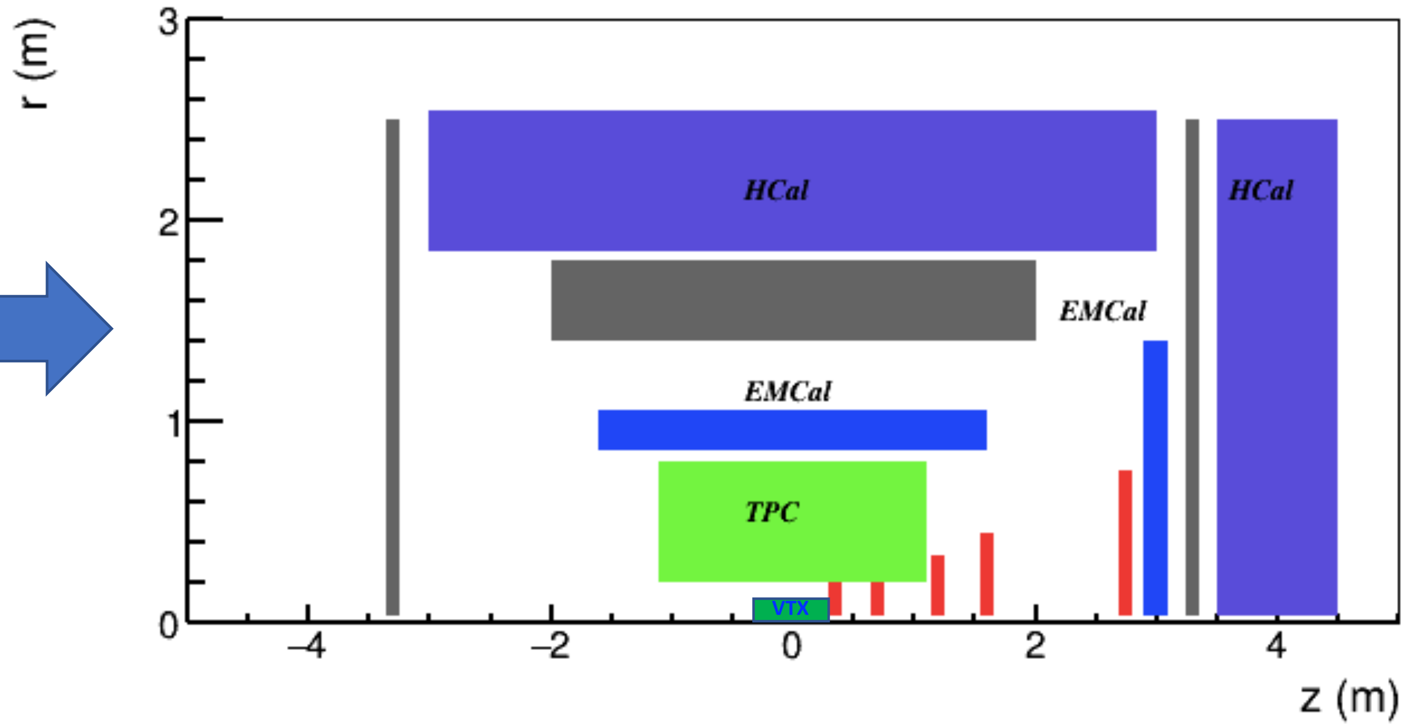
Forward Upgrade Proposal

Forward upgrade will bring in new physics capability – TMD, small-x physics etc.



sPHENIX Barrel Detectors:

- MVTX, INTT, TPC
- EMCal, HCal

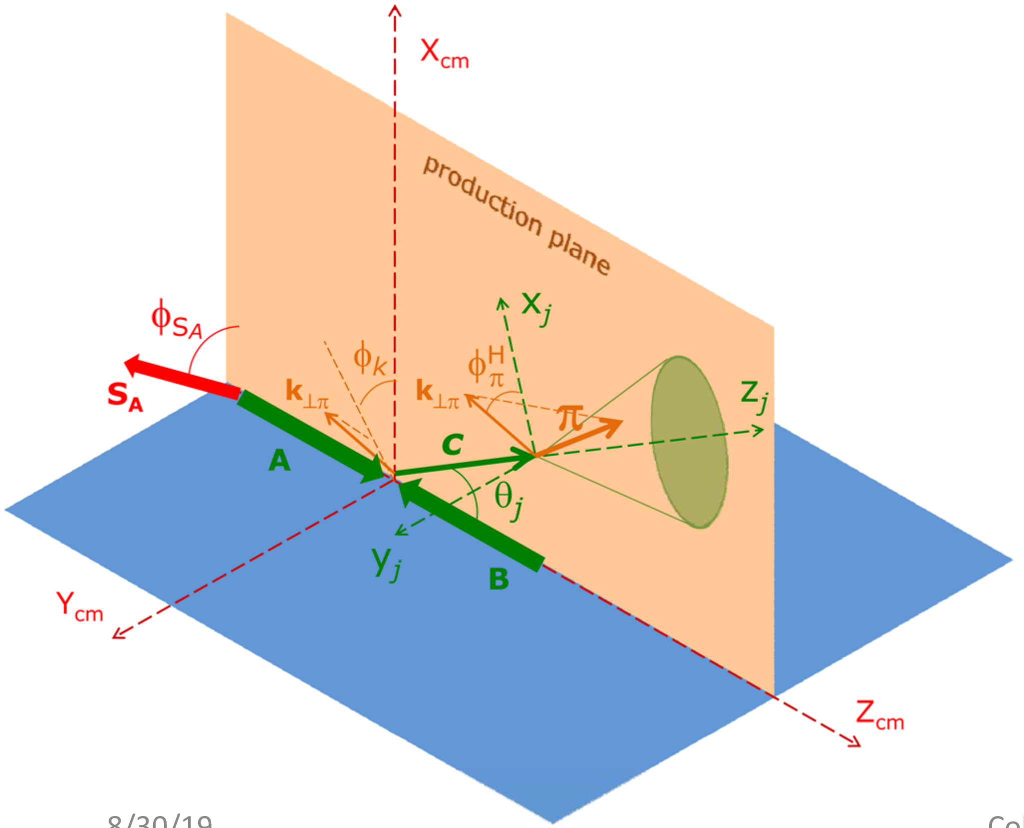


sPHENIX Forward Upgrade

- EMCal, Hcal, Tracking

Access Sivers and Collins with Jet and Hadron Azimuthal Distributions in Transversely Polarized p+p Collisions

Feng Yuan, PRL 100, 032003 (2008)
Umberto D'Alesio et al PRD 83 034021 (2011)



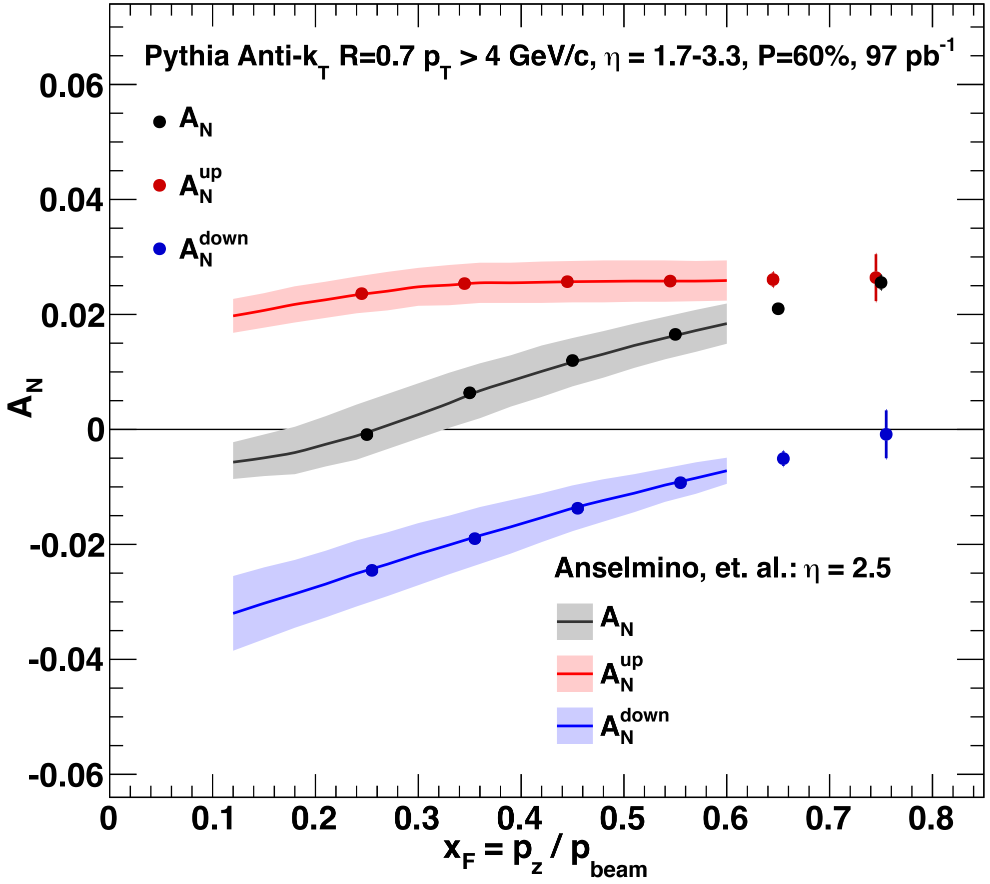
$$\frac{E_j d\sigma^{A(S_A)B\to \text{jet}+\pi+X}}{d^3\boldsymbol{p}_j dz d^2\boldsymbol{k}_{\perp\pi}} = \sum_{a,b,c,d,\{\lambda\}} \int \frac{dx_a dx_b}{16\pi^2 x_a x_b s} d^2\boldsymbol{k}_{\perp a}$$
$$\times d^2\boldsymbol{k}_{\perp b} \rho^{a/A,S_A}_{\lambda_a \lambda'_a} \hat{f}_{a/A,S_A}(x_a, \boldsymbol{k}_{\perp a}) \rho^{b/B}_{\lambda_b \lambda'_b} \hat{f}_{b/B}(x_b, \boldsymbol{k}_{\perp b})$$
$$\times \hat{M}_{\lambda_c,\lambda_d;\lambda_a,\lambda_b} \hat{M}^*_{\lambda'_c,\lambda_d;\lambda'_a,\lambda'_b} \delta(\hat{s}+\hat{t}+\hat{u}) \hat{D}^{\pi}_{\lambda_c,\lambda'_c}(z, \boldsymbol{k}_{\perp\pi}).$$

$A_N^{\sin\phi_{S_A}}$ → "Sivers-like" (Jet)

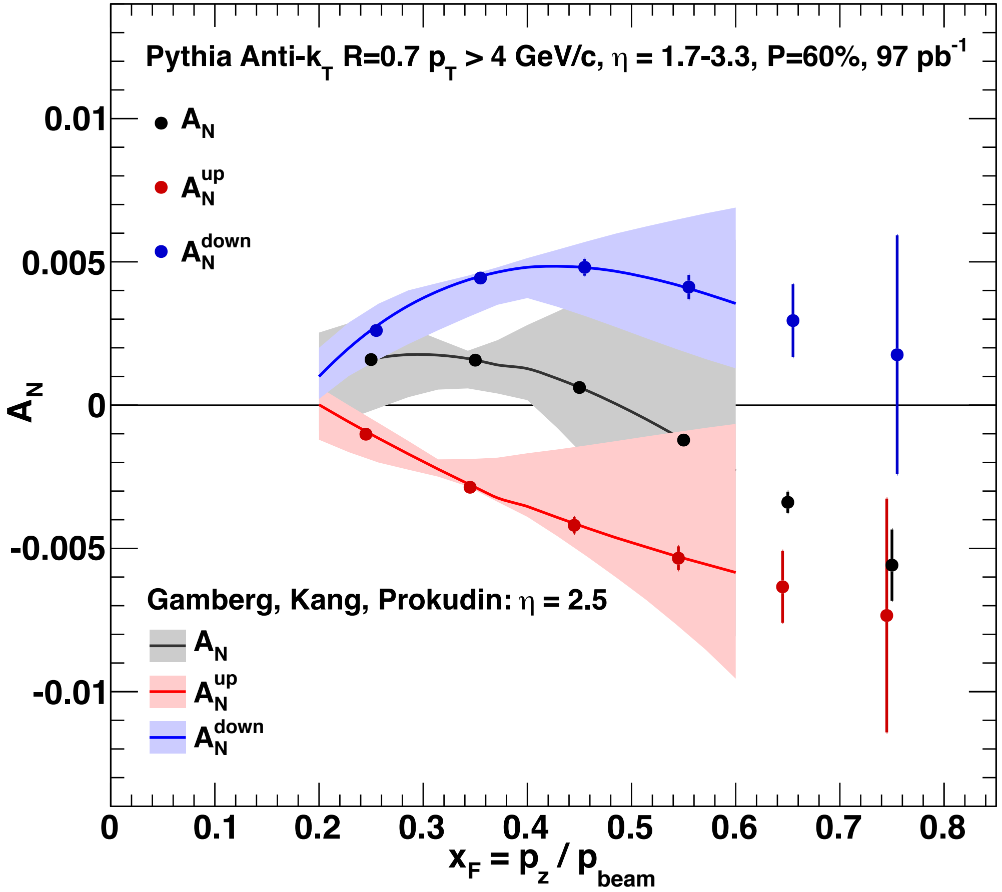
$A_N^{\sin(\phi_{S_A} \mp \phi_\pi^H)}$ → "Collins-like" (hadron)

