New Physics Opportunities with Hadron Beams at RHIC and FNAL, and J-PARC?

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Spinfest 2015, J-PARC

Outline

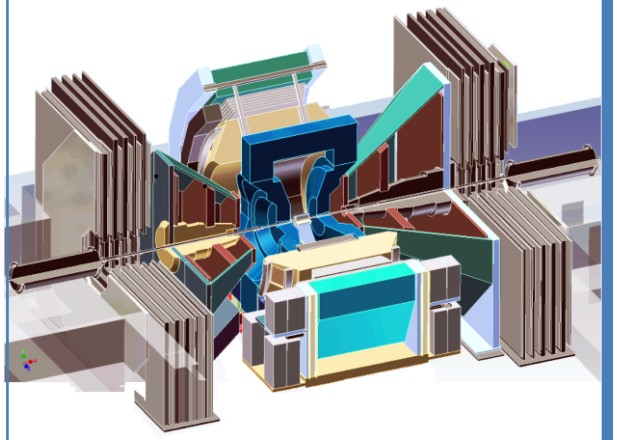
- Transverse spin physics with Forward sPHENIX at RHIC
  - A few key questions
    - TMD, Twist-3 etc.
  - Jet TSSA
    - “Sivers-like” and “Collins”

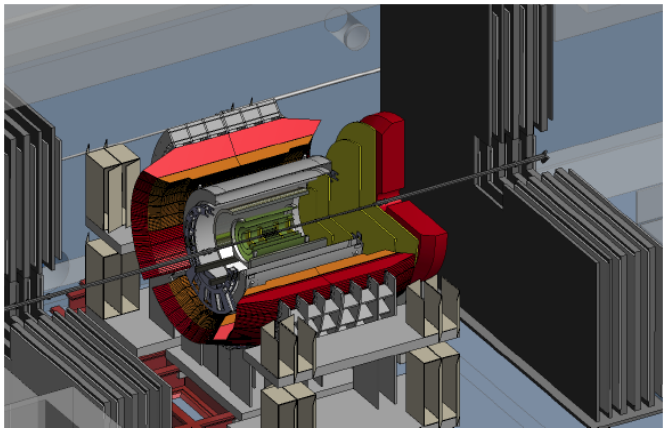
- New physics opportunities at Fermilab
  - Sea-quark TSSA at large x = 0.1 ~ 0.3
    - E1039 polarzied fixed target Drell-Yan
  - Direct search for dark photon and dark Higgs
    - E-1067 Dimuon beam-dump experiment at Fermilab (120GeV)
  - J-PARC (30GeV) opportunity?

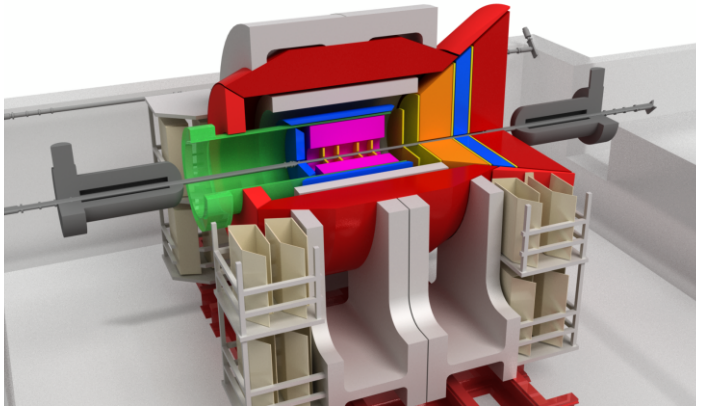
PHENIX -> Forward/sPHENIX->ePHENIX

Documented: http://www.phenix.bnl.gov/plans.html

Current PHENIX	*f*/*s*PHENIX	An EIC detector
• Current PHENIX as discussed in many previous talks • 14y+ work 100+M$ investment • 130+ published papers to date • Last run in this form 2016	‣ Comprehensive central upgrade based on BaBar magnet ‣ fsPHENIX: forward tracking, HCal and muon ID ‣ Key tests of theoretical frameworks for transverse spin	‣ Path of PHENIX upgrade leads to a capable EIC detector ‣ Large coverage of tracking, calorimetry and PID ‣ New collaboration/new ideas







~2000 2017→2021 ~2025 Time

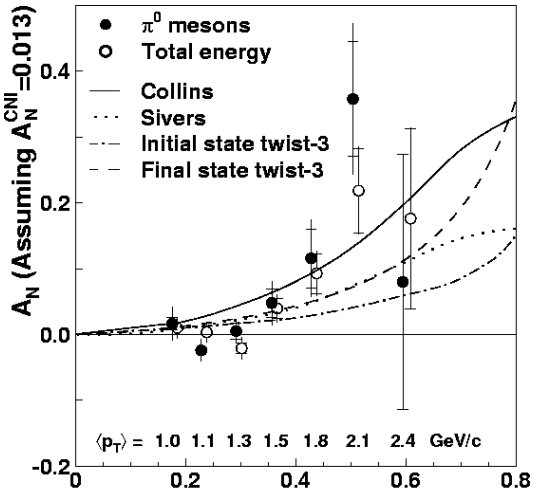
RHIC: A+A, polarized p+p, polarized p+A

eRHIC: e+p, e+A

Topic-I: Large TSSA
Do We Understand the Physics?

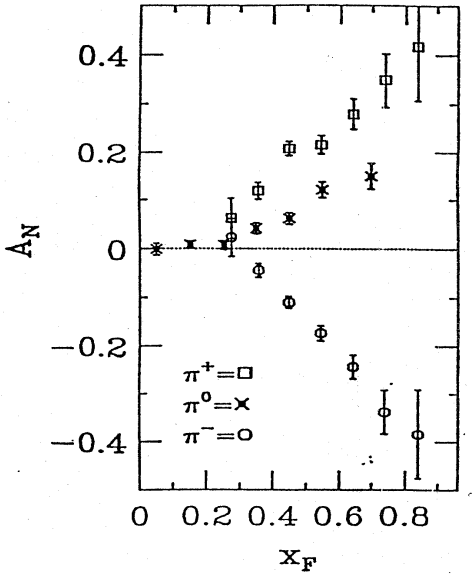
Large Transverse Single Spin Asymmetry (TSSA) in forward hadron production persists up to RHIC energy.

RHIC 200 GeV CMS



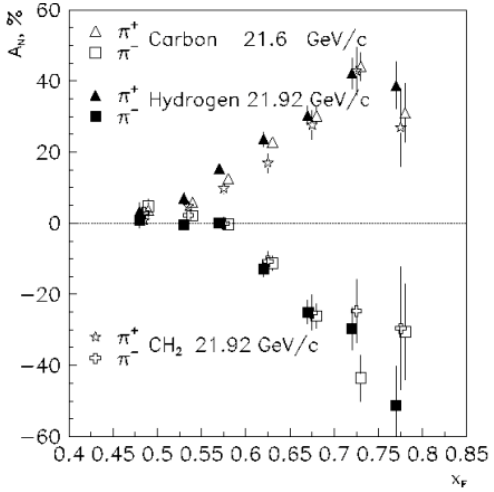
PRL (2004)

00 GeV beam



PLB261, 201 (1991)
PLB264, 462 (1991)

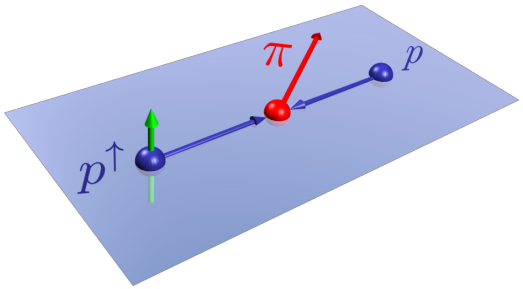
AGS 22 GeV beam



PRD65, 092008 (2002)

ZGS 12 GeV beam

PRL36, 929 (1976)



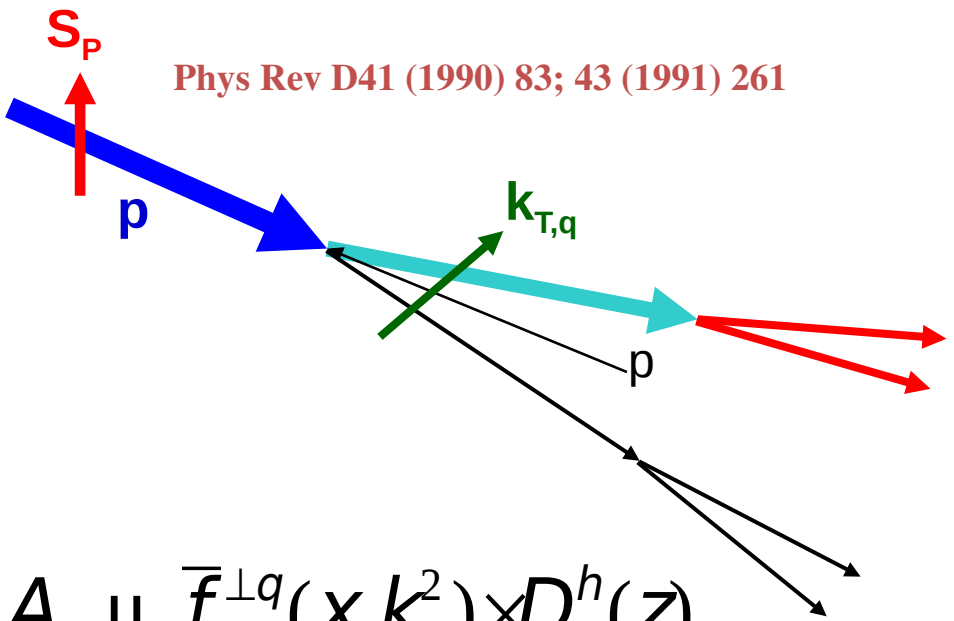
Sivers, Collins, Twist-3 ….

Non-Perturbative cross section → Perturbative cross section

Study the Physics via Hard Scatterings at RHIC

(i) Sivers mechanism:

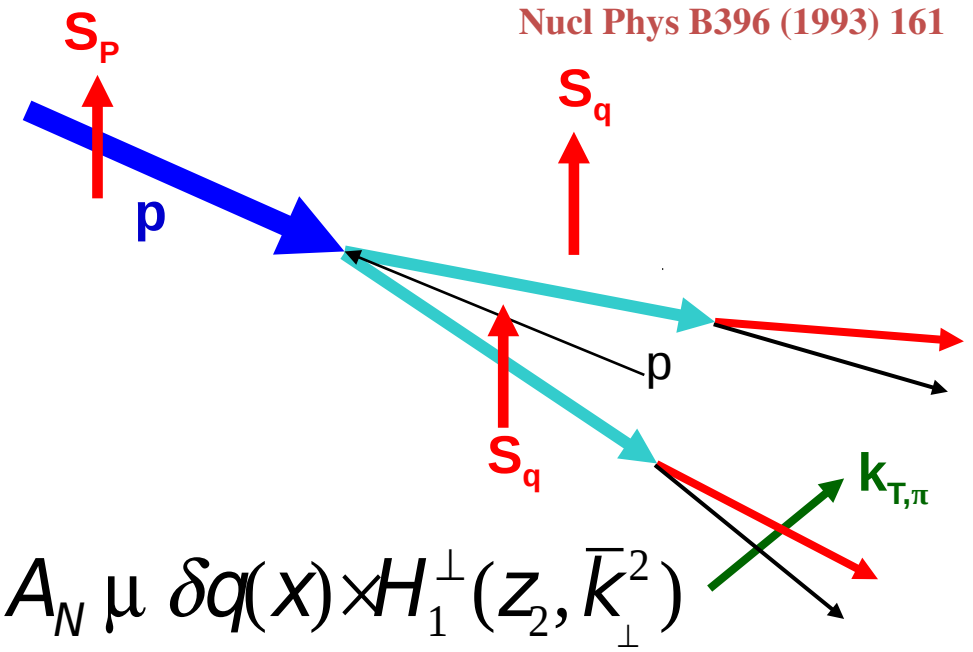
correlation between proton spin & parton k_T



$$A_N \mu \ \overline{f}_{1T}^{\perp q}(x, k_\perp^2) \times D_q^h(z)$$

(ii) Collins mechanism:

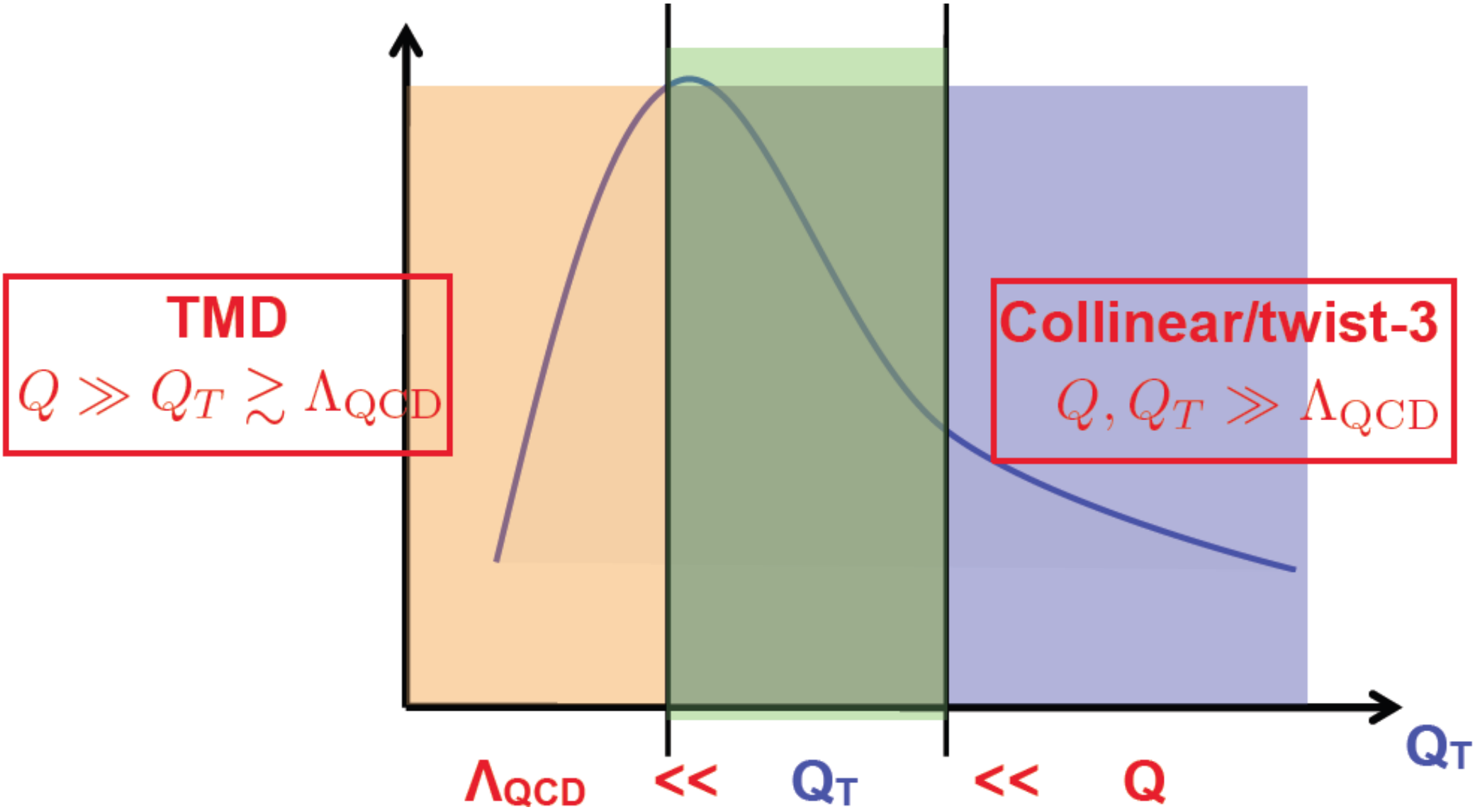
Transversity × spin-dep fragmentation



$$A_N \mu \ \delta q(x) \times H_1^\perp(z_2, \overline{k}_\perp^2)$$

Collinear Twist-3: quark-gluon/gluon-gluon correlation

TMD and Collinear Twist-3



Key Questions in Transverse Spin physics

- Non-universality of TMD distribution functions
  - Opposite-sign contribution of TMD distribution function to TSSA in semi-Inclusive DIS (SIDIS) process and Drell-Yan process

$$f_{1T}^{\perp q}|_{\rm SIDIS} = -f_{1T}^{\perp q}|_{\rm DY}$$

  - Fundamental property based on Gauge-Link formalism of QCD
  - Experimental verification needed