Precision Charged Tagged Jet TSSA

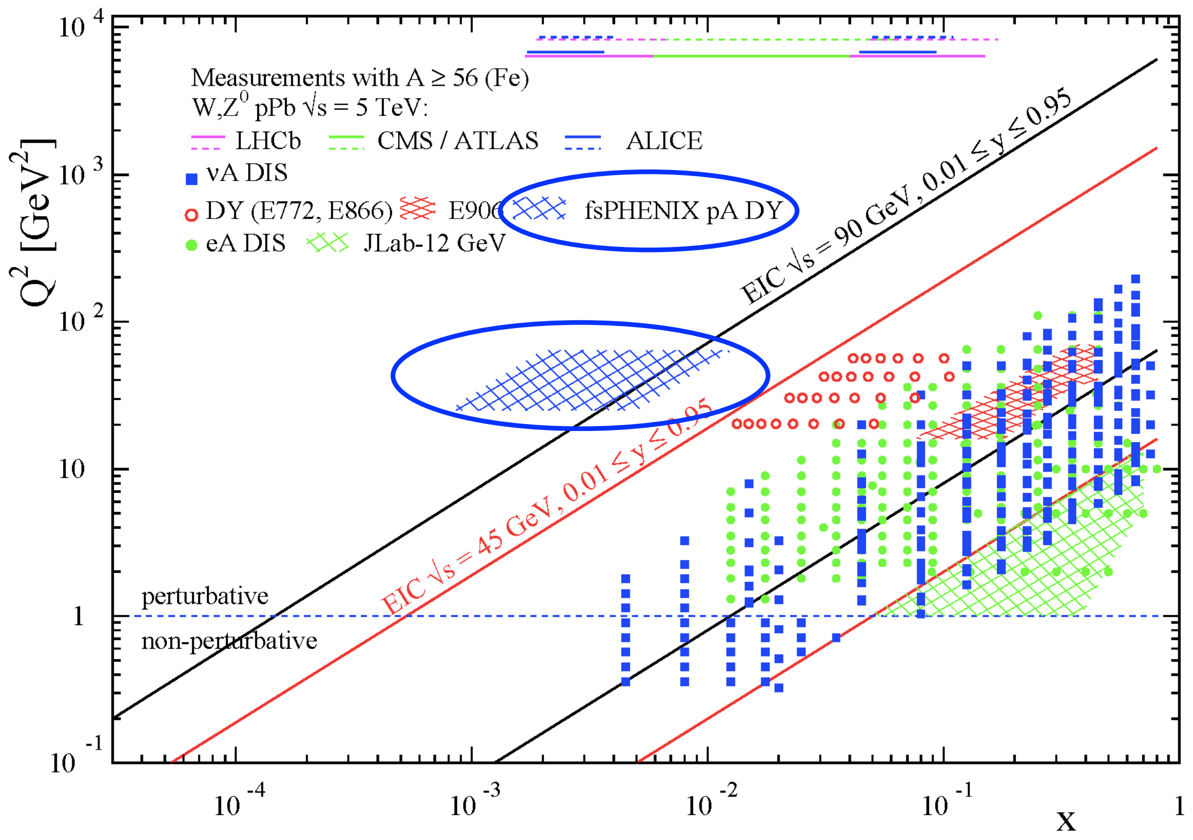
Naïve direct mapping
from SIDIS Sivers (GPM)
- “u-quark jet” $A_N > 0$