- Consistency between SIDIS/TMD and pp/Twist-3
  - Tmd description at low p_t region, higher-twist description at high pt region, and consistent description in the middle region

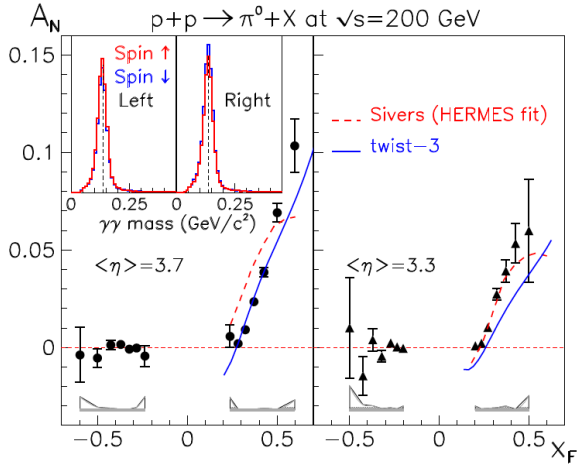
  - But, sign mismatch of each description obtained from experiments

$$T_{q,F}(x,x) = -\int d^2k_\perp \frac{|k_\perp^2|}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{\rm SIDIS}$$

A_N Sign Mismatch?

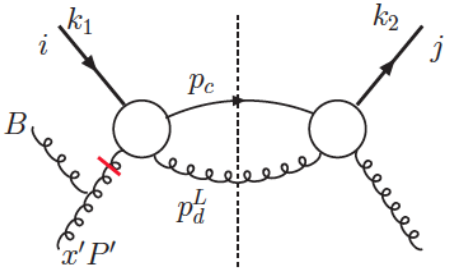
First attempt to check the "Universality of QCD description of TSSA"

- Twist-3 (RHIC) v.s. Sivers (SIDIS)



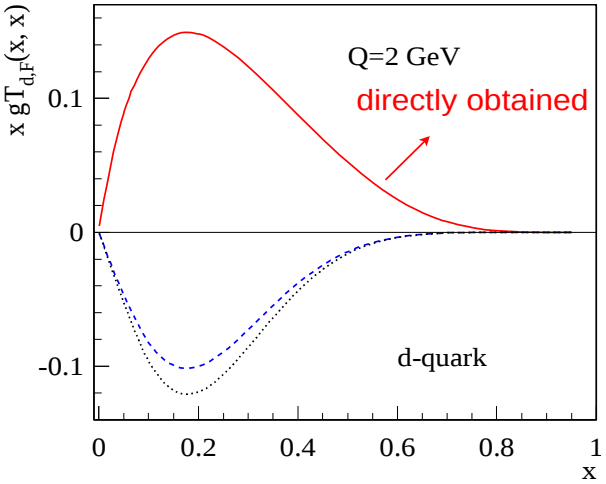
Kang, Qiu, Vogelsang, Yuan PRD 2011

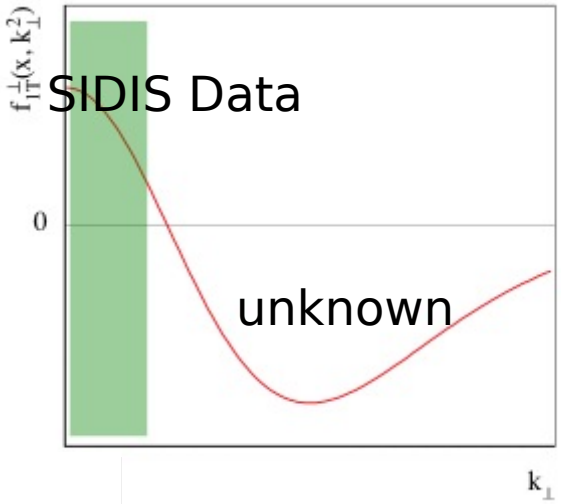
$$gT_{q,F}(x,x) = -\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x,k_\perp^2)\Big|_{SIDIS}$$



Qiu,Sterman
Kouvaris et al.
Kanazawa,Koike
Kang,Prokudin

A possible solution? Kang, Prokudin PRD (2012)





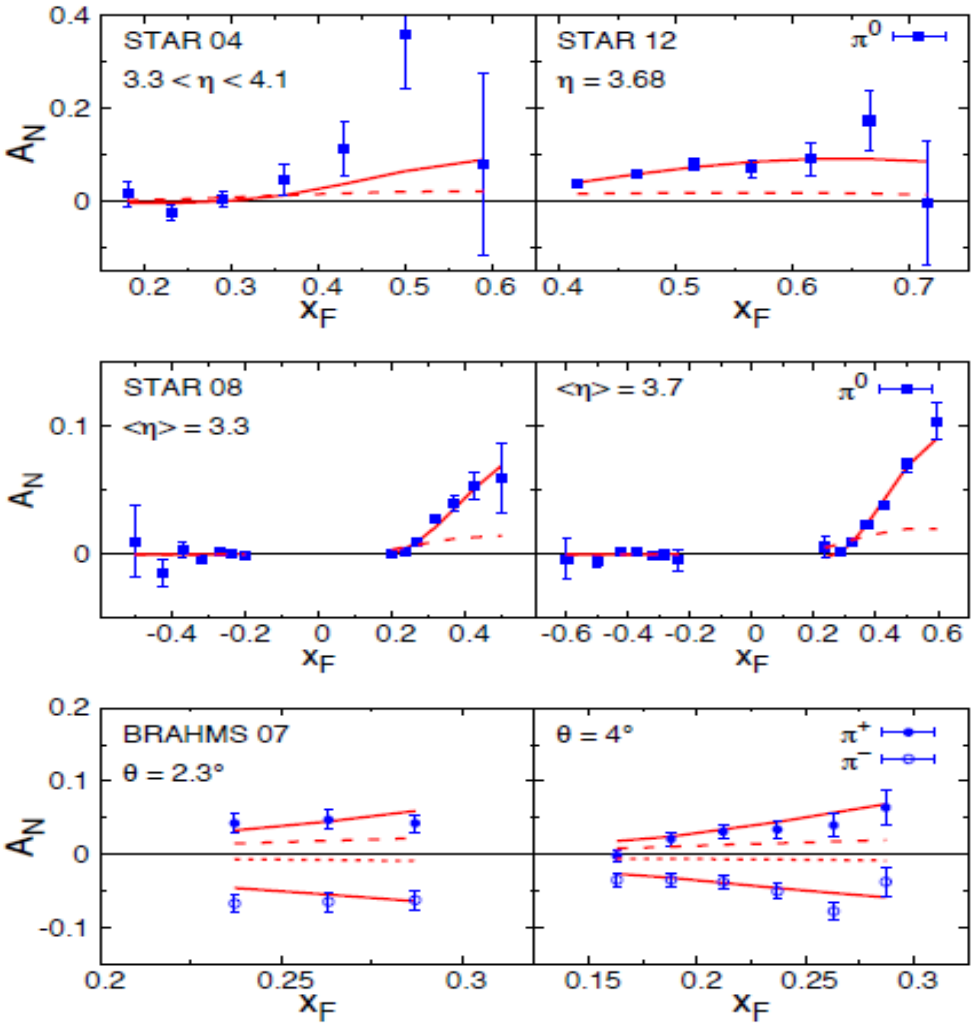
Collins dominates?

Need more data to check other possibilities!

Could "Collins" be the Solution?

A_N from twist-3 fragmentation functions

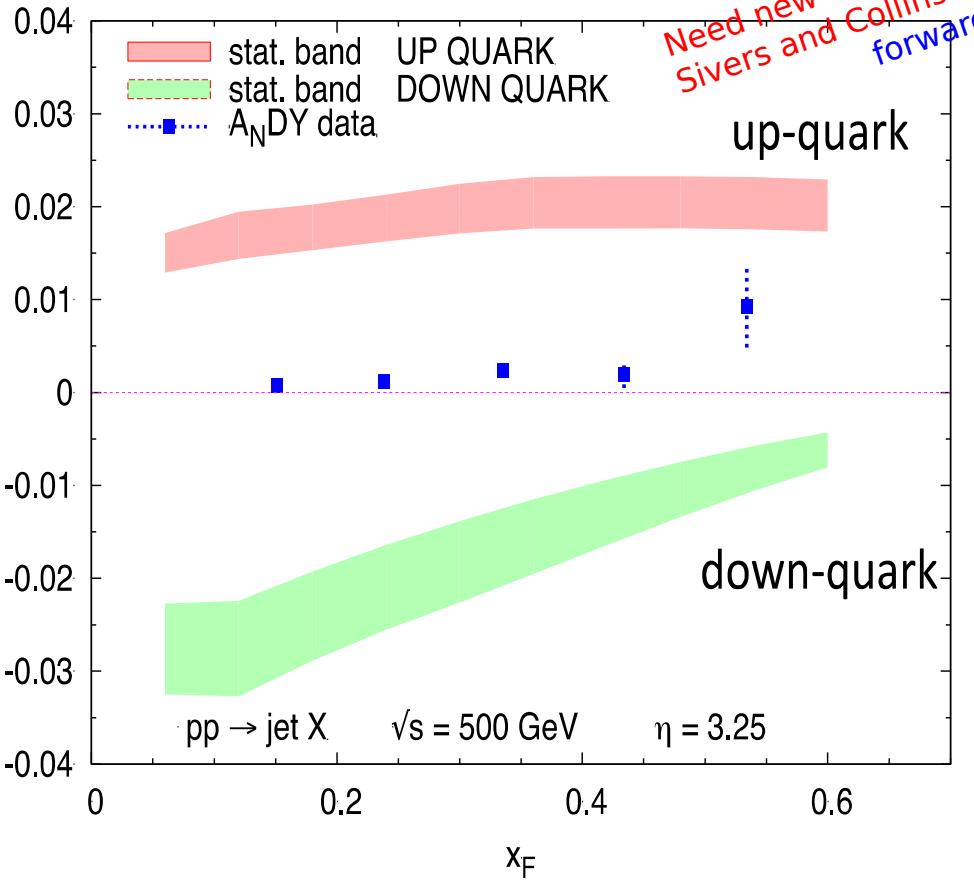
(Kanazawa, Koike, Metz, Pitoniak, arXiv:1404.1033)



good fit of A_N mainly due to the new twist-3 fragmentation function

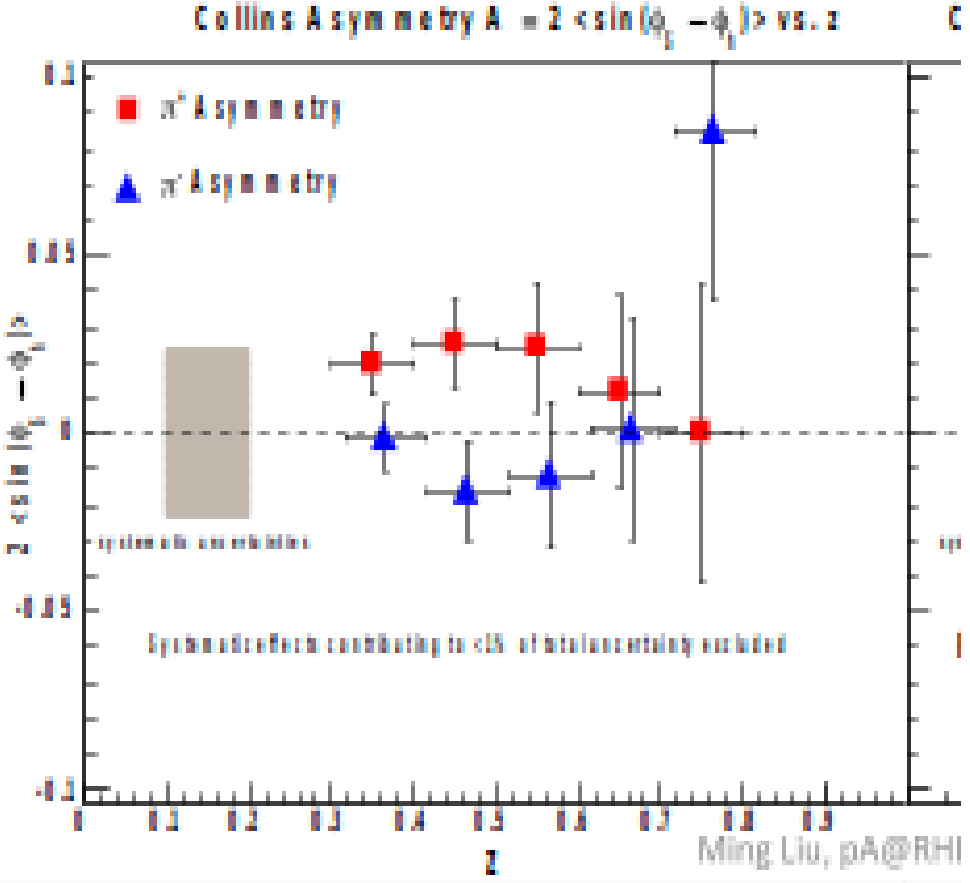
AnDY Inclusive Jet TSSA and STAR Jet Collins

- AnDY jet TSSA
  - Very small, u and d cancellation?