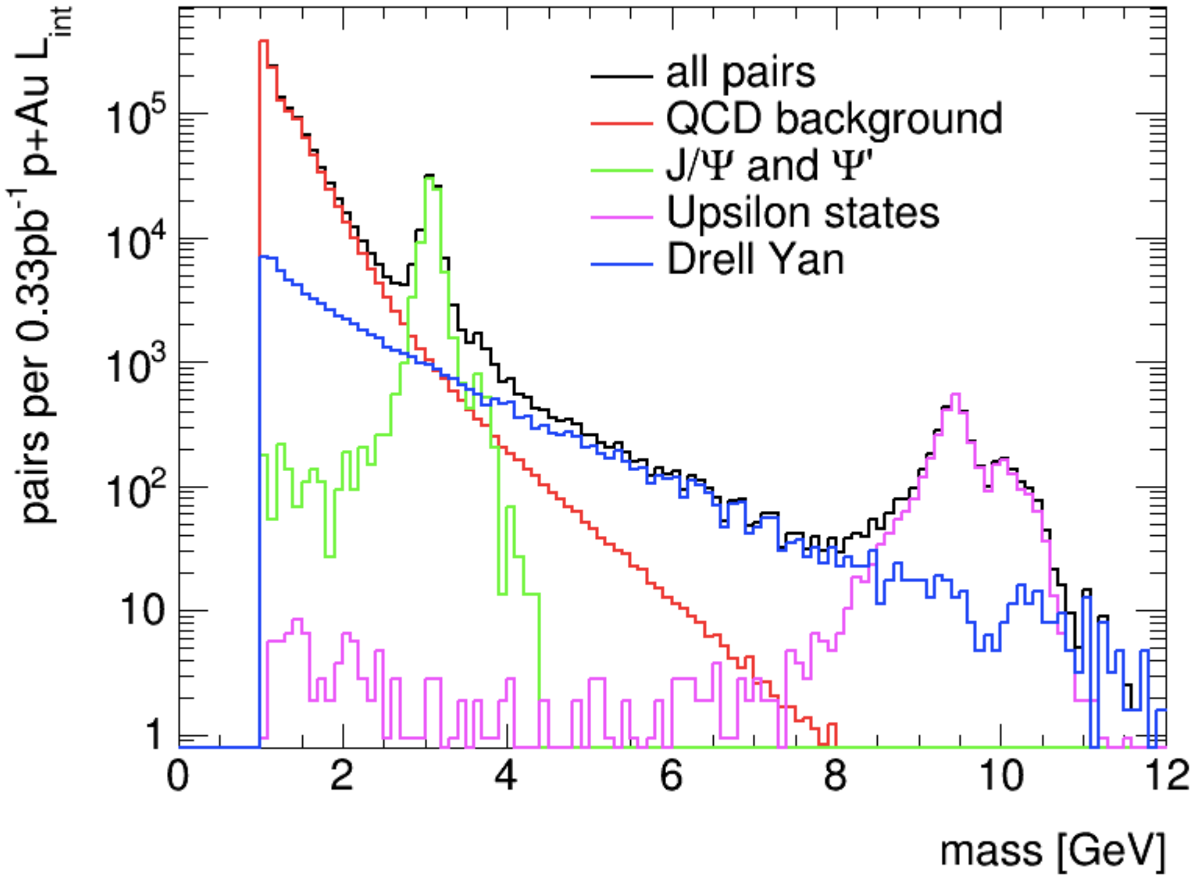


With process-dependence
from SIDIS Sivers (Twist-3)
- “u-quark jet” $A_N < 0$

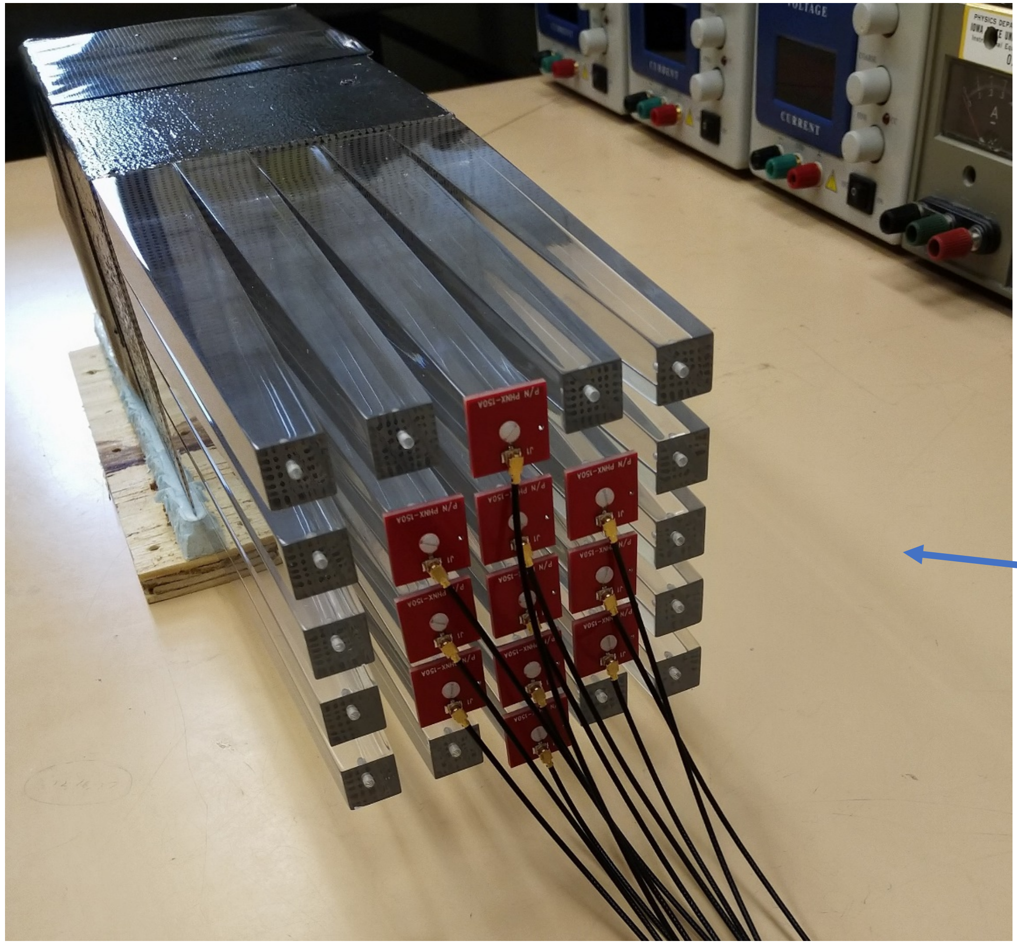


Drell-Yan in the Forward Rapidity: p+A



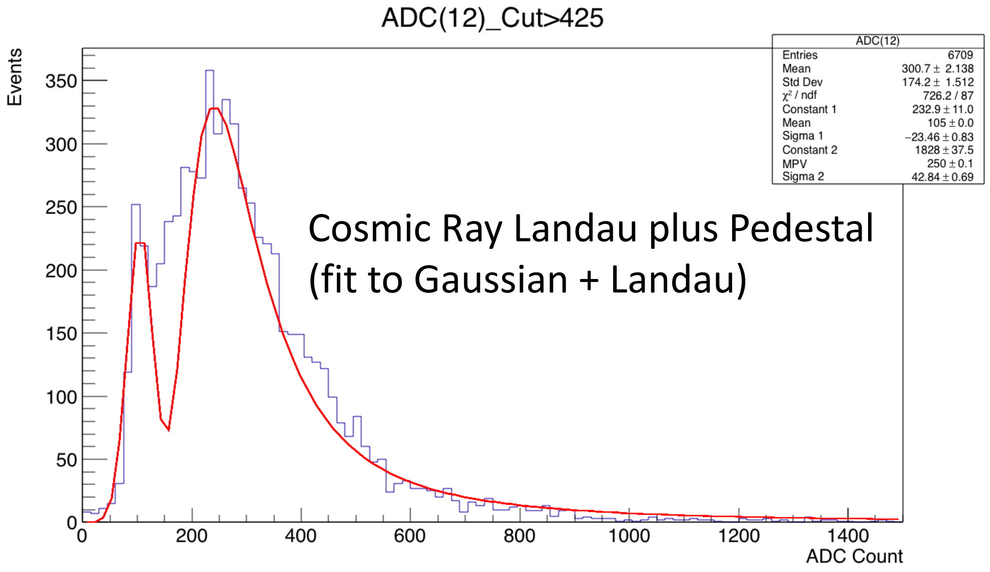


Forward EMCal R&D
- Recycled Modules from AGS/E864



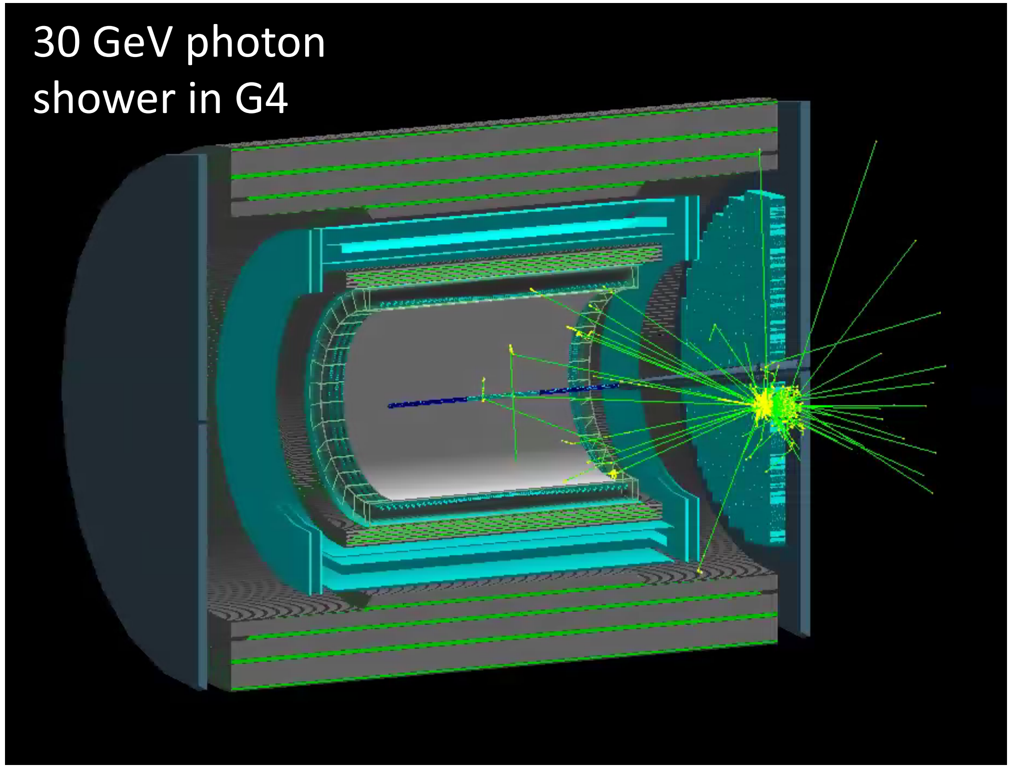
Use the existing E864 HCal modules for high density and high granularity EMCal

- Compensating SPACAL design: 10x10x117 cm^3
- $X0=7.8mm$, $RM=2cm$
- 5x5 light guide array for 10x10 cm^2 modules => 2x2 cm^2
- 117 cm long => 7 cuts for 16 cm long modules (20 X0)

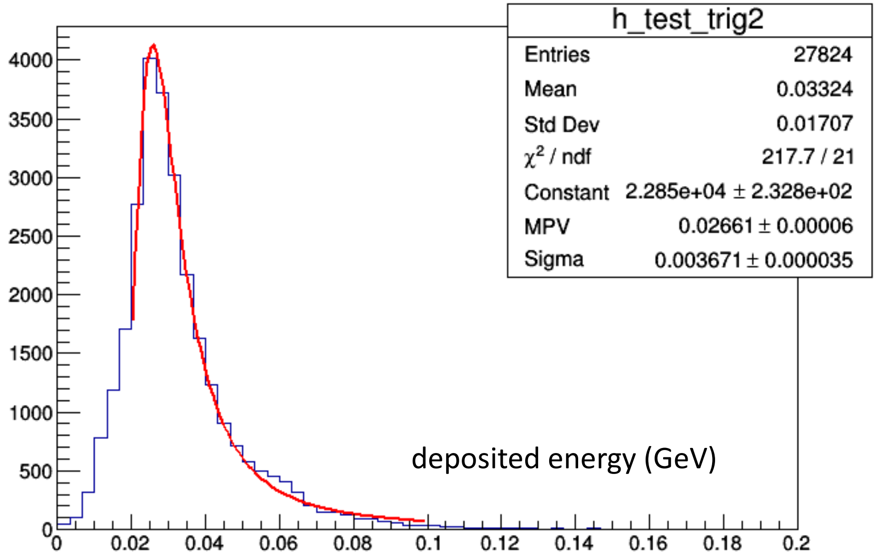


Forward EMCal Simulations and Calibration

Full simulation setup exists in G4:



Cosmics energy response determined with vertical muons down into fEMC stack in standard G4 setup (3% sampling):



MPV is 26.6 MeV

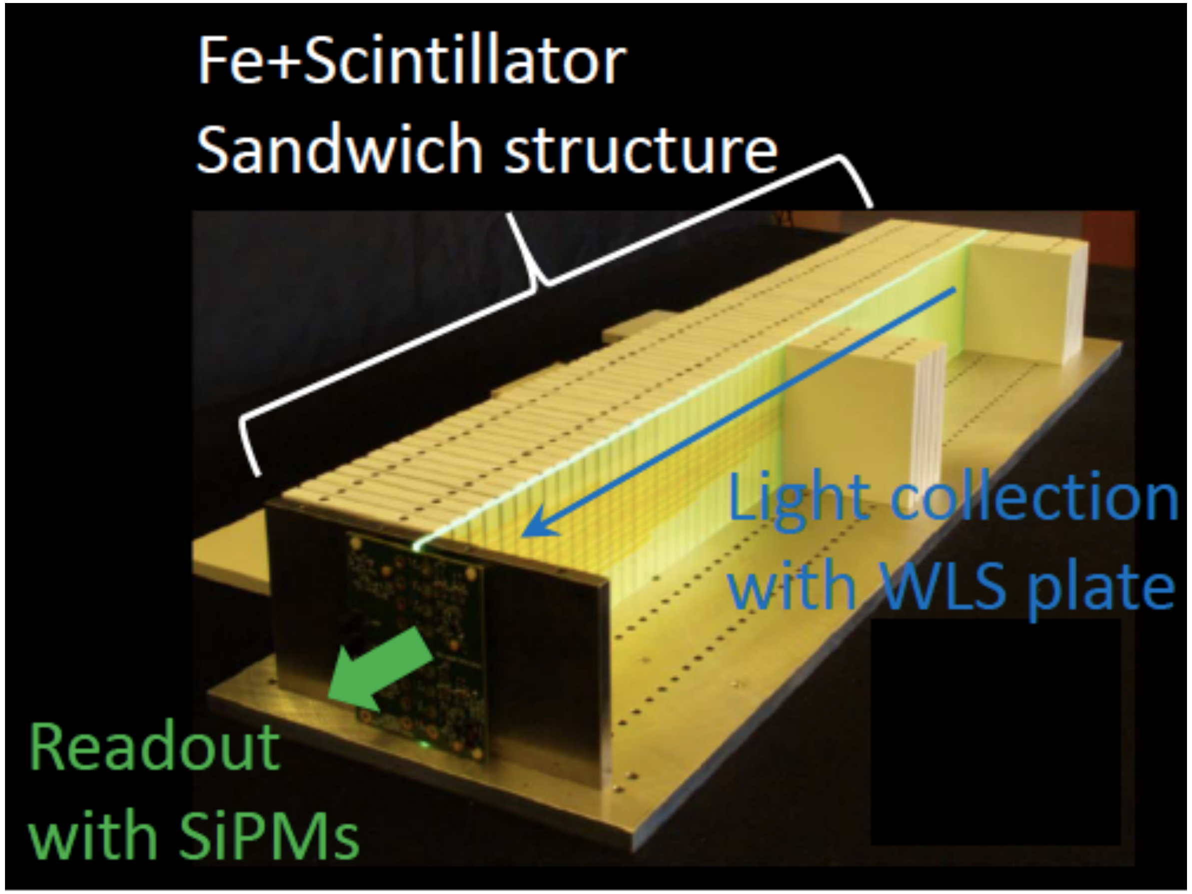
~3 pixels/0.0266 GeV = 113 SiPM pixels/GeV

NIM A 406 (1998) 227-258:
- 136 +/- 5 p.e. /GeV (BCF-10, cosmics)
- 217 +/- 68 p.e. /GeV (BCF-12, laser)

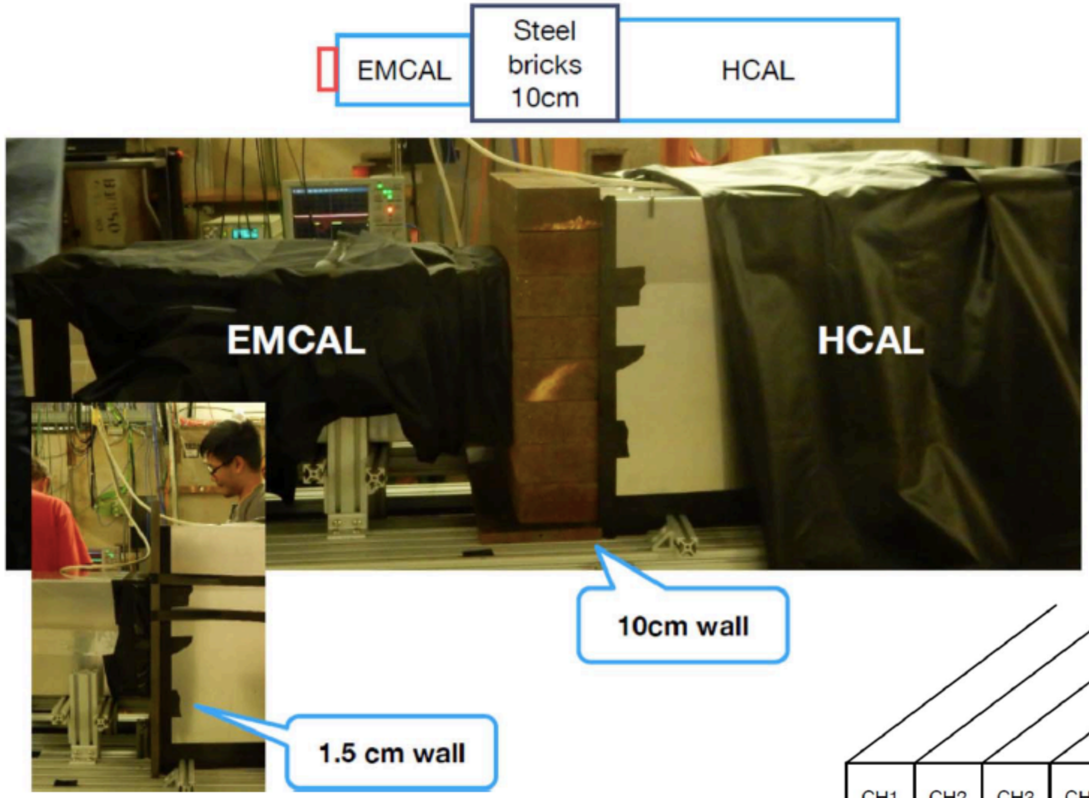
Forward Hadronic Calorimeter R&D

- Essential for forward jet reconstruction, hadron energy measurement, and triggering

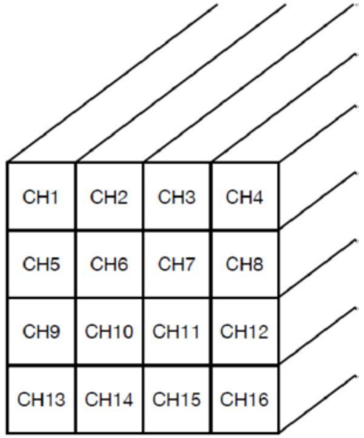
- Collaboration with UCLA group for STAR upgrade and EIC detector R&D