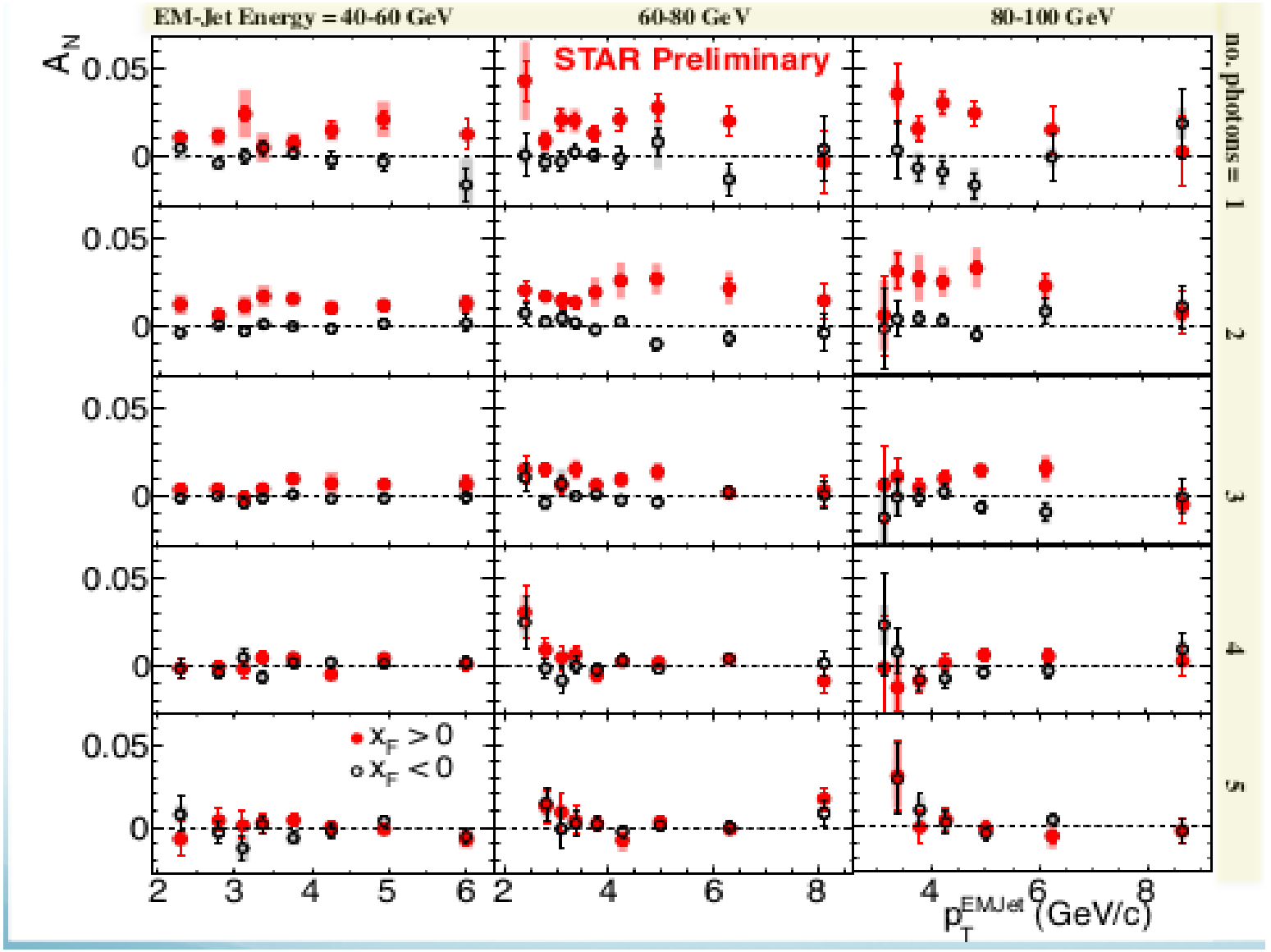


Need new direct measurements of Sivers and Collins TSSA in p+p! forward sPHE etc.

- STAR Collins in jet
  - Consistent sign w/ SIDIS
  - Central rapidity



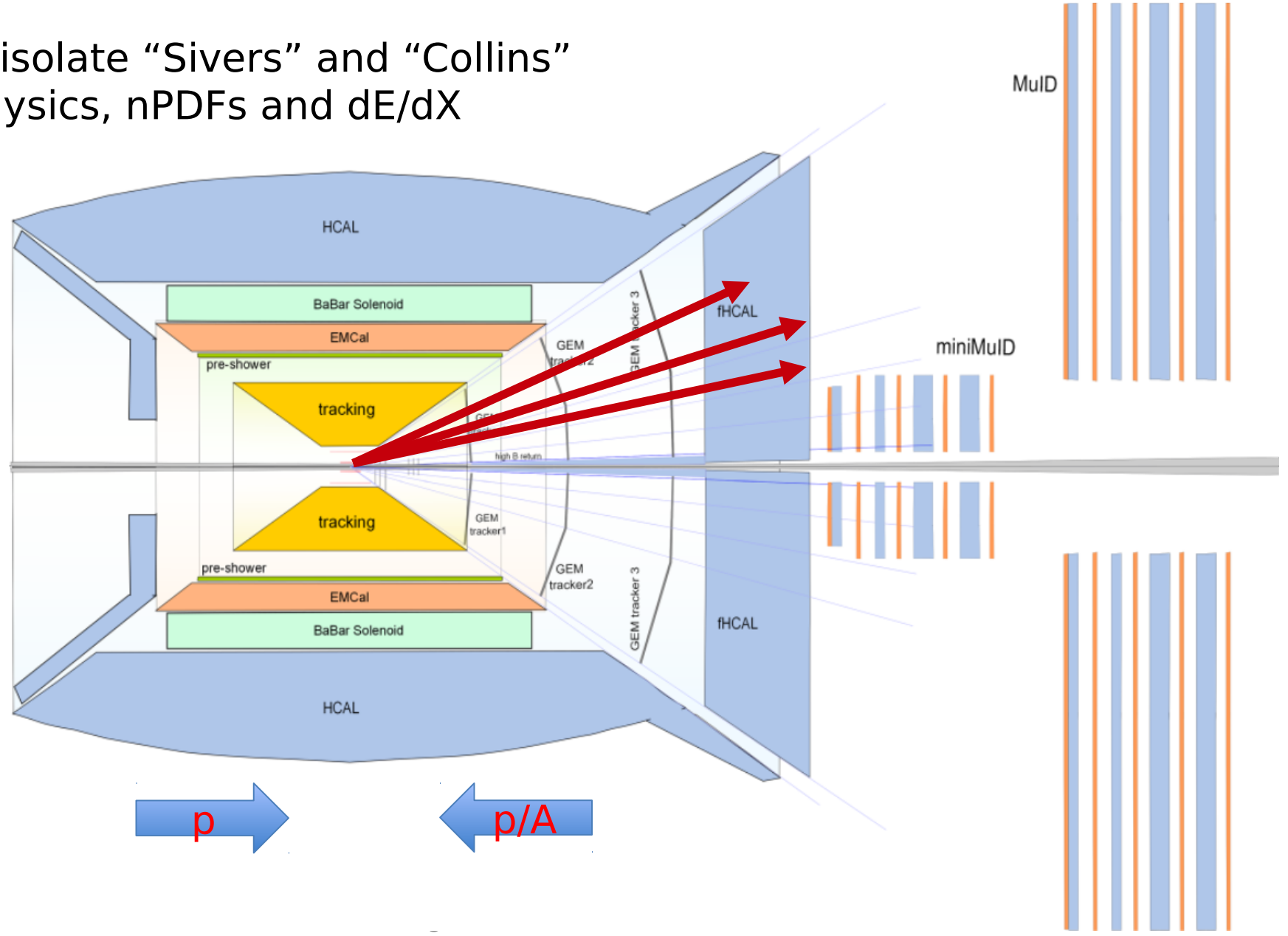
STAR: Forwrd pi0 TSSA w/ EM-Jet



Forward sPHENIX

-1 < eta < 4

- Clearly isolate “Sivers” and “Collins”
- CNM physics, nPDFs and dE/dX



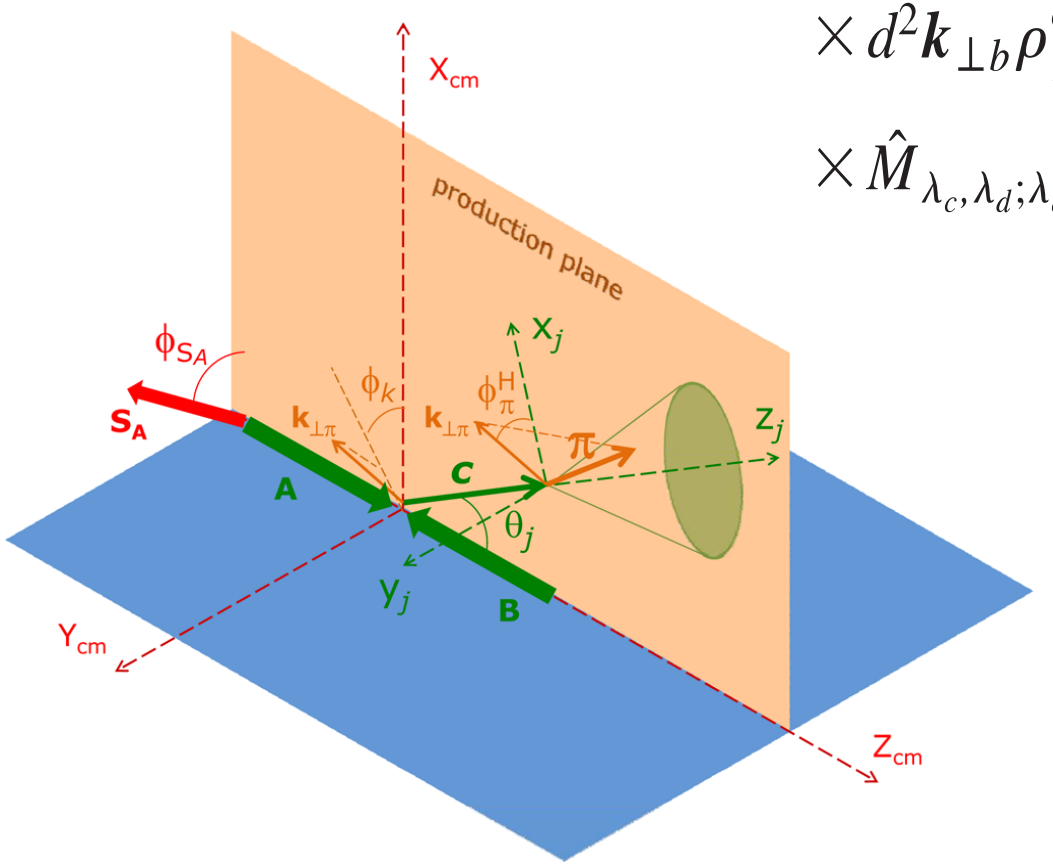
Access “Sivers” and “Collins” Asymmetries with Jets

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

$$\frac{E_j d\sigma^{A(S_A)B\to \text{jet}+\pi+X}}{d^3\boldsymbol{p}_j dz d^2\boldsymbol{k}_{\perp\pi}} = \sum_{a,b,c,d,\{\lambda\}} \int \frac{dx_a dx_b}{16\pi^2 x_a x_b s} d^2\boldsymbol{k}_{\perp a}$$

$$\times d^2\boldsymbol{k}_{\perp b} \rho^{a/A,S_A}_{\lambda_a\lambda'_a} \hat{f}_{a/A,S_A}(x_a,\boldsymbol{k}_{\perp a}) \rho^{b/B}_{\lambda_b\lambda'_b} \hat{f}_{b/B}(x_b,\boldsymbol{k}_{\perp b})$$

$$\times \hat{M}_{\lambda_c,\lambda_d;\lambda_a,\lambda_b} \hat{M}^*_{\lambda'_c,\lambda_d;\lambda'_a,\lambda'_b} \delta(\hat{s}+\hat{t}+\hat{u}) \hat{D}^{\pi}_{\lambda_c,\lambda'_c}(z,\boldsymbol{k}_{\perp\pi}).$$



Experimental variables:

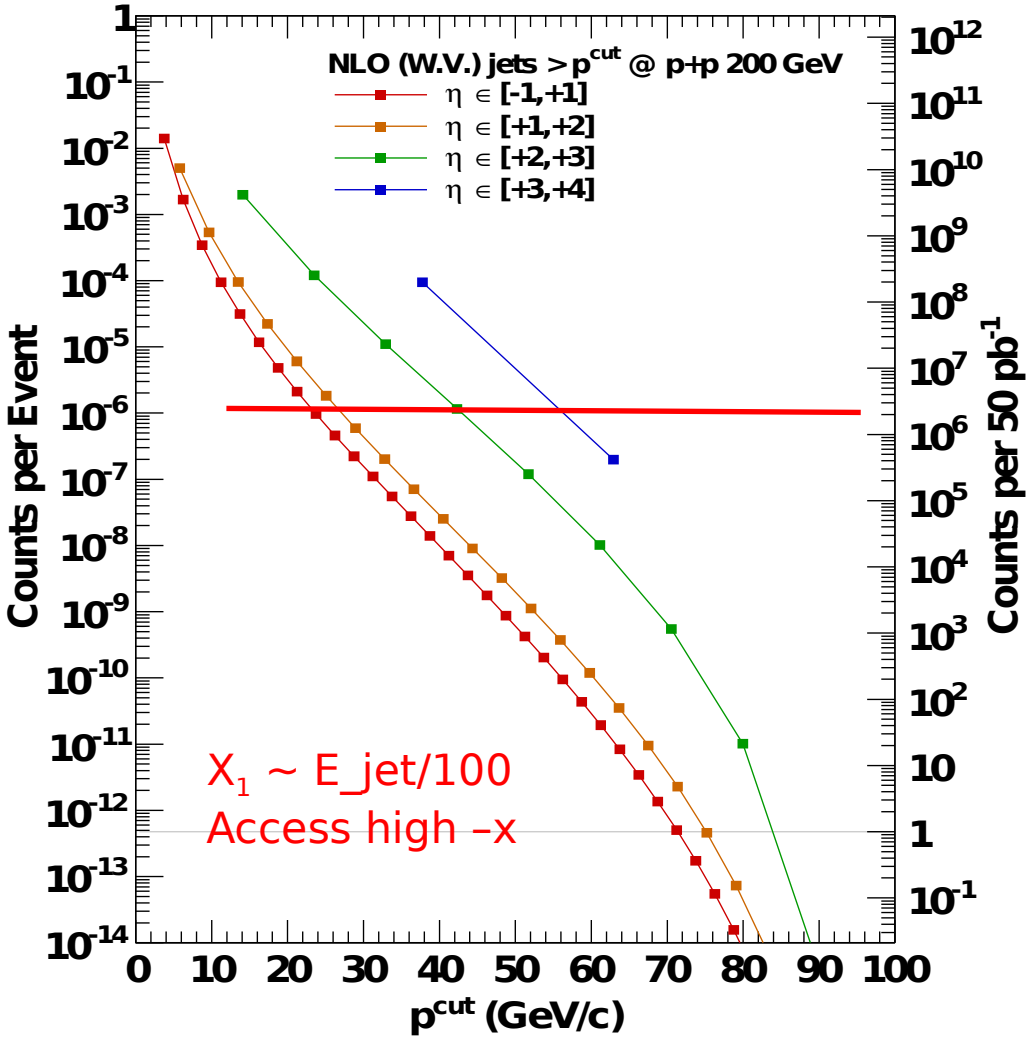
- Jet $P_{j,\,xF}$
- Hadrons , Charge and PID
- Beam polarization