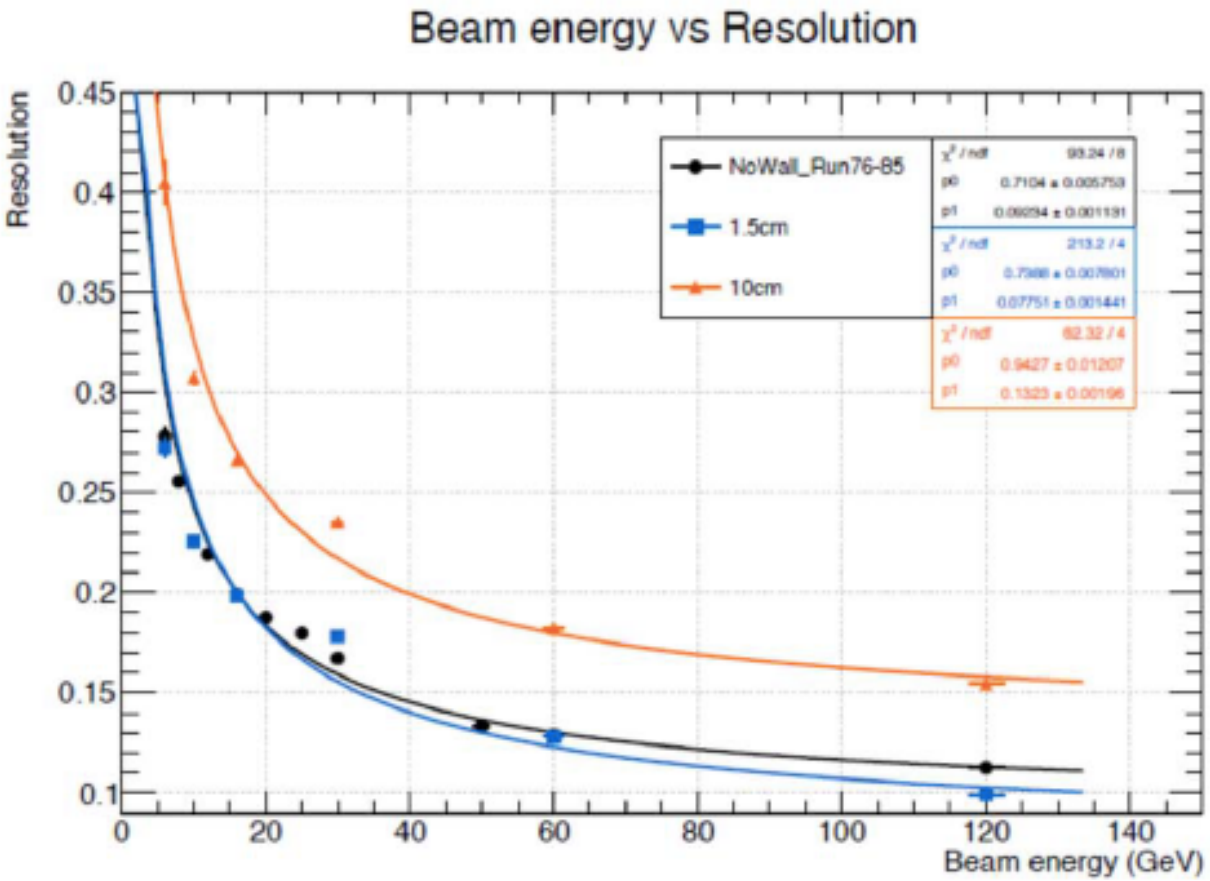
HCal Prototype Test Beam Results



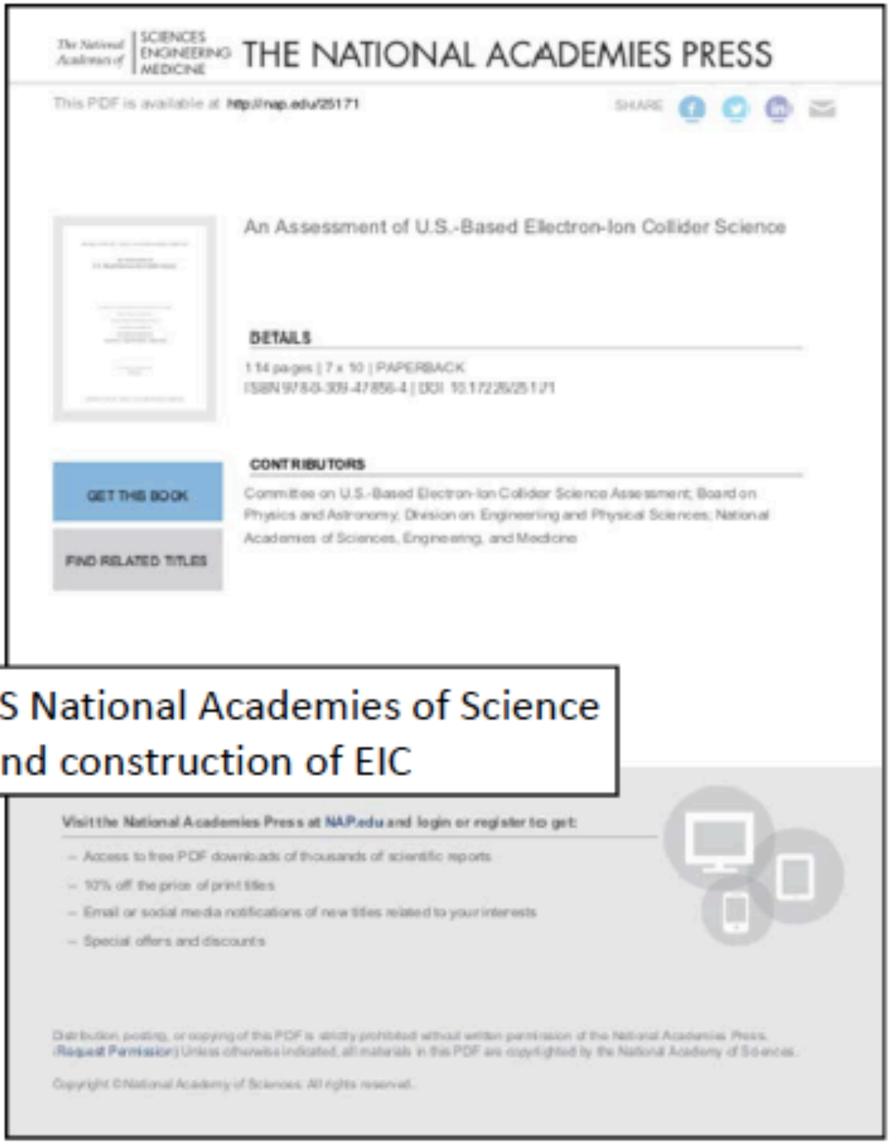
$$\sigma_E/E = 70\%/\sqrt{E}\ (\mathrm{GeV})$$



Calorimeters consist of 4×4 towers.



sPHENIX at Electron Ion Collider (EIC)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DETAILS

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Committee on U.S.-Based Electron-Ion Collider Science Assessment; Board on Physics and Astronomy; Division on Engineering and Physical Sciences; National Academies of Sciences, Engineering, and Medicine

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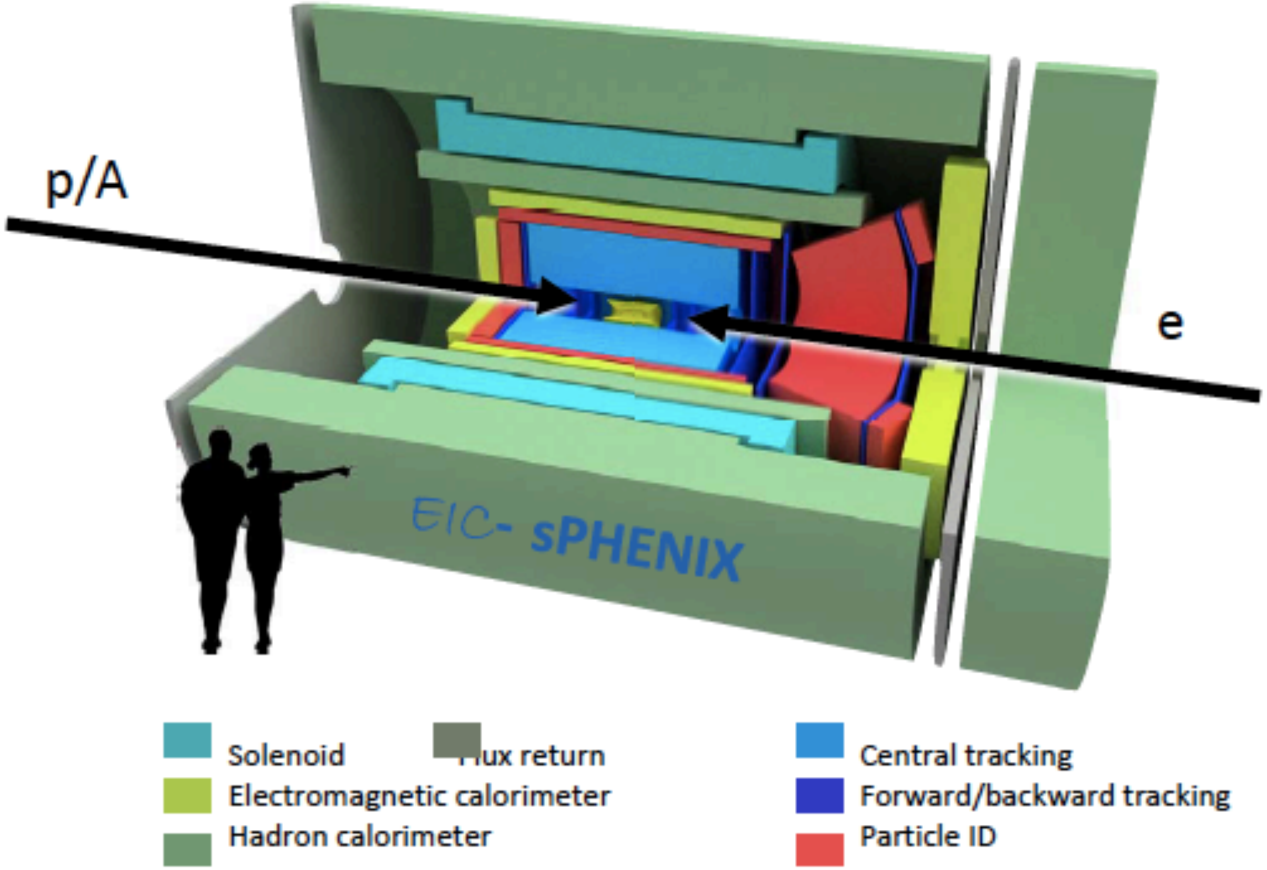
Timely: US National Academies of Science recommend construction of EIC

Study group (incl. non-sPHENIX members) working on EIC detector design based on sPHENIX



A Day-1 EIC Detector based on sPHENIX

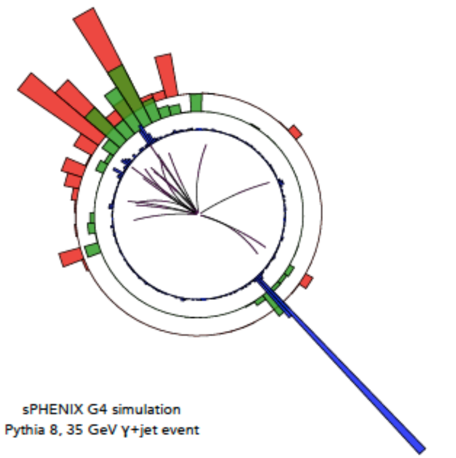
Summary and Outlook

A great opportunity for new collaborators to join the sPHENIX experiment!