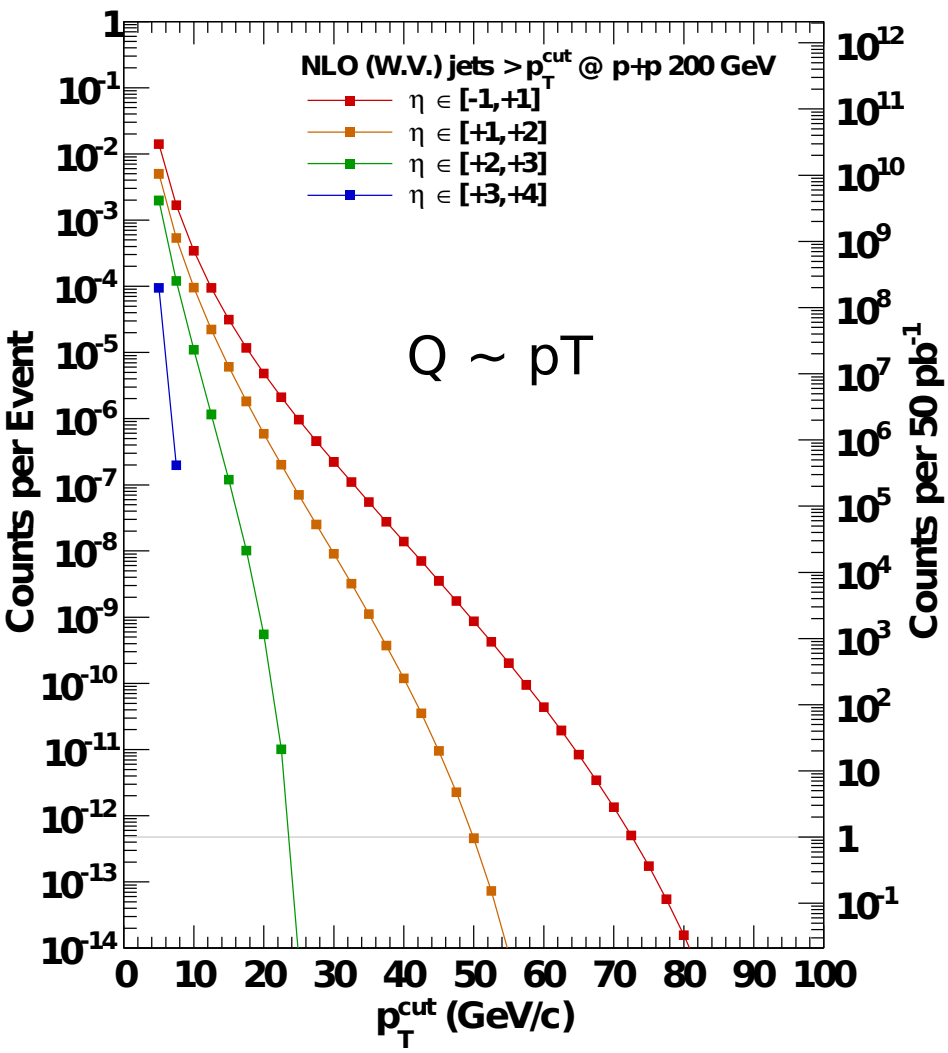
$A_N^{\sin\phi_{S_A}}$ “Sivers-Like”

$A_N^{\sin(\phi_{S_A} \mp \phi_\pi^H)}$ “Collins”

Jet Production Rates @NLO

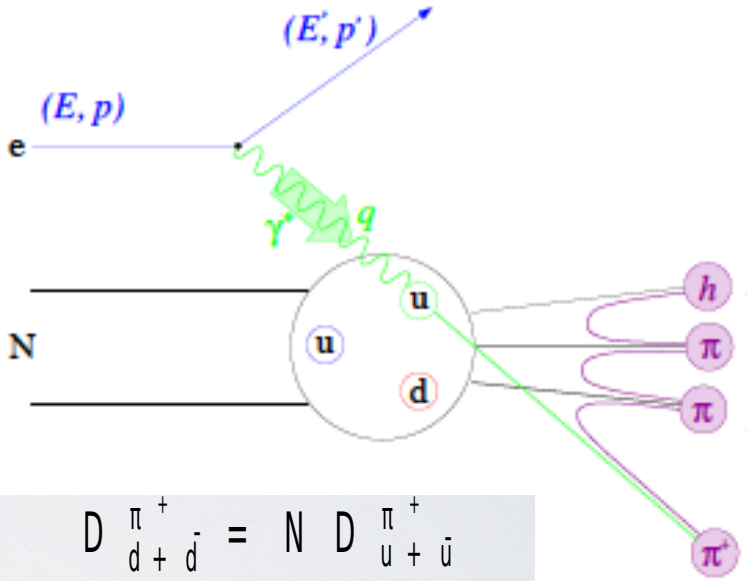
200GeV p+p: Lumi = 50pb^{-1}





Tag Quark Flavor with Leading Charged Hadrons

- @Z = 0.5



$$D^{\pi^+}_{d+\bar{d}} = N\, D^{\pi^+}_{u+\bar{u}}$$

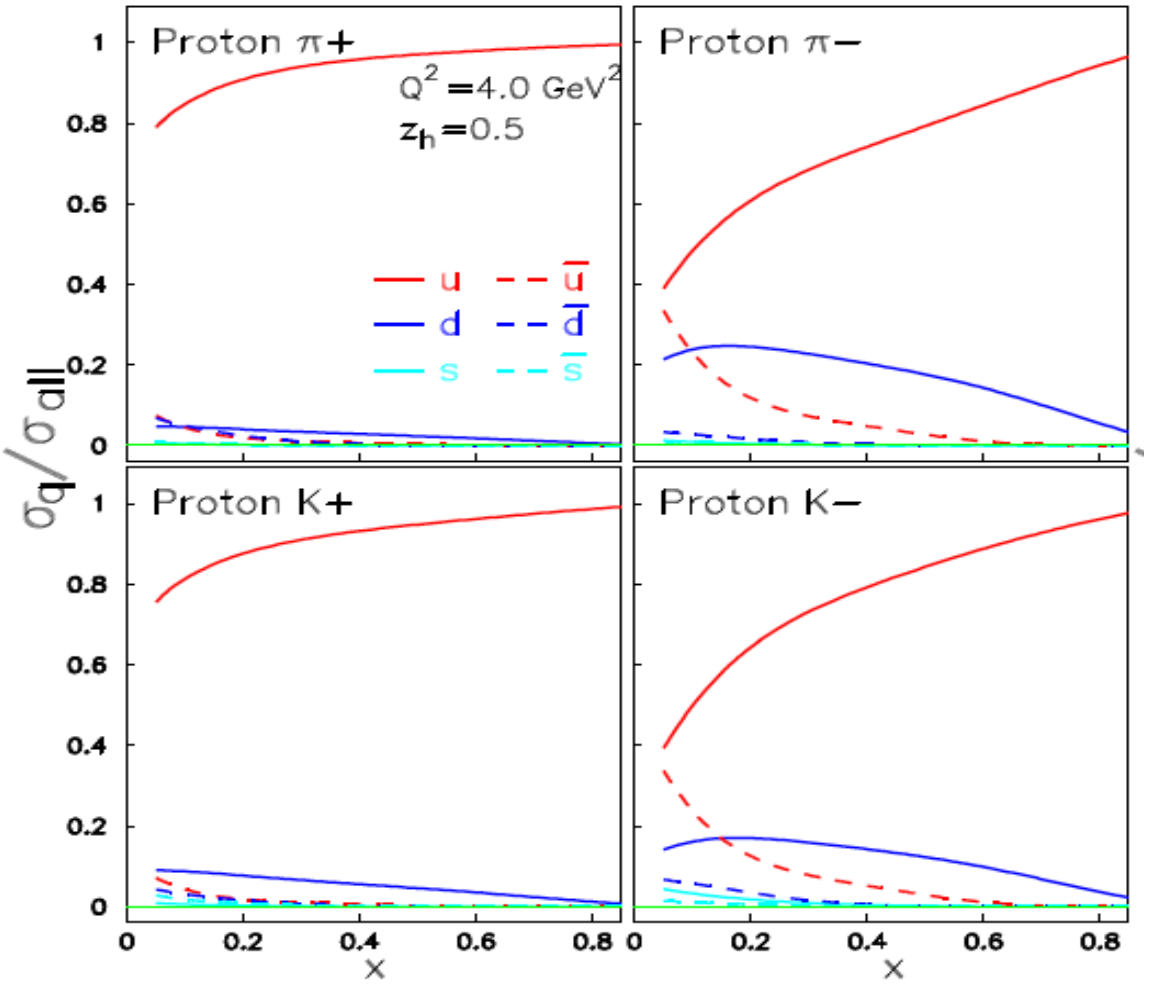
$$D^{\pi^+}_{s} = D^{\pi^+}_{\bar{s}} = N'\, D^{\pi^+}_{\bar{u}}$$

DSS FF

$$D^{\pi^+}_{\bar{u}} = D^{\pi^+}_{d}$$

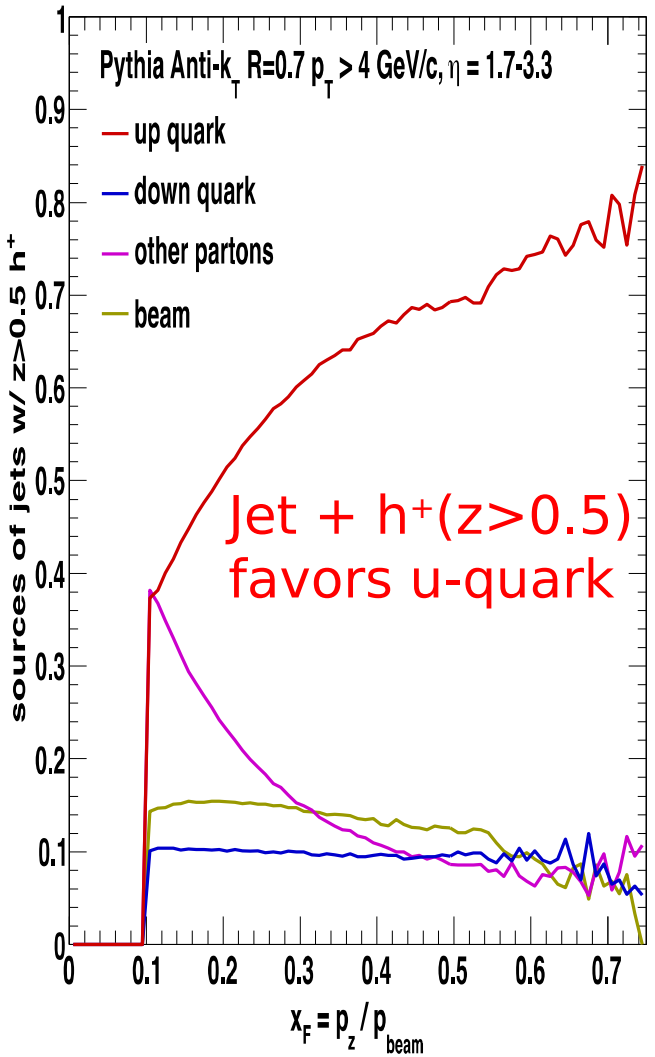
$$D^{K^+}_{\bar{u}} = D^{K^+}_{s} = D^{K^+}_{d} = D^{K^+}_{\bar{d}}\,.$$

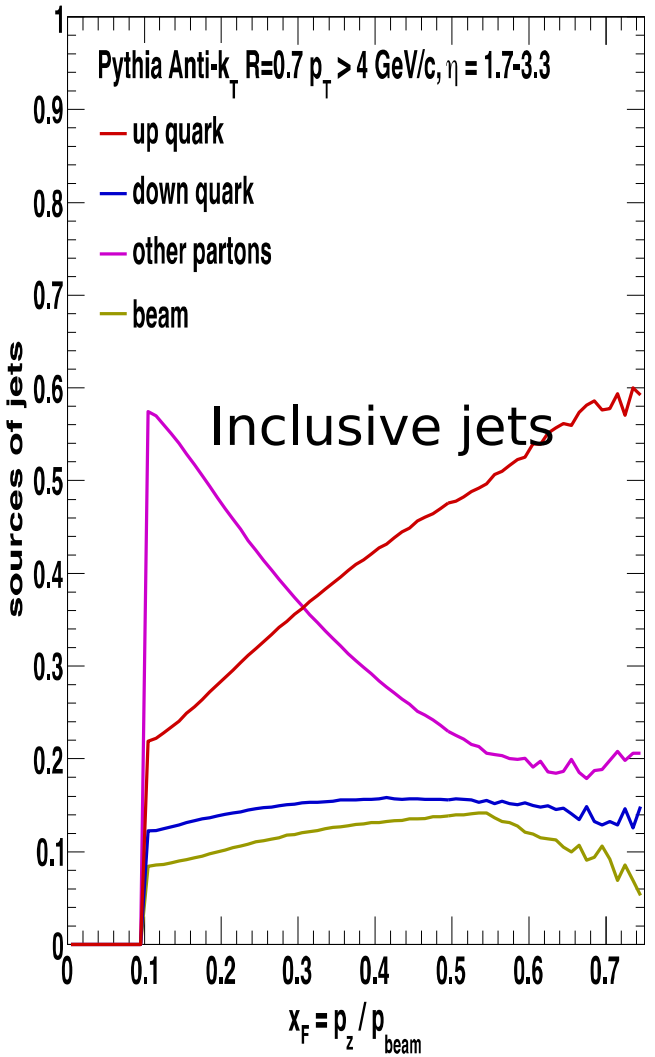
$$\sigma_q/\sigma_{all} = e_f^2 q_f \cdot D_f^h / \sum e_i^2 q_i \cdot D_i^h$$