Baseline detectors

sPHENIX-note sPH-cQCD-2017-002

Medium-Energy Nuclear Physics Measurements with the sPHENIX Barrel



sPHENIX G4 simulation
Pythia 8, 35 GeV γ+jet event

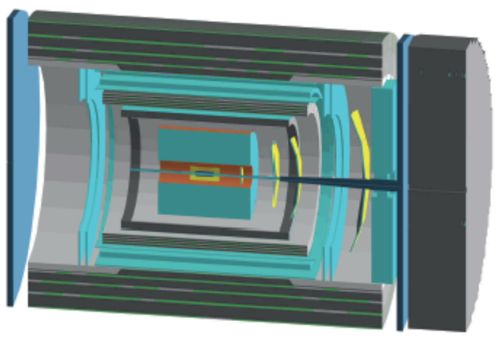
The sPHENIX Collaboration
October 10, 2017

Forward upgrade

sPHENIX-note sPH-cQCD-2017-001

sPHENIX Forward Instrumentation

A Letter of Intent



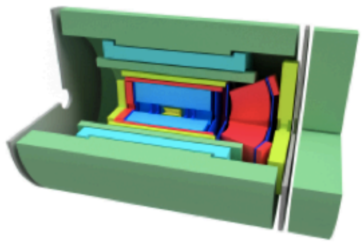
The sPHENIX Collaboration
June 2017

An EIC detector

sPHENIX-note sPH-cQCD-2018-001

An EIC Detector Built Around The sPHENIX Solenoid

A Detector Design Study



Christine Aidala, Alexander Bazilevsky, Giorgian Borca-Tasciuc, Nils Feege, Enrique Gamez, Yuji Goto, Xiaochun He, Jin Huang, Athira K V, John Lajoie, Gregory Matousek, Kara Mattioli, Pawel Nadel-Turonski, Cynthia Nunez, Joseph Osborn, Carlos Perez, Ralf Seidl, Desmond Shangase, Paul Stankus, Xu Sun, Jinlong Zhang

For the EIC Detector Study Group
and the sPHENIX Collaboration

October 2018

The *Growing* sPHENIX Collaboration

Augustana University
Banaras Hindu University
Baruch College, CUNY
Brookhaven National Laboratory
China Institute for Atomic Energy
CEA Saclay
Central China Normal University
Chonbuk National University
Columbia University
Eötvös University
Florida State University
Fudan University
Georgia State University
Howard University
Hungarian sPHENIX Consortium
Insititut de physique nucléaire d'Orsay
Institute for High Energy Physics, Protvino
Institute of Nuclear Research, Russian Academy of Sciences, Moscow
Institute of Physics, University of Tsukuba
Institute of Modern Physics, China
Iowa State University
Japan Atomic Energy Agency
Joint Czech Group
Korea University
Lawrence Berkeley National Laboratory
Lawrence Livermore National Laboratory
Lehigh University
Los Alamos National Laboratory
Massachusetts Institute of Technology
Muhlenberg College
Nara Women's University
National Research Centre "Kurchatov Institute"
National Research Nuclear University "MEPhI"
New Mexico State University
Oak Ridge National Laboratory
Ohio University
Peking University
Petersburg Nuclear Physics Institute
Purdue University
Rice University
RIKEN
RIKEN BNL Research Center
Rikkyo University
Rutgers University
Saint-Petersburg Polytechnic University
Shanghai Institute for Applied Physics
Stony Brook University
Sun Yat Sen University
Temple University
Tokyo Institute of Technology
Tsinghua University
Universidad Técnica Federico Santa María
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University of California, Los Angeles
University of California, Riverside
University of Colorado, Boulder
University of Debrecen
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University of New Mexico
University of Tennessee, Knoxville
University of Texas, Austin
University of Tokyo
University of Science and Technology, China
Vanderbilt University
Wayne State University
Weizmann Institute
Yale University
Yonsei University

BNL, June '18

Santa Fe, Dec '17

BNL, June '17

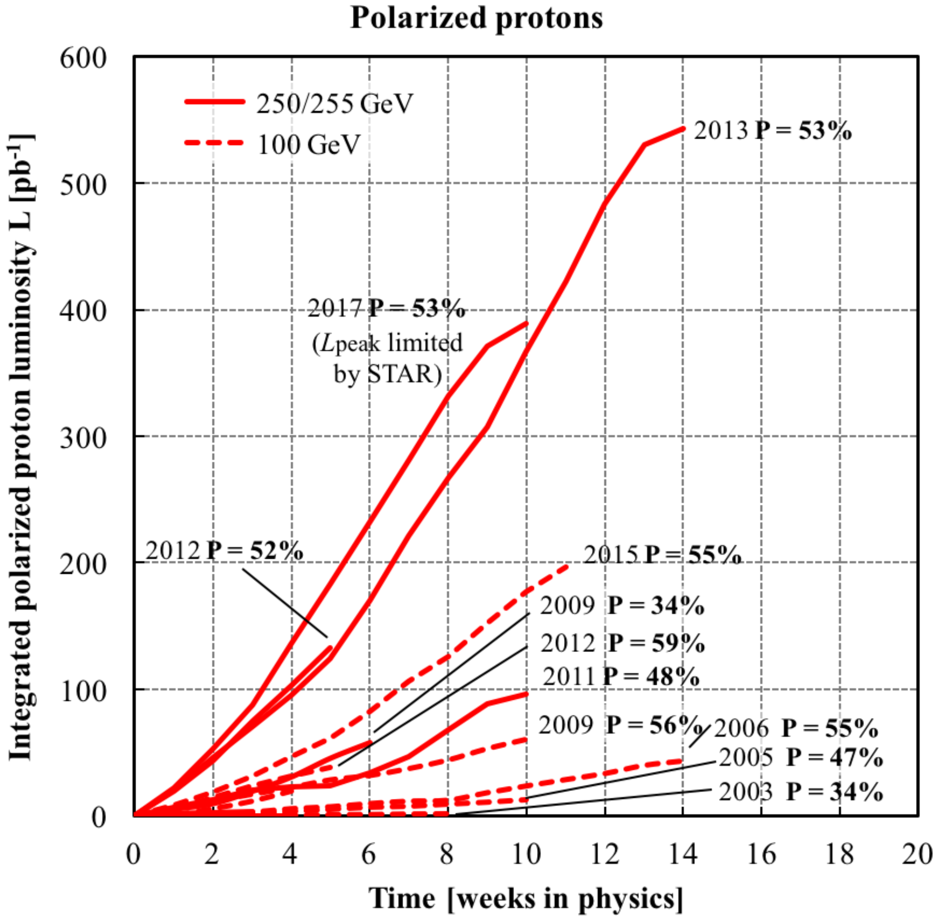
GSU (Atlanta), Dec '16

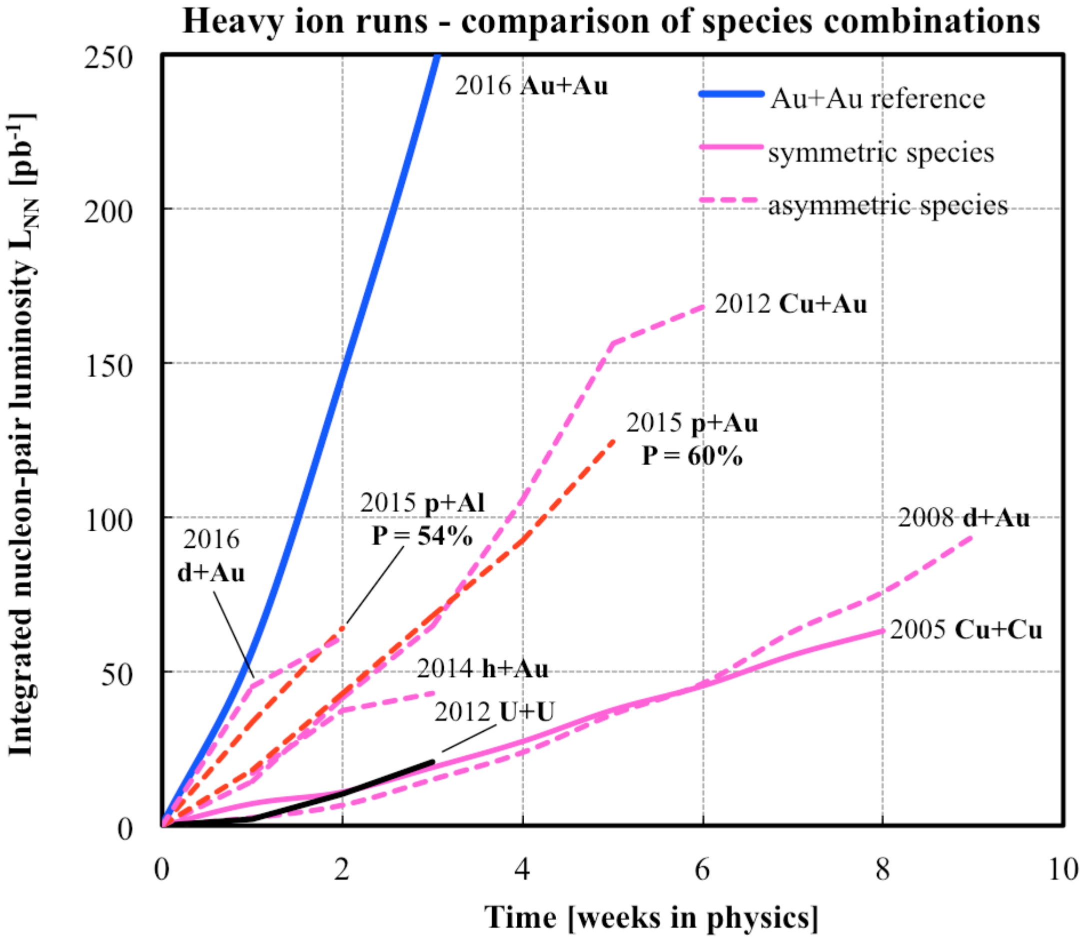
BNL, June '16

Rutgers, Dec'15

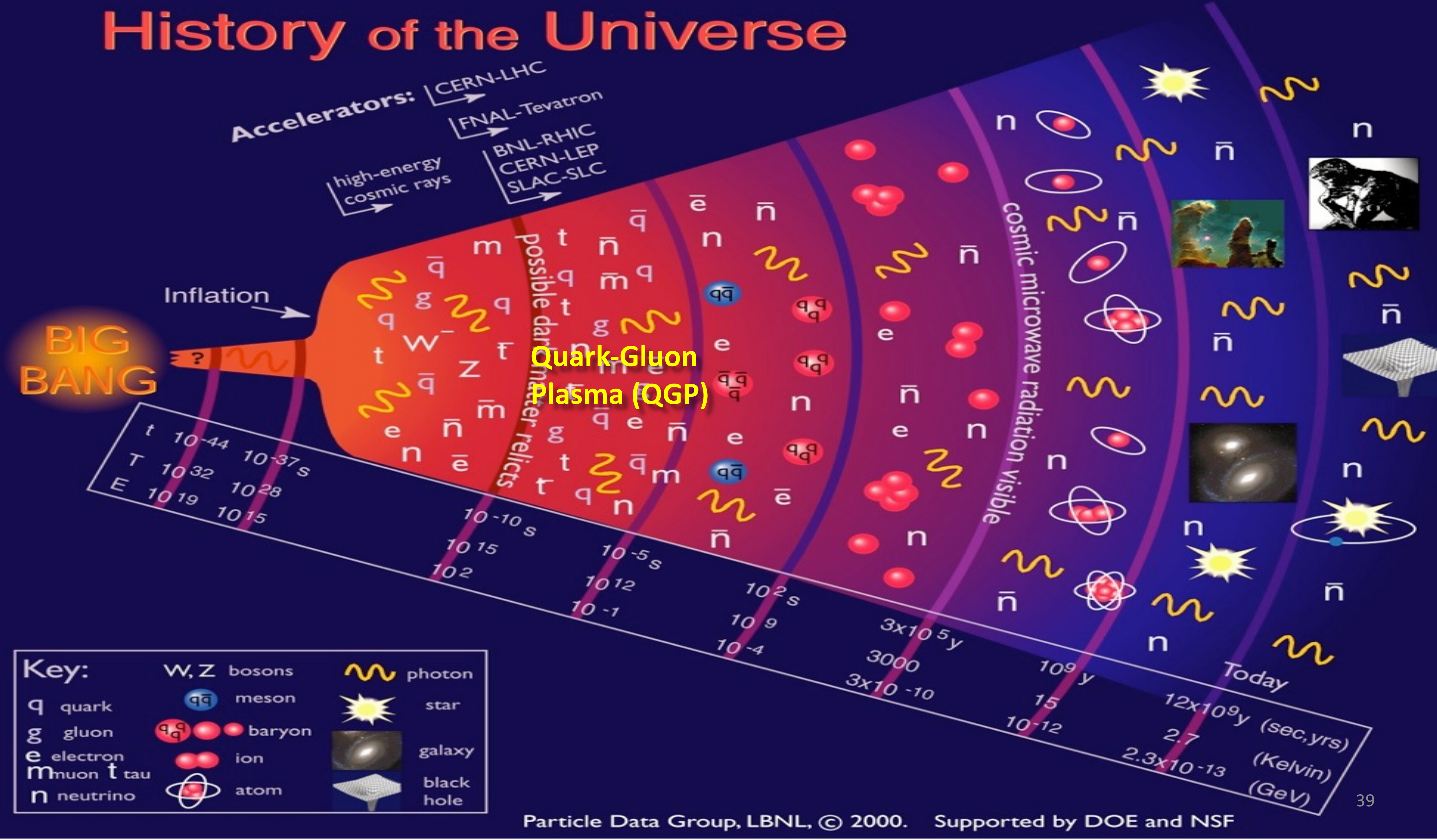
History of RHIC Runs

RHIC is capable of delivering the polarized p+p/A for precision spin, CNM physics