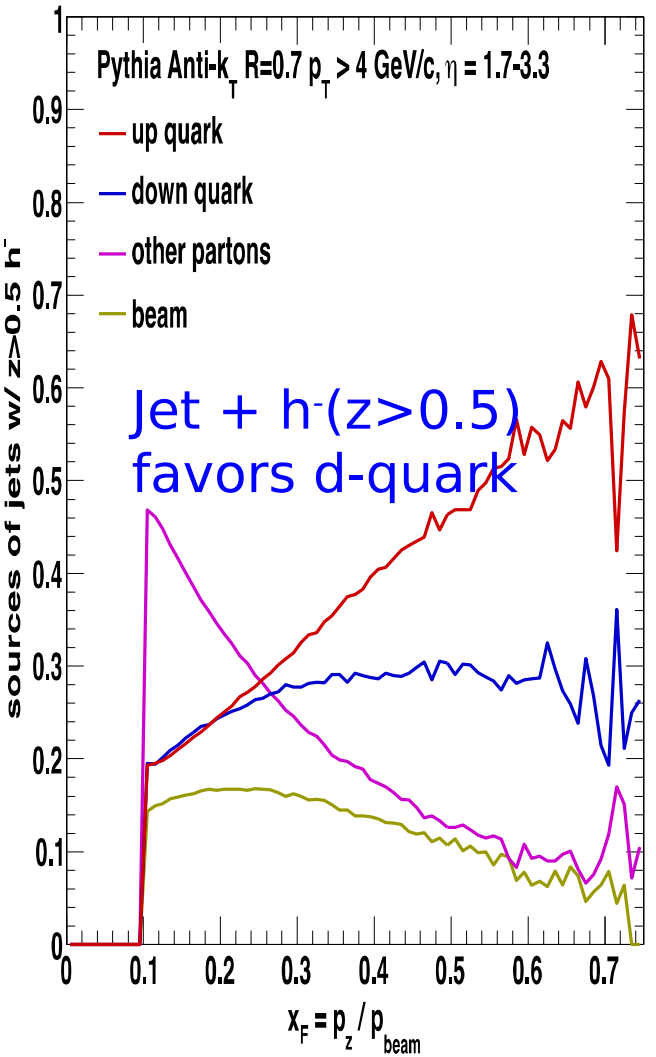


u-quark dominates in proton

Jet Quark-Flavor Tagging with Charged Hadrons





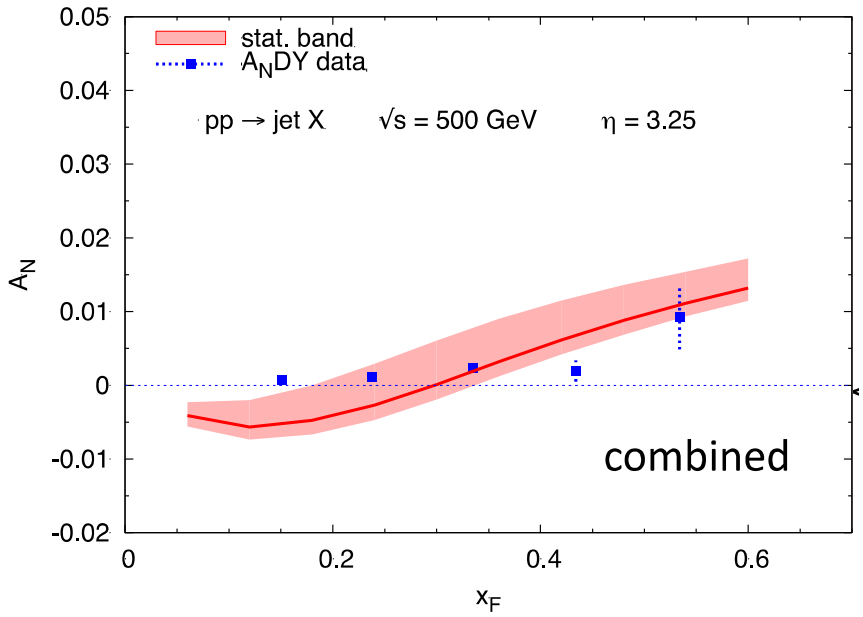


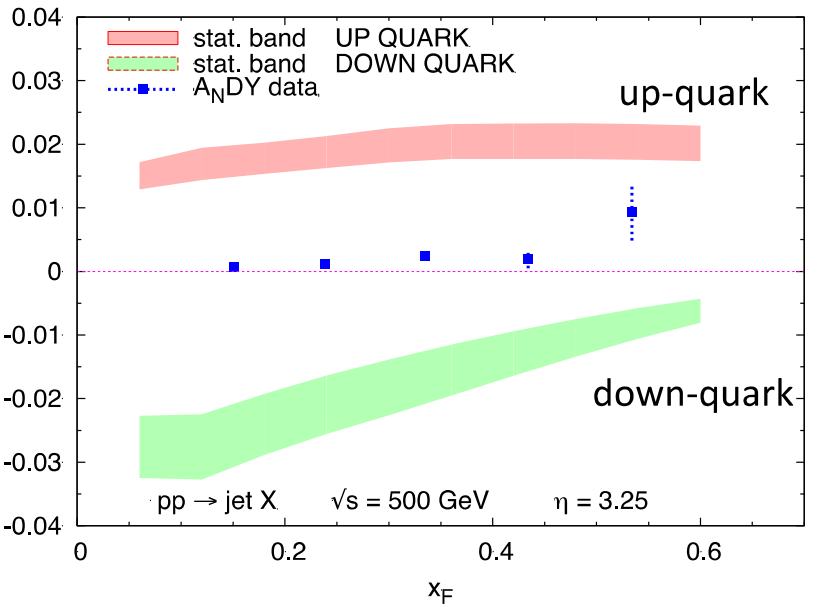
Flavor Tagged Jet "Sivers" Asymmetry

- Jet and leading h^+ and h^-
- jet_eta= [1,4]

We can do this!

Directly use Sivers function from SIDIS fit

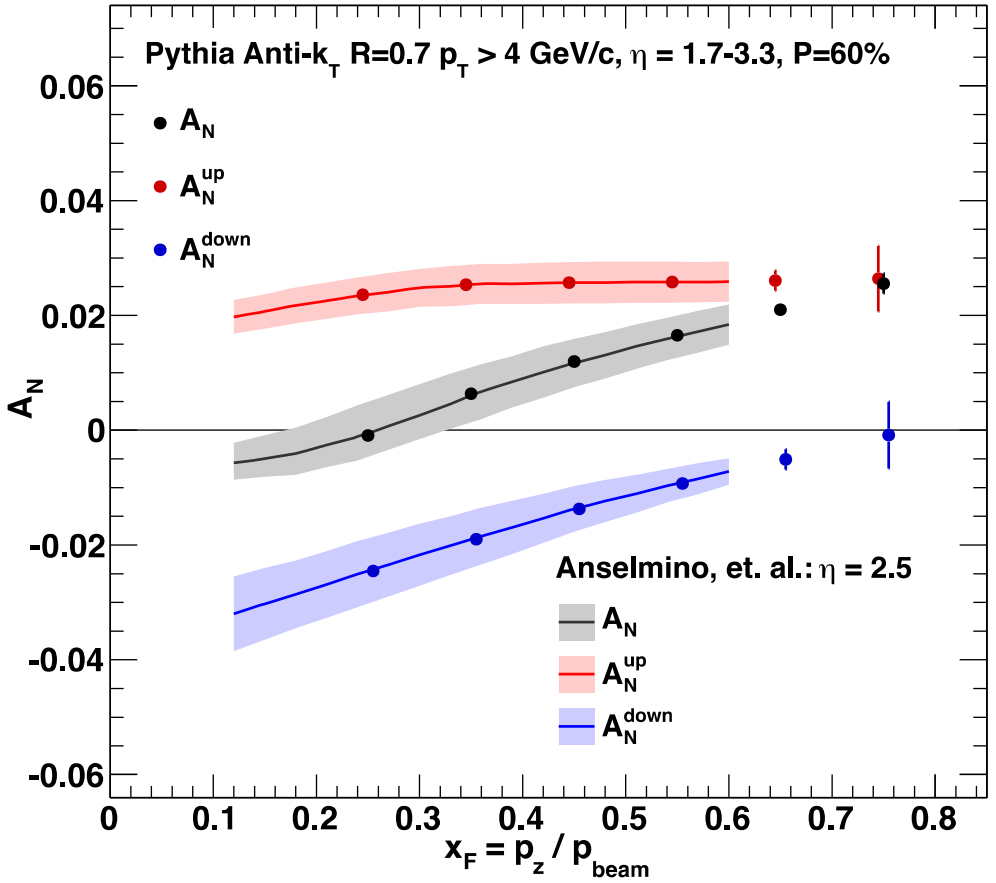




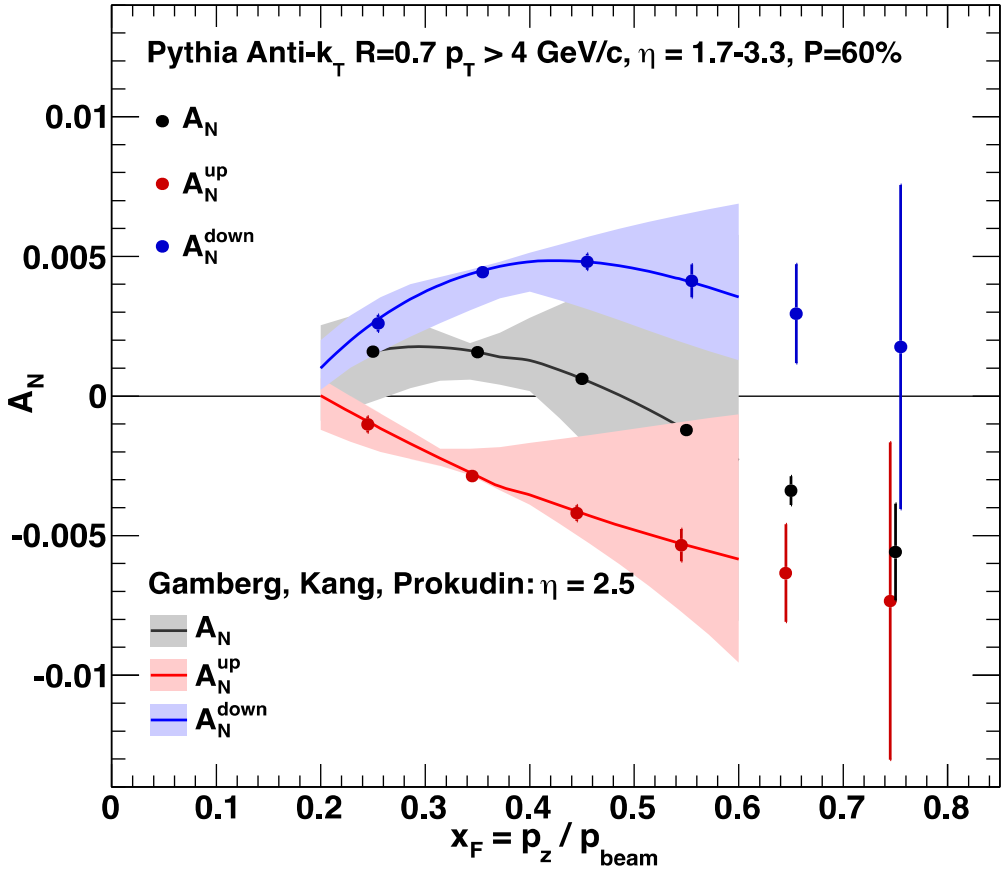
Jet TSSA: Test Process Dependence

- Change of sign in flavor-tagged Jet TSSA

Naïve DIS Fit Sivers



Included 1) process dependence and 2) Q^2 evolution

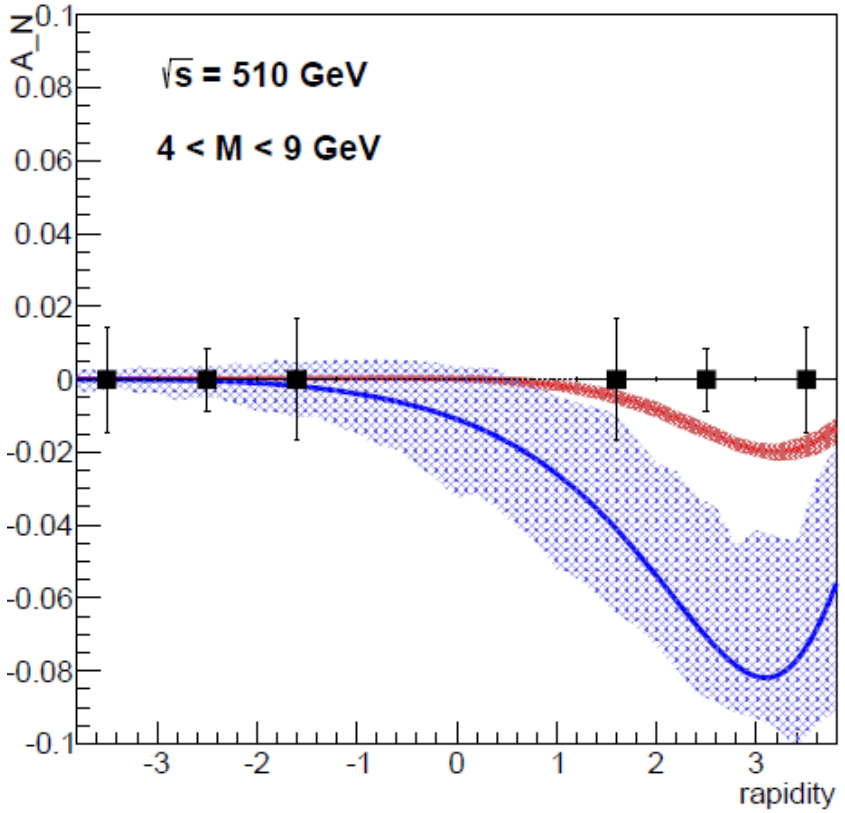


Drell-Yan TSSA: Test Sign Change

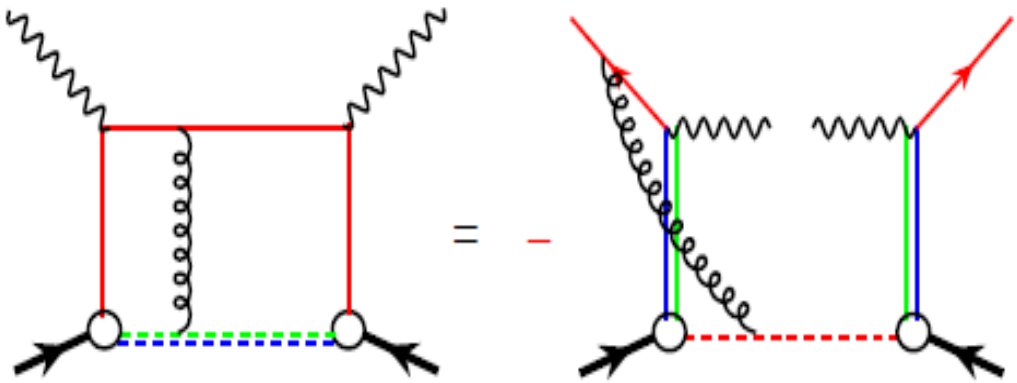
Fundamental test of pQCD factorization and gauge-link formalism