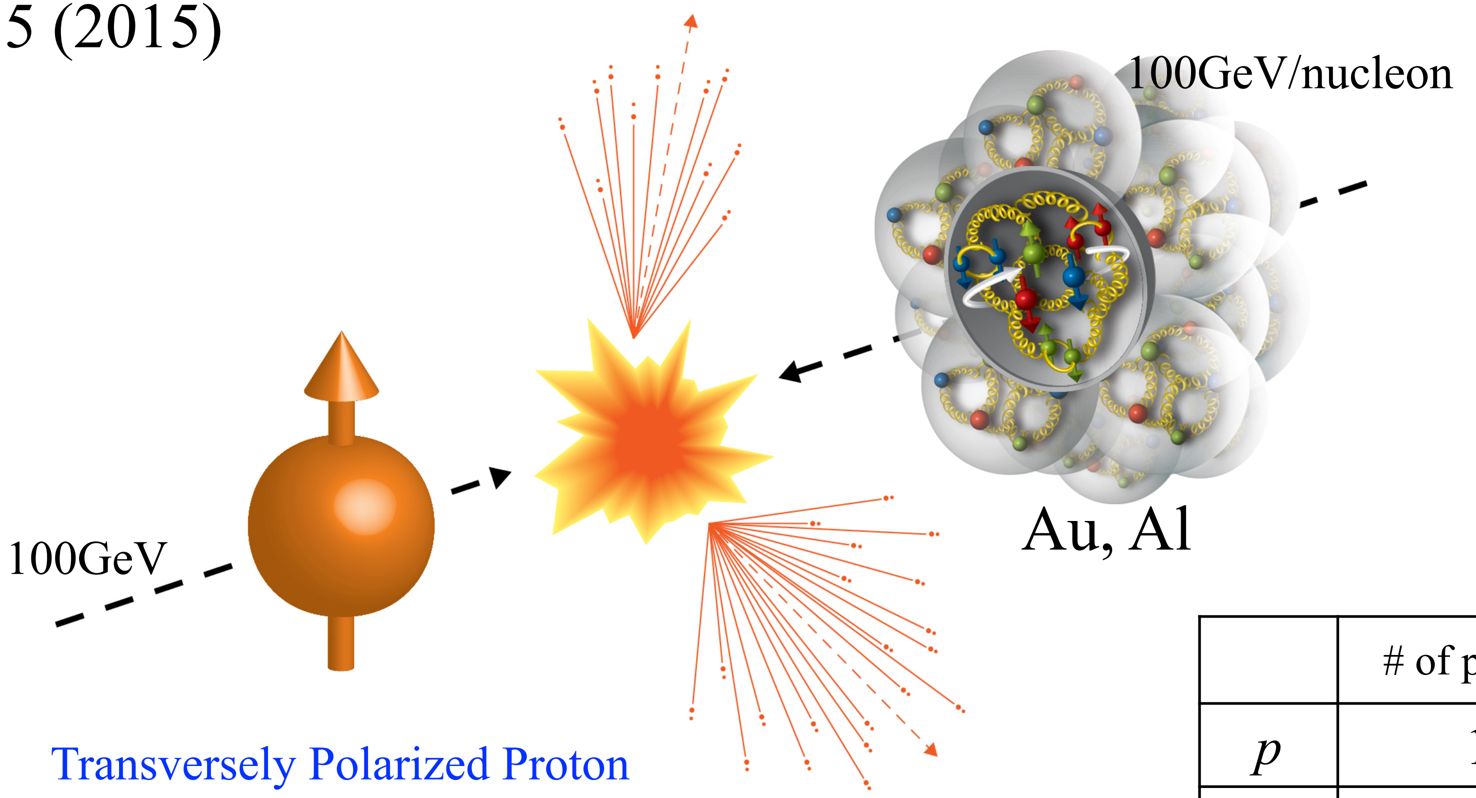


- A very challenging task to deliver polarized p+p, excellent performance from 2012+
- Longitudinally and transversely polarized p+p,
- Transversely polarized p+Au and p+Al, in 2015


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
Quark-Gluon Plasma (QGP)
t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15
10 -10 s
10 15
10 2
10 -5 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10 -12
Today
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

First Transversely Polarized p+A collisions at RHIC

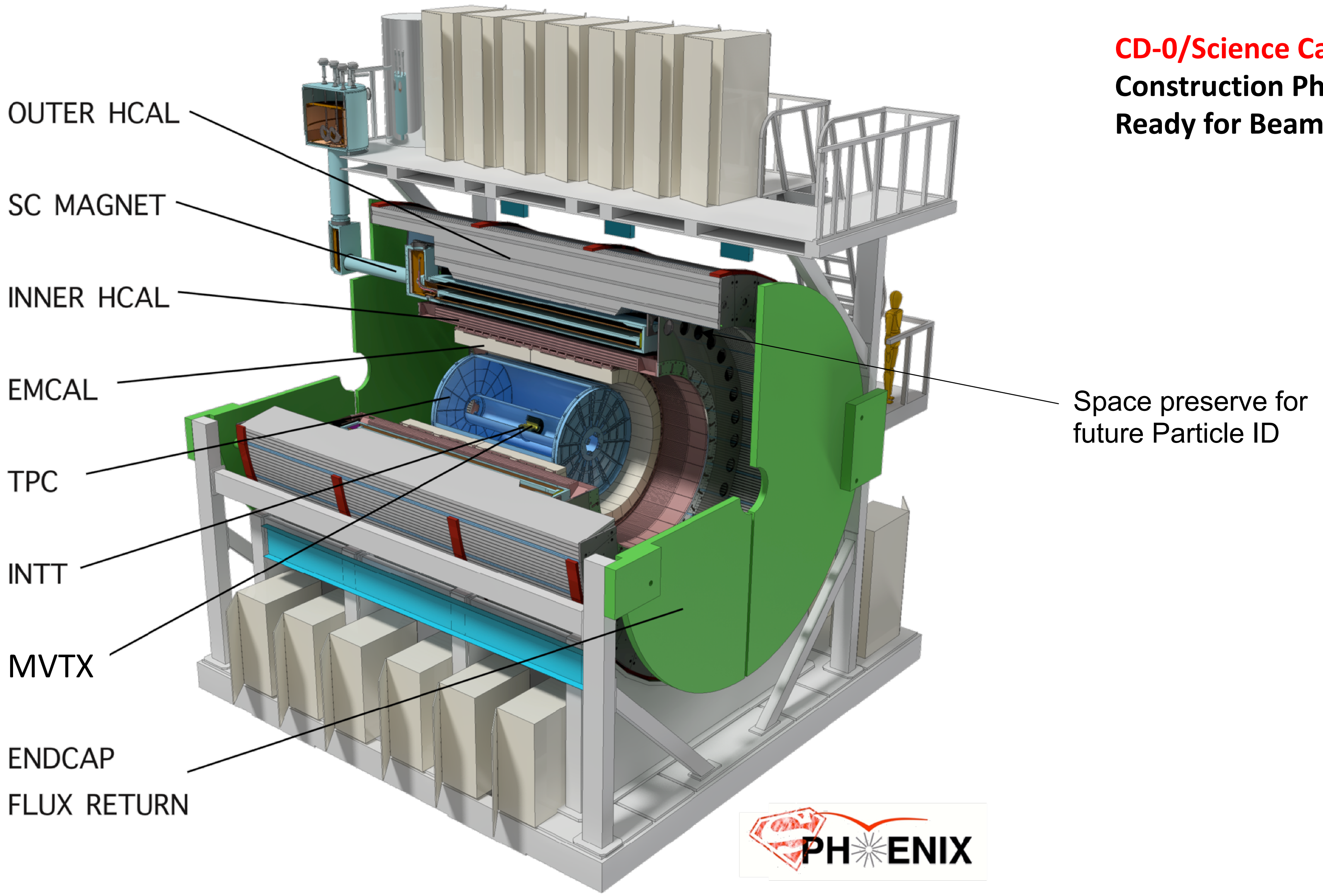
Run15 (2015)



	# of proton	# of neutron
p	1	0
Al	13	14
Au	79	118

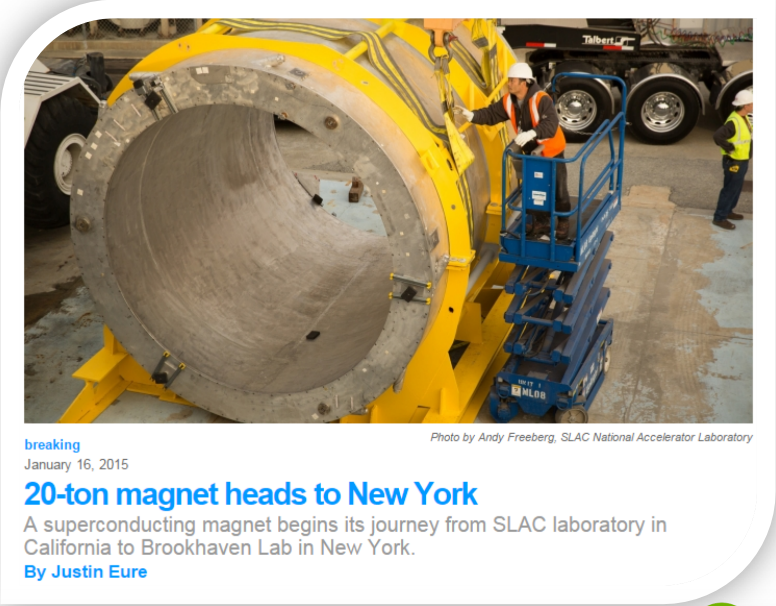
sPHENIX: a State of the Art Detector for Heavy Ion Physics at RHIC

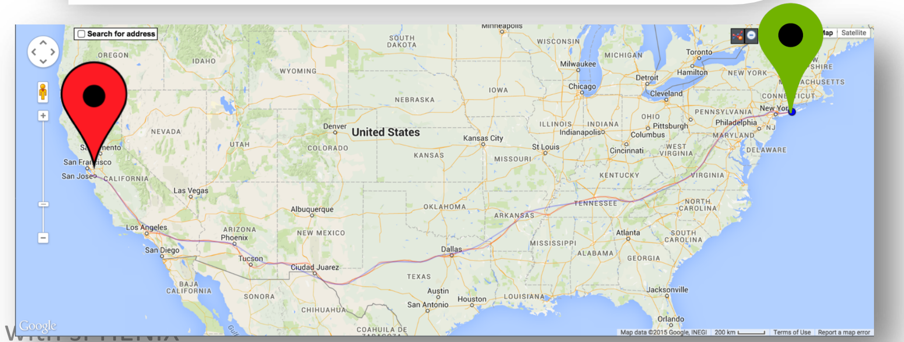
CD-0/Science Case	**Sept 2016**
Construction Phase	**Jul 2018 -22**
Ready for Beam	**Jan 2023**



Super conducting magnet

- 1.4 Tesla magnet, Φ = 2.8 m, L = 3.8 m Previously used in BaBar @ SLAC
- Moved to BNL in Feb 2015
- Successful cold low field test in 2016
- Full field test in 2018





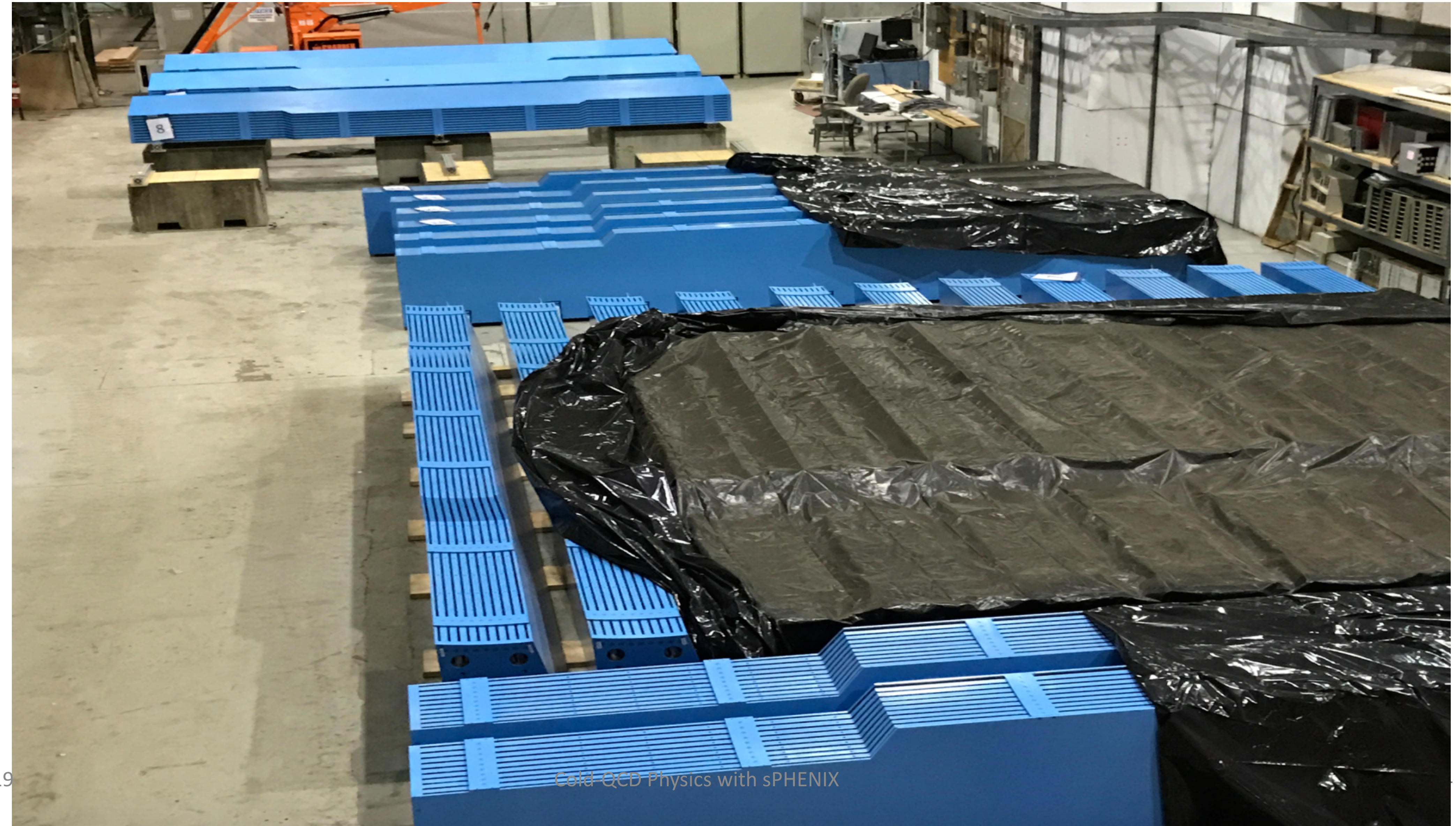
Assembly of EMCal Sector 0

Assembly of Sector 0 at BNL

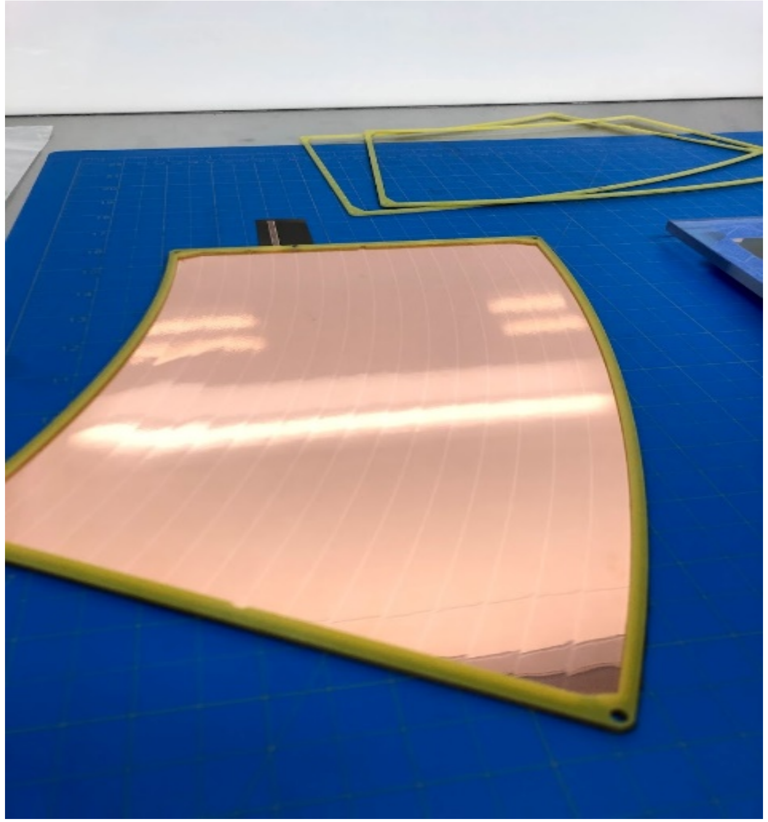
Sector 0 cooling system

- Sector 0 assembly continues to make good progress at BNL.
- Fit-up of the Sector electronics cooling system underway
- Sector 1 block construction ongoing at UIUC

All 32 Barrel Magnet Steel Sectors at BNL



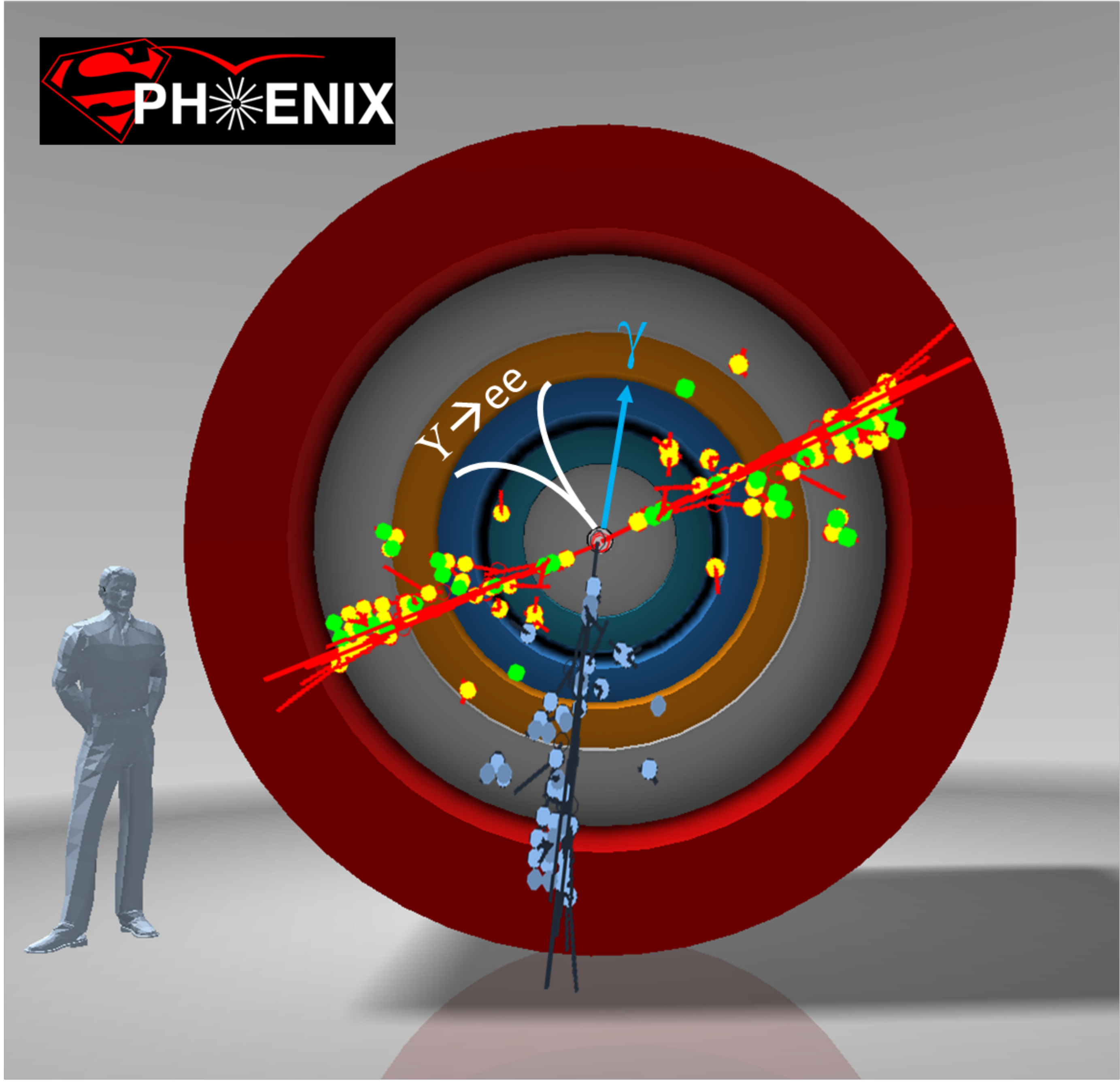
TPC Preproduction Components



Left: TPC R2 module four-layer GEM stack used in the test beam. **Right:** Preproduction TPC FEE cards carrying eight SAMPA version 4 chips, an Artix-7 FPGA, and double SFP+ links.