- Theoretically clean
- Experimentally challenging
- TMD (pp) vs TMD (SIDID)

Kang and Qiu, PRD 84 054020
Exchevarria et. al., arXiv 1401.5078

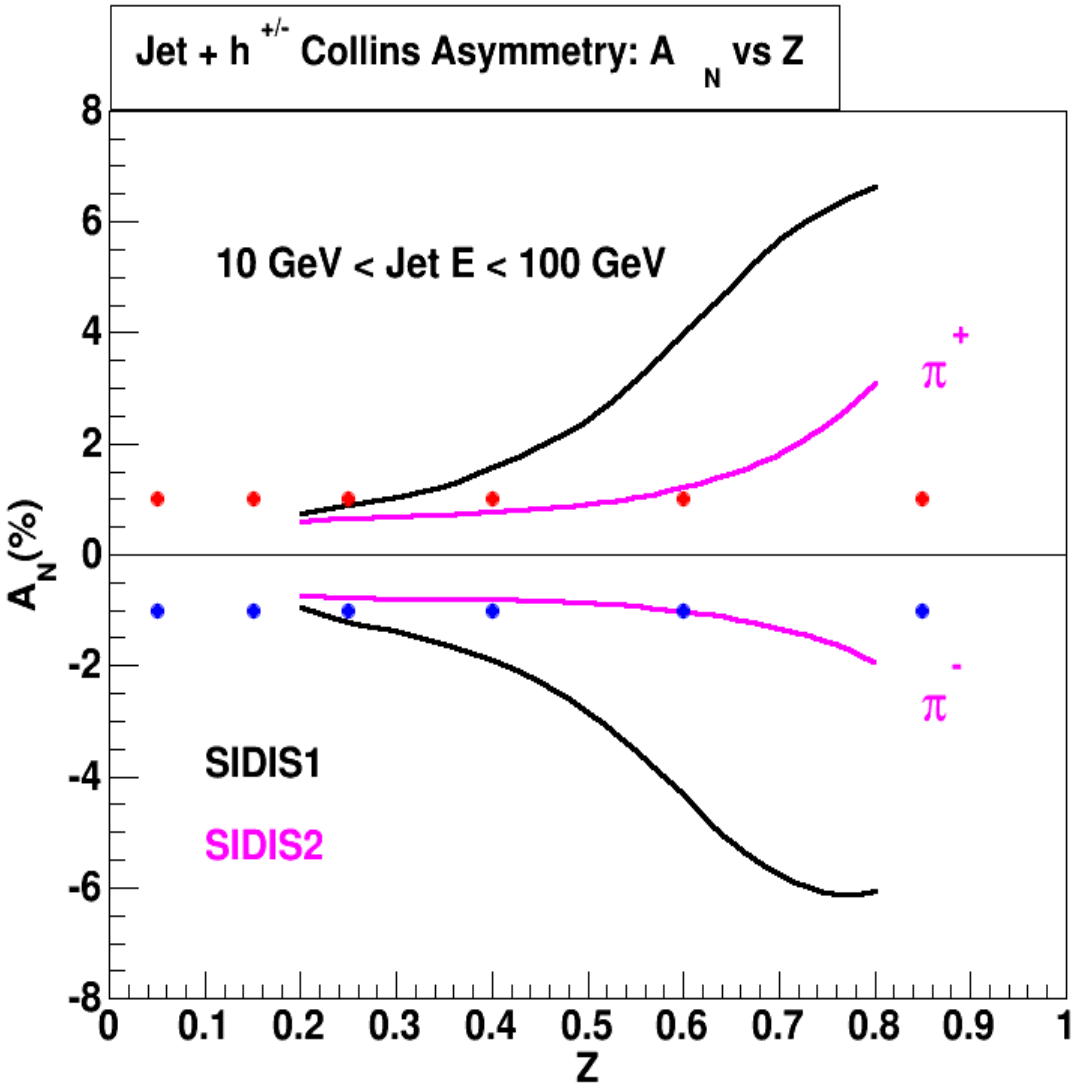


$$\Delta^N f_{q/h^\uparrow}^{\mathrm{SIDIS}}(x,k_\perp) = -\Delta^N f_{q/h^\uparrow}^{\mathrm{DY}}(x,k_\perp)$$



SIDIS = – DY

Hadron Collins Asymmetry in Jets



- Test universality of Collins FF
- SIDIS vs pp
  - TMD
  - Twist-3

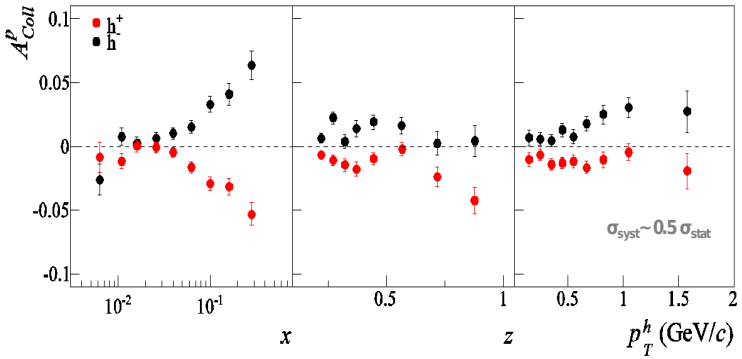
Collins asymmetry on proton

charged hadrons - published 2007 & 2010 data results

PLB 692 (2010) 240 PLB 717 (2012) 376

very good agreement between the two independent data sets

combined 2007 – 2010 results



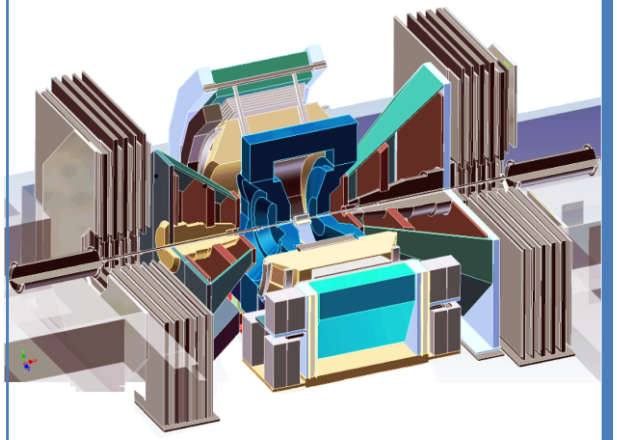
- **precise measurements**
- **clear signal at x > 0.3, with opposite sign for h+ and h-**

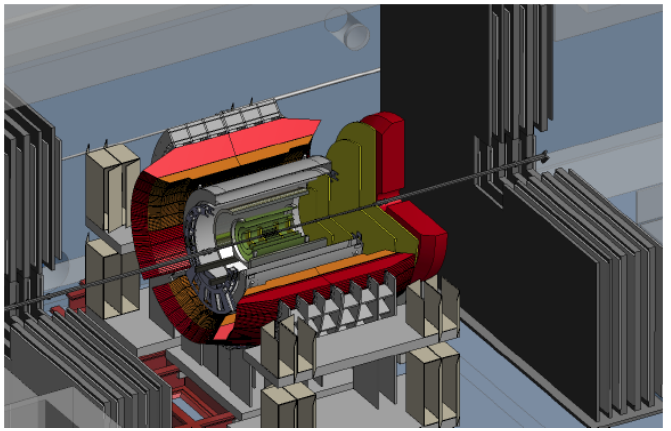
Anna Martin

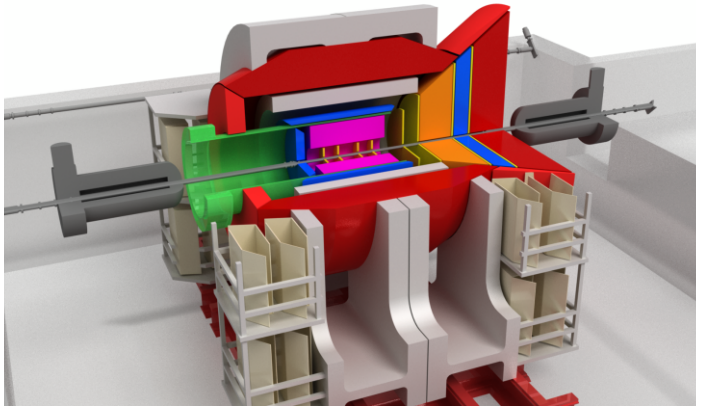
PHENIX -> Forward/sPHENIX->ePHENIX

Documented: http://www.phenix.bnl.gov/plans.html

Current PHENIX	*f*/*s*PHENIX	An EIC detector
• Current PHENIX as discussed in many previous talks • 14y+ work 100+M$ investment • 130+ published papers to date • Last run in this form 2016	‣ Comprehensive central upgrade based on BaBar magnet ‣ fsPHENIX: forward tracking, HCal and muon ID ‣ Key tests of theoretical frameworks for transverse spin	‣ Path of PHENIX upgrade leads to a capable EIC detector ‣ Large coverage of tracking, calorimetry and PID ‣ New collaboration/new ideas







~2000 2017→2020 ~2025 Time

RHIC: A+A, polarized p+p, polarized p+A

eRHIC: e+p, e+A

Topic-II:

New Physics Opportunities at Fermilab (J-PARC?)

- Sea quark OAM and TSSA at large x
- Direct search for dark photons and dark Higgs in p+A

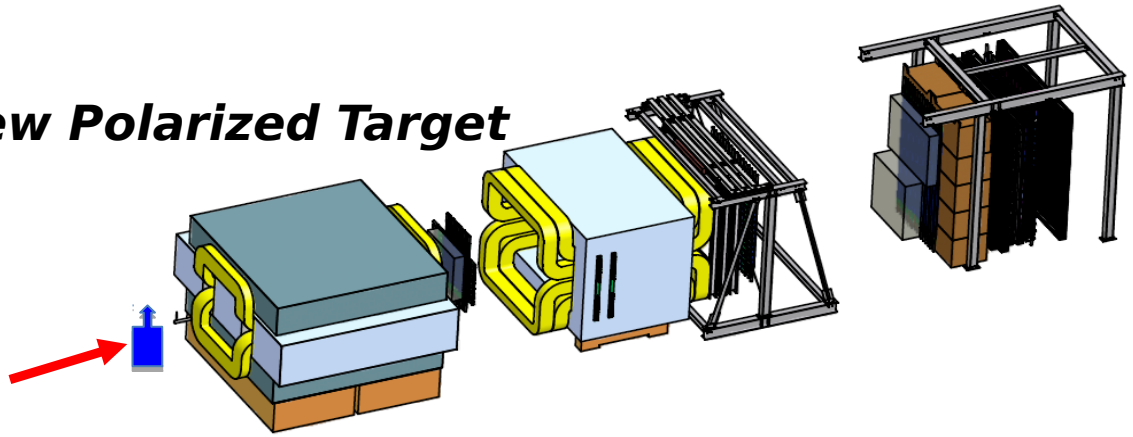
- J-PARC possibility?

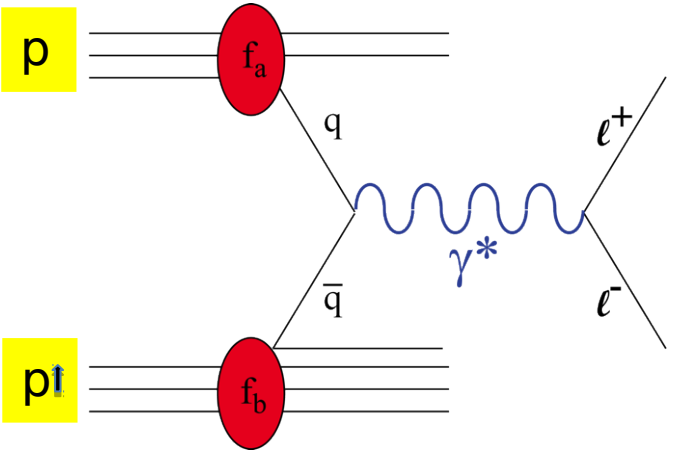
E1039 Experiment @Fermilab

Take advantage of the current E906 Drell-Yan Exp. @Fermilab,
Develop a new polarized hadron physics Program

Kei's talk

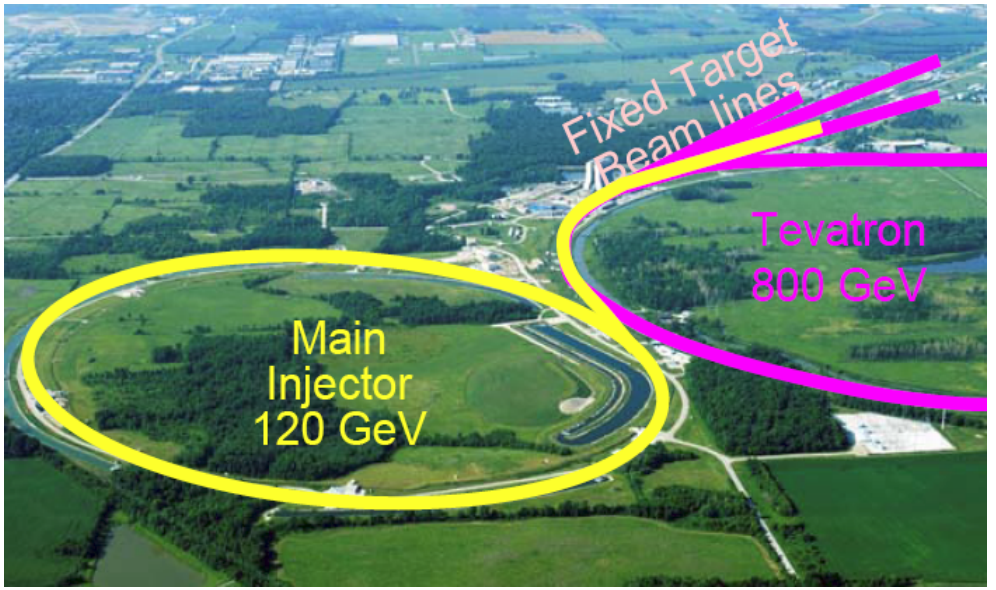
A New Polarized Target





Drell-Yan Transverse Single Spin Asymmetry Study at Fermilab:

- Polarized Target Drell-Yan, E1039 (LOI submitted 2013)
  - Polarized proton (NH_3) target, design & construction at LANL
- Polarized 120 GeV proton beam from the Fermilab's Main Injector, E-1027

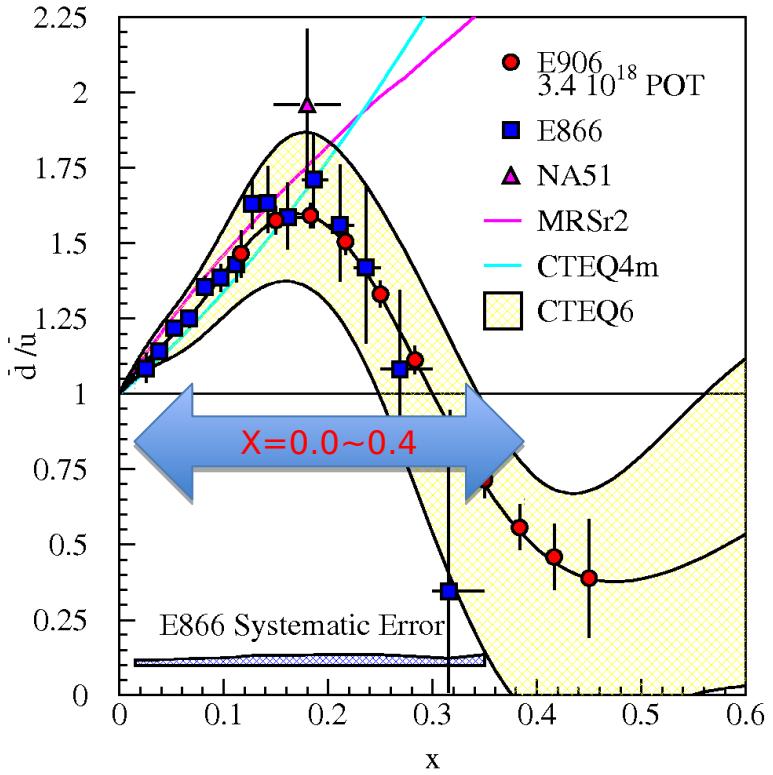


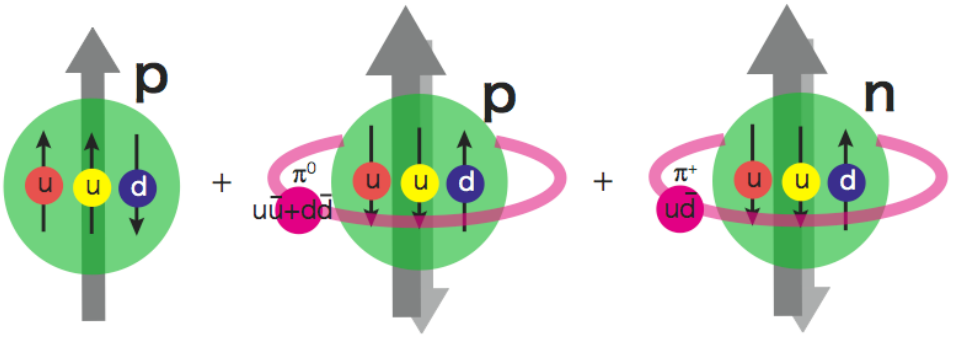
The Physics: Sea Quarks

- ***Sea-quark*** flavor asymmetry
- ***Sea-quark*** orbital angular motion and Sivers function at x = 0.0 ~ 0.4
- Proton spin puzzle

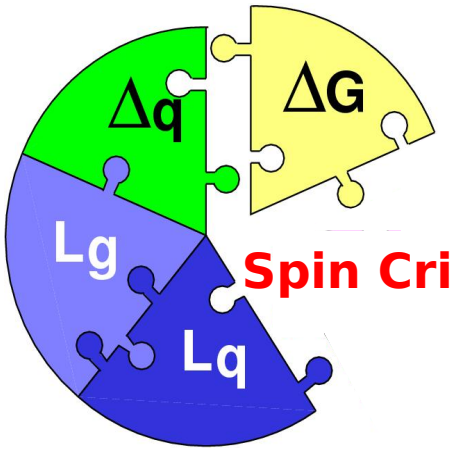
$$|P\rangle = c_1|p\rangle + c_2|p,\pi^0\rangle + c_3|n,\pi^+\rangle + \ldots$$

dbar/ubar asymmetry





L = 0 L = 1



Spin Crisis?

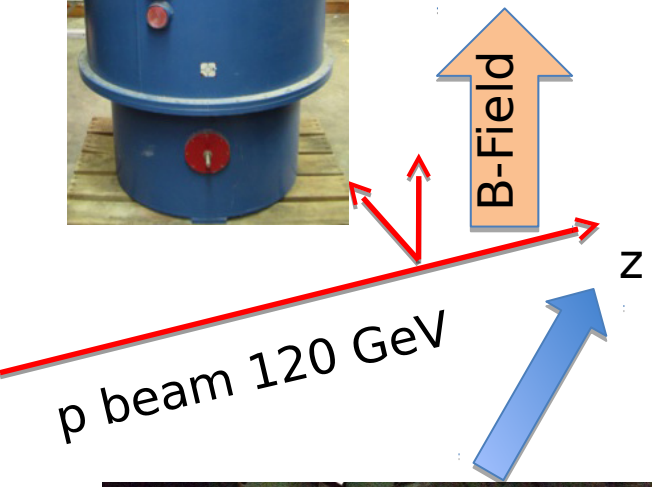
$$\frac{1}{2} = \frac{1}{2}\Delta q + L_q^z + \Delta G + L_g^z$$

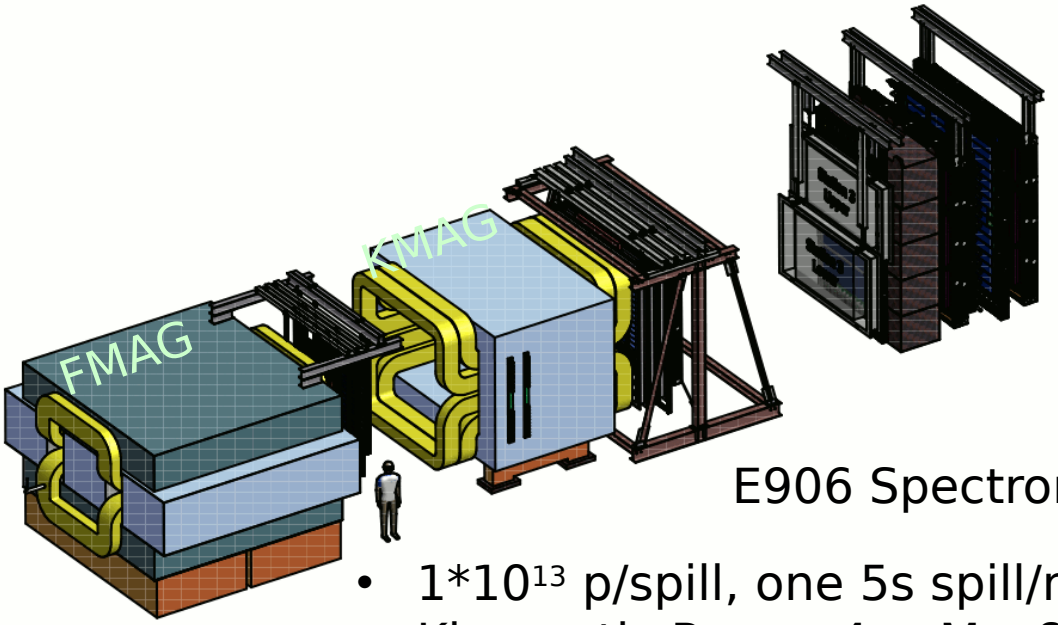
$\Delta q \sim 30\%$ $(pol.\ SIDIS)$

$\Delta G \sim \frac{1}{2} \times 30\%$ $(RHIC-spin)$

$L \sim 30\%?$ $(FNAL?)$

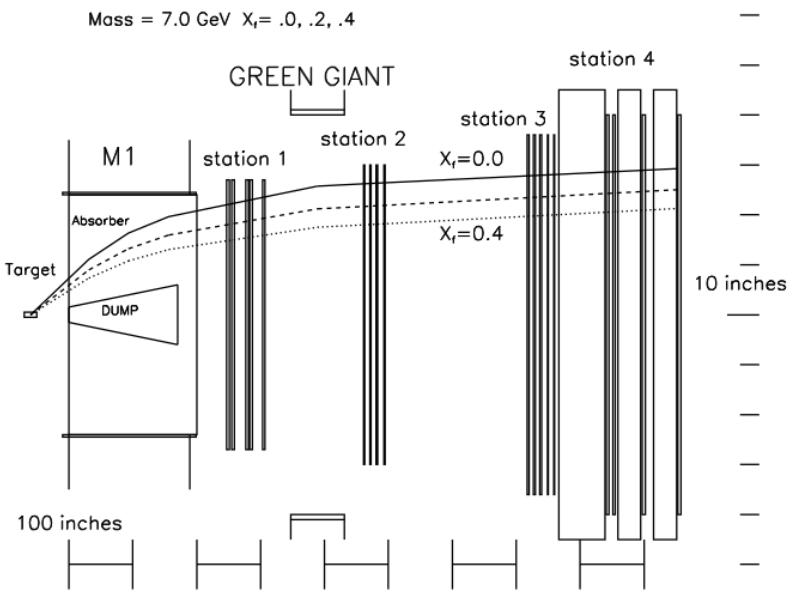
Access Sea Quarks Sivers Distributions





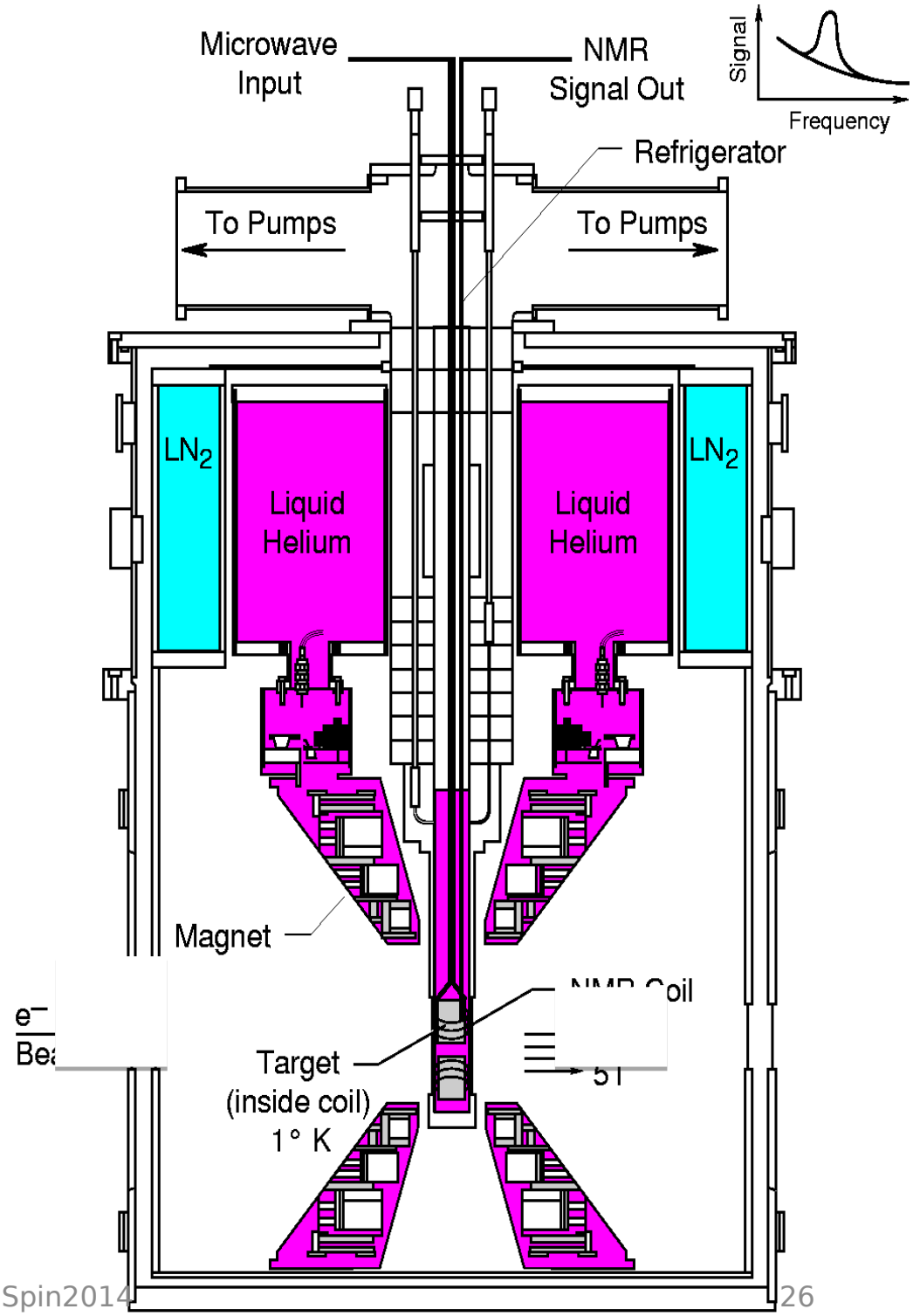
E906 Spectrometer

- $1*10^{13}$ p/spill, one 5s spill/minute
- Kinematic Range 4 < M <8 GeV



LANL High Density Polarized Proton (Neutron) Target

- Superconducting dipole magnet
  - Temperature ~ 1 K
  - Magnetic Field: 5 Tesla
  - 10cm long NH_3 target
- Proved capable of handling high luminosity
  - Same technology used at Jlab
- Magnet tested good at UVa in early 2014
- At Oxford now to rotate the field orientation