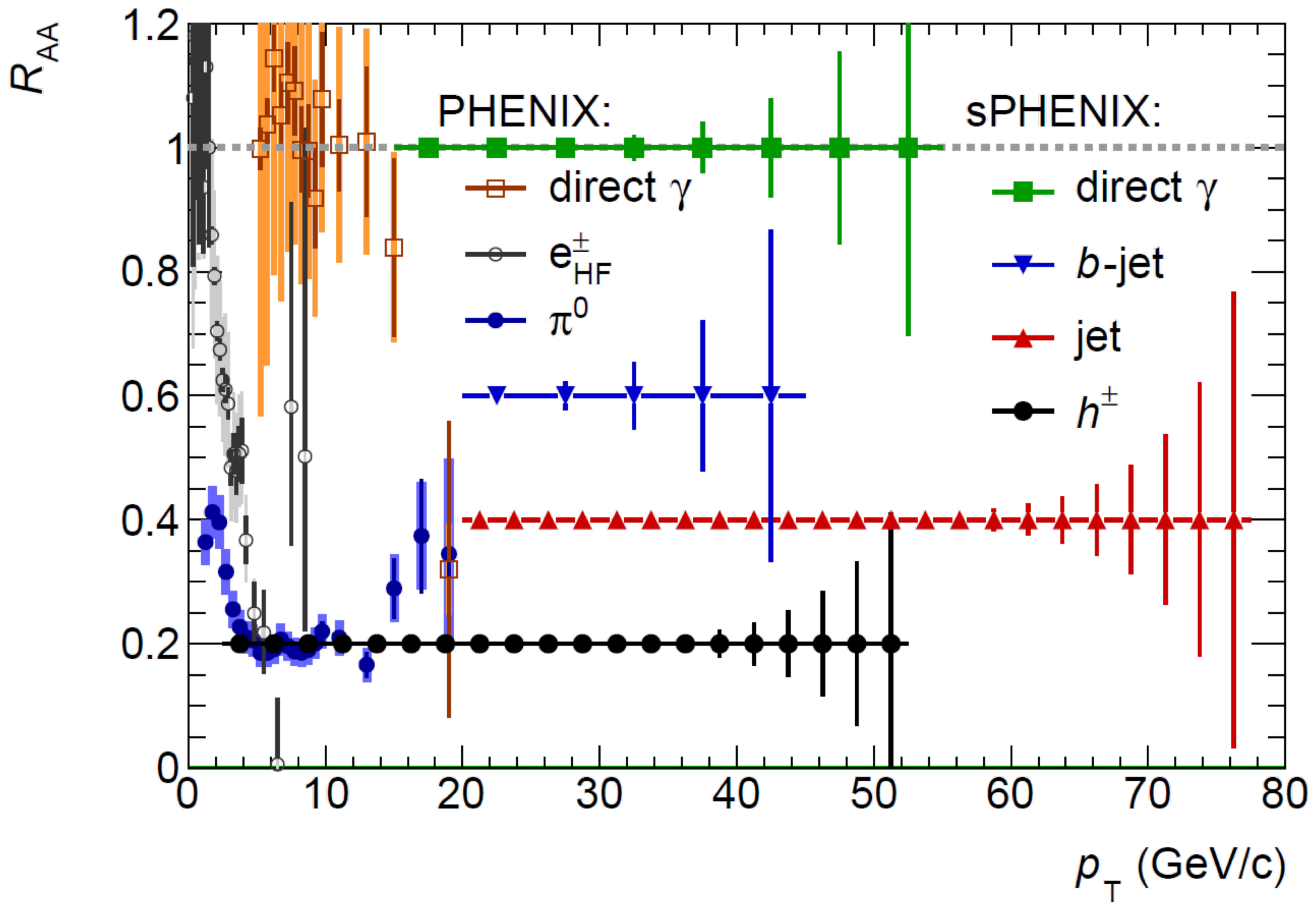
sPHENIX 3 Physics Pillars

1. Jets
2. Upsilons
3. Heavy Quarks



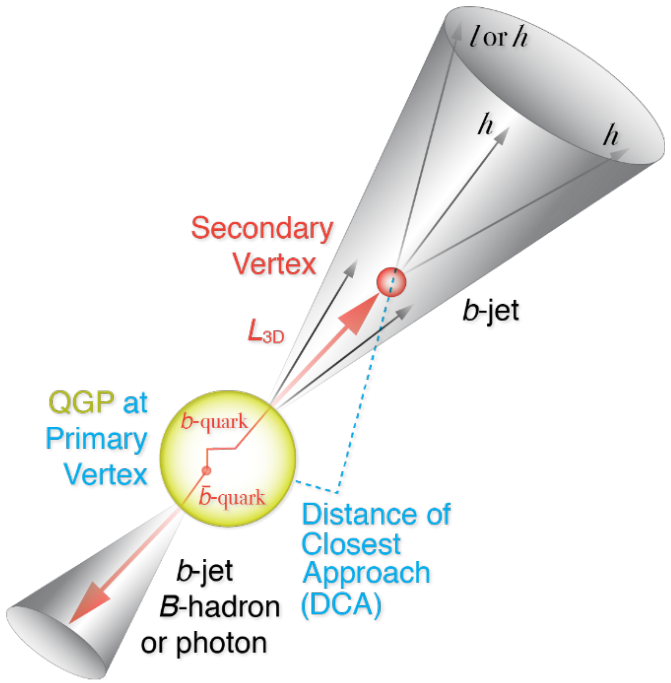
A Broad Physics Program with Jets @sPHENIX

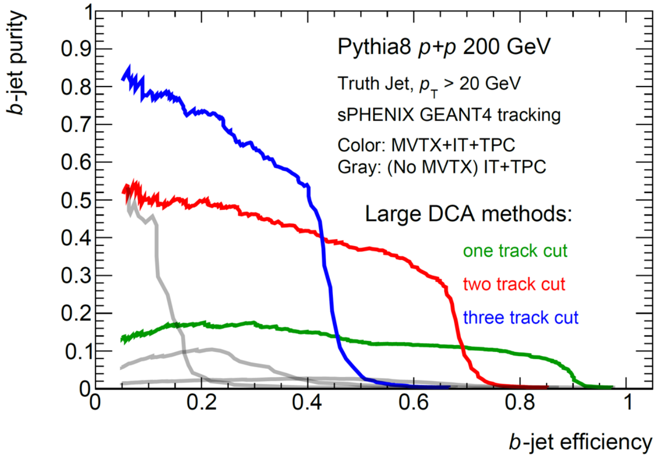
Parton Mass and Flavor Dependence of Jet Suppression and more

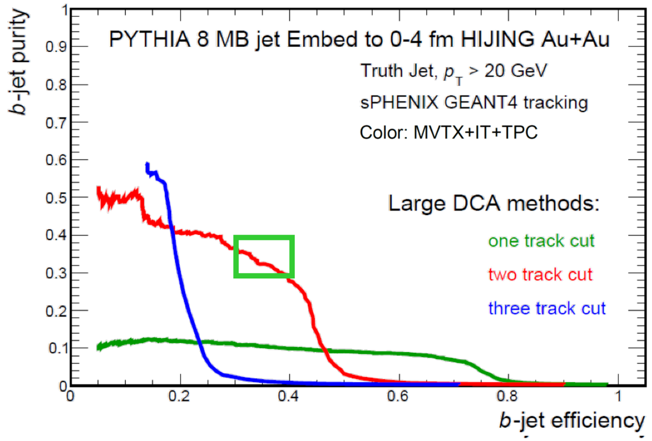


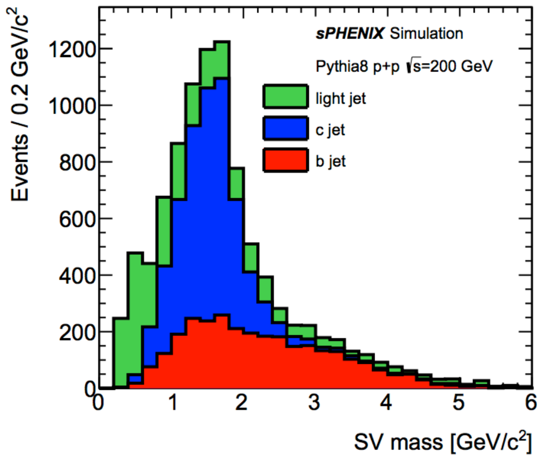
B-jet tagging

- Multi-tracks w/ large DCA
- 2nd vertex mass reco'd



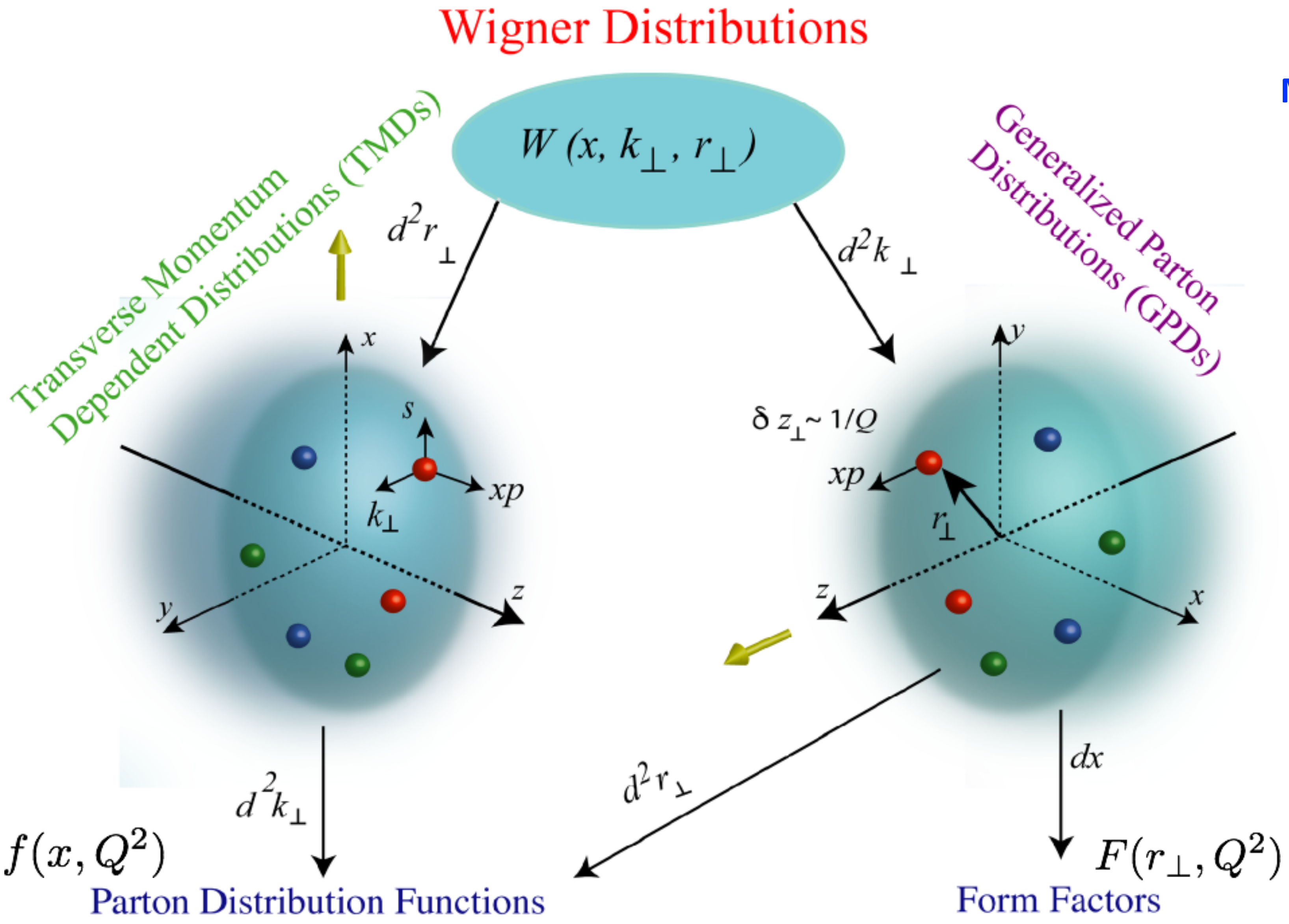






CMS work-point, Phys. Rev. Lett. 113, 132301 (2014)

Toward a Unified Picture of Nucleon Structure



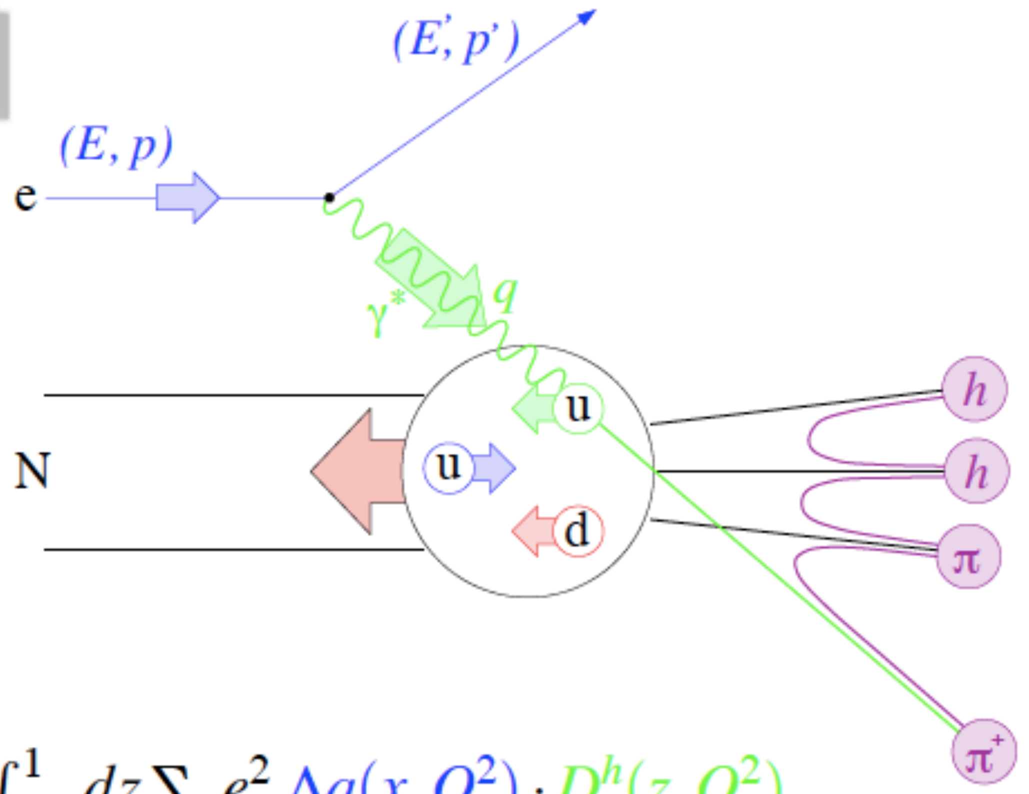
Momentum and Spatial Tomography

Some data, recent progress

Good data, long history

Semi-Inclusive DIS (SIDIS)

*In SIDIS, a **hadron h** is detected **in coincidence** with the scattered lepton*



Flavor Tagging in LO QCD:

$$A_1^h(x,Q^2) = \frac{\int_{z_{min}}^{1} dz \sum_q e_q^2\, \Delta q(x,Q^2) \cdot D_q^h(z,Q^2)}{\int_{z_{min}}^{1} dz \sum_q e_q^2\, q(x,Q^2) \cdot D_q^h(z,Q^2)}$$

$D_q^h(z,Q^2)$: **Fragmentation function**

Measures probability for struck quark q to produce a hadron h with

Energy fraction

$$z \equiv \frac{E_h}{\nu}$$