4-94

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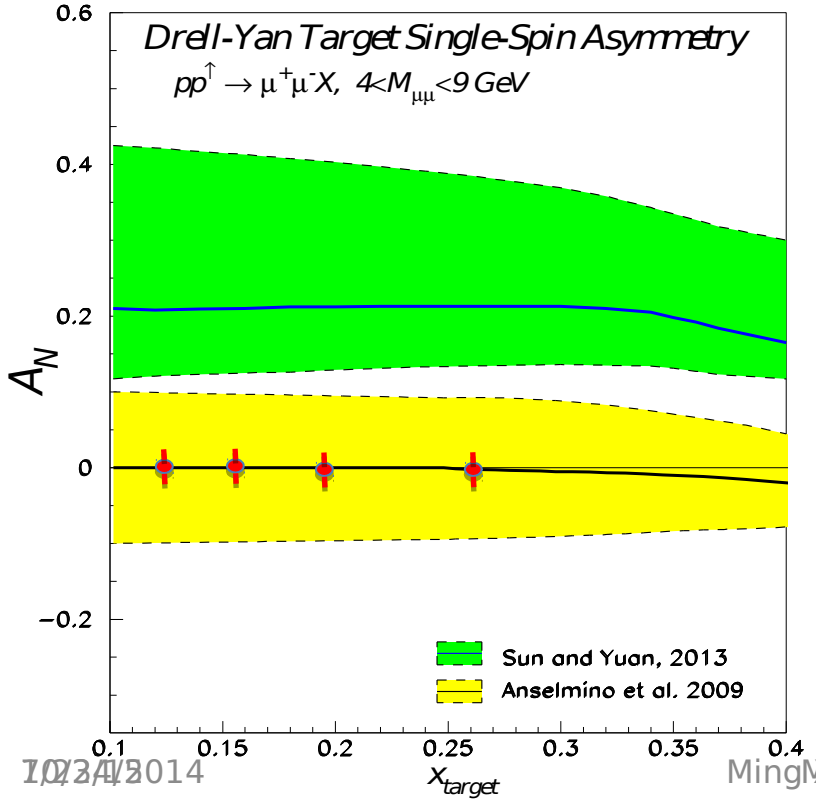
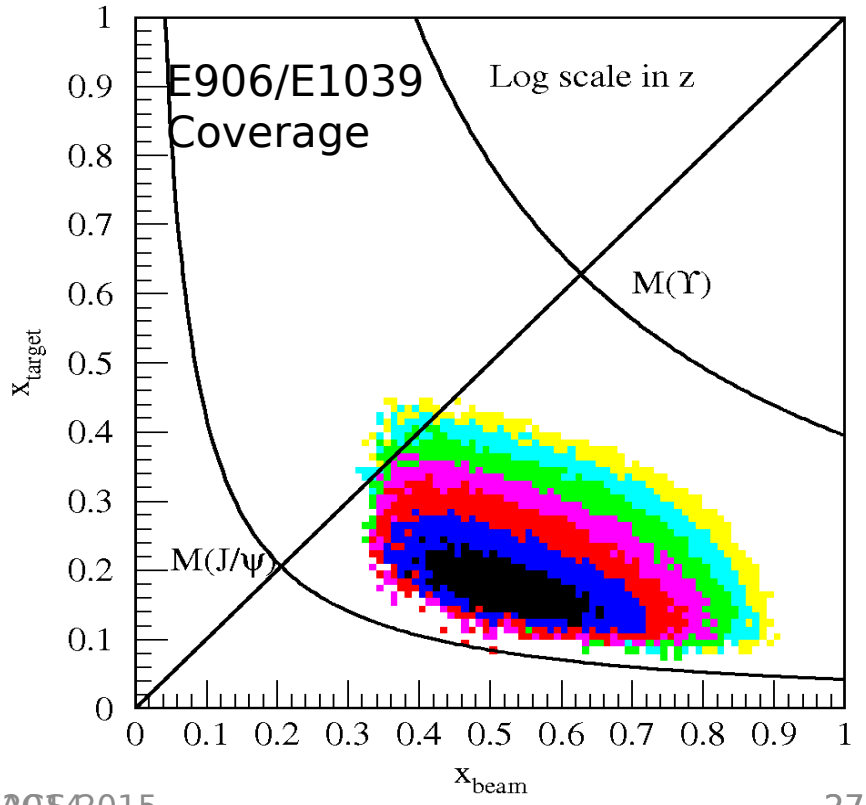
E1039 Outlook

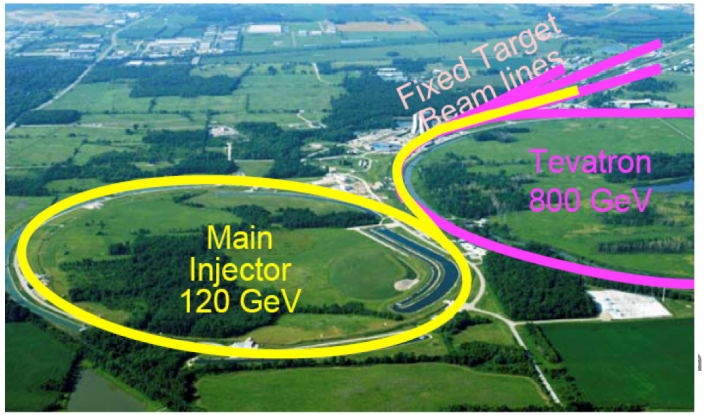
- First p+p Drell-Yan experiment approved with polarized target at Fermilab, E1039
- A new high density polarized proton (deuteron) targets being developed
- First precise measurements of the poorly known sea-quark Sivers distributions
- First run: ~ 2017
- First results: ~2019
- **Move to J-PARC afterward? ~2020?**

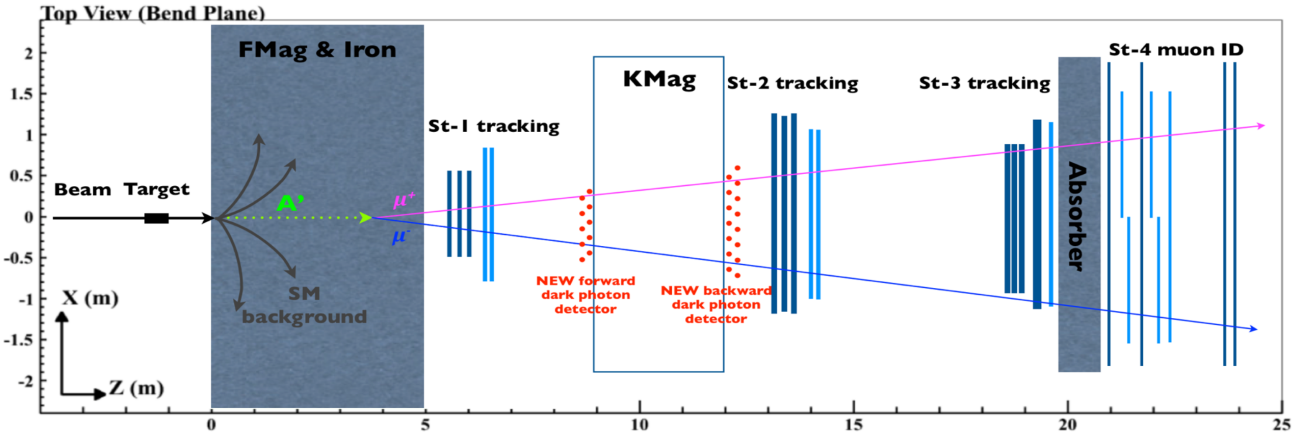




A Direct Search for Dark Photon and Dark Higgs Particles with the SeaQuest Spectrometer in Beam Dump Mode at Fermilab

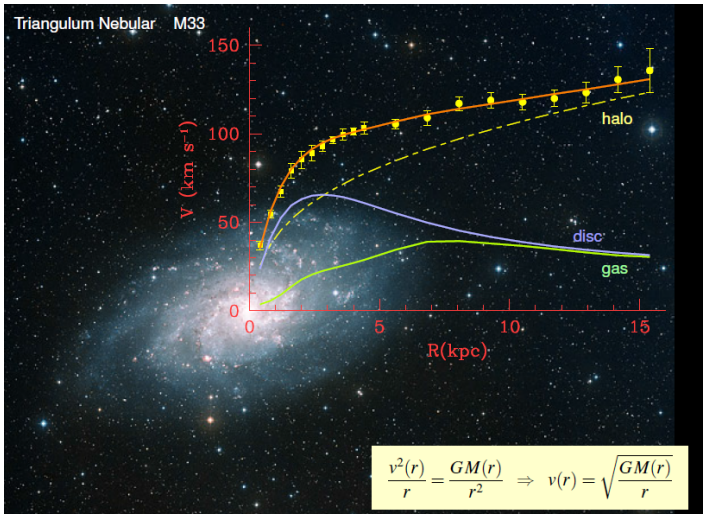
E-1067 Collaboration



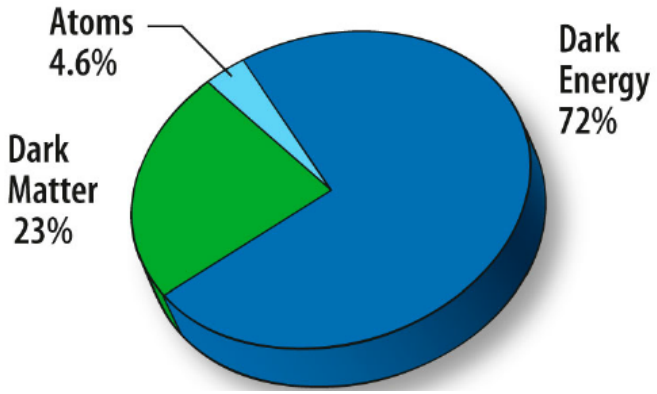


Dark Matter?

Galaxies' rotation curve



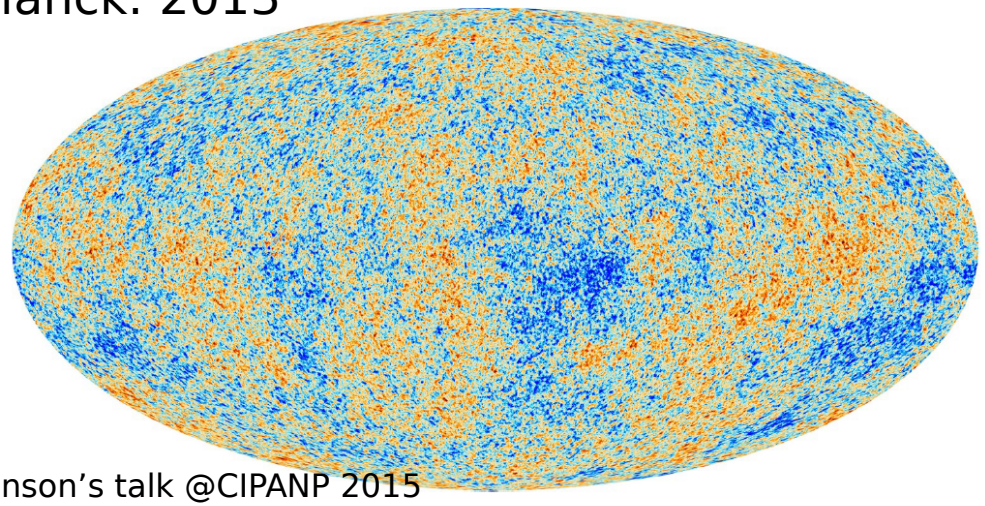
F. Zwicky, ApJ 86 (1937) 217, V. Rubin et al, ApJ 238 (1980) 471



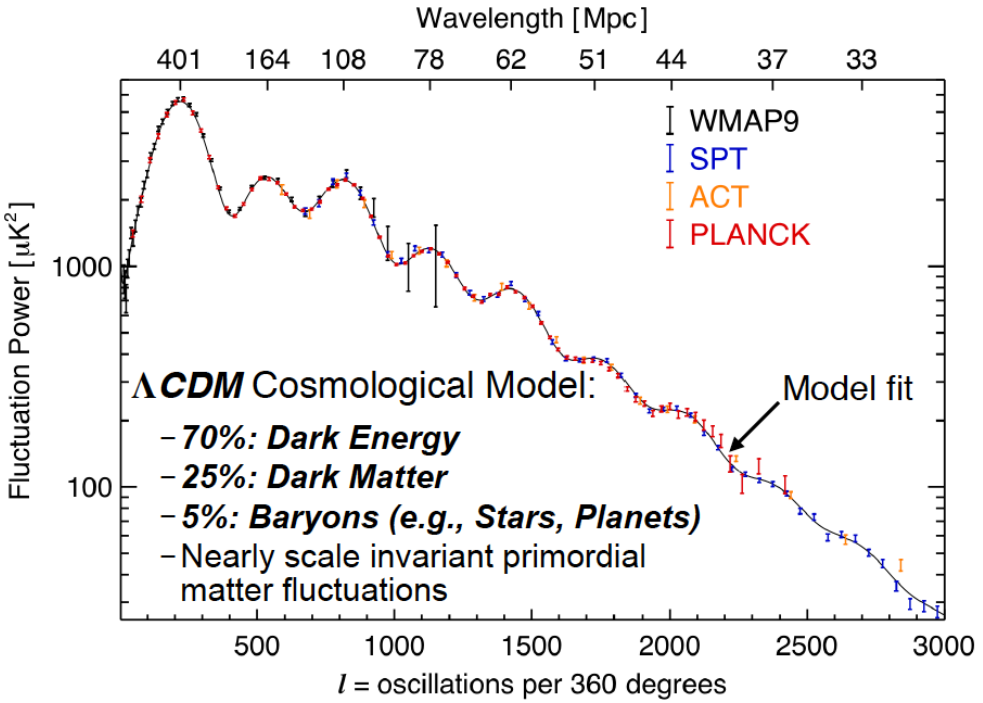
Gravitational lensing (Hubble 2007)

30μK RMS fluctuations on 3 K background

Planck: 2013



Benson's talk @CIPANP 2015



What Are the Dark Particles?

- WIMP being excluded?
- Recent anomalies observed by satellite and terrestrial experiments have motivated dark matter models introducing a new dark sector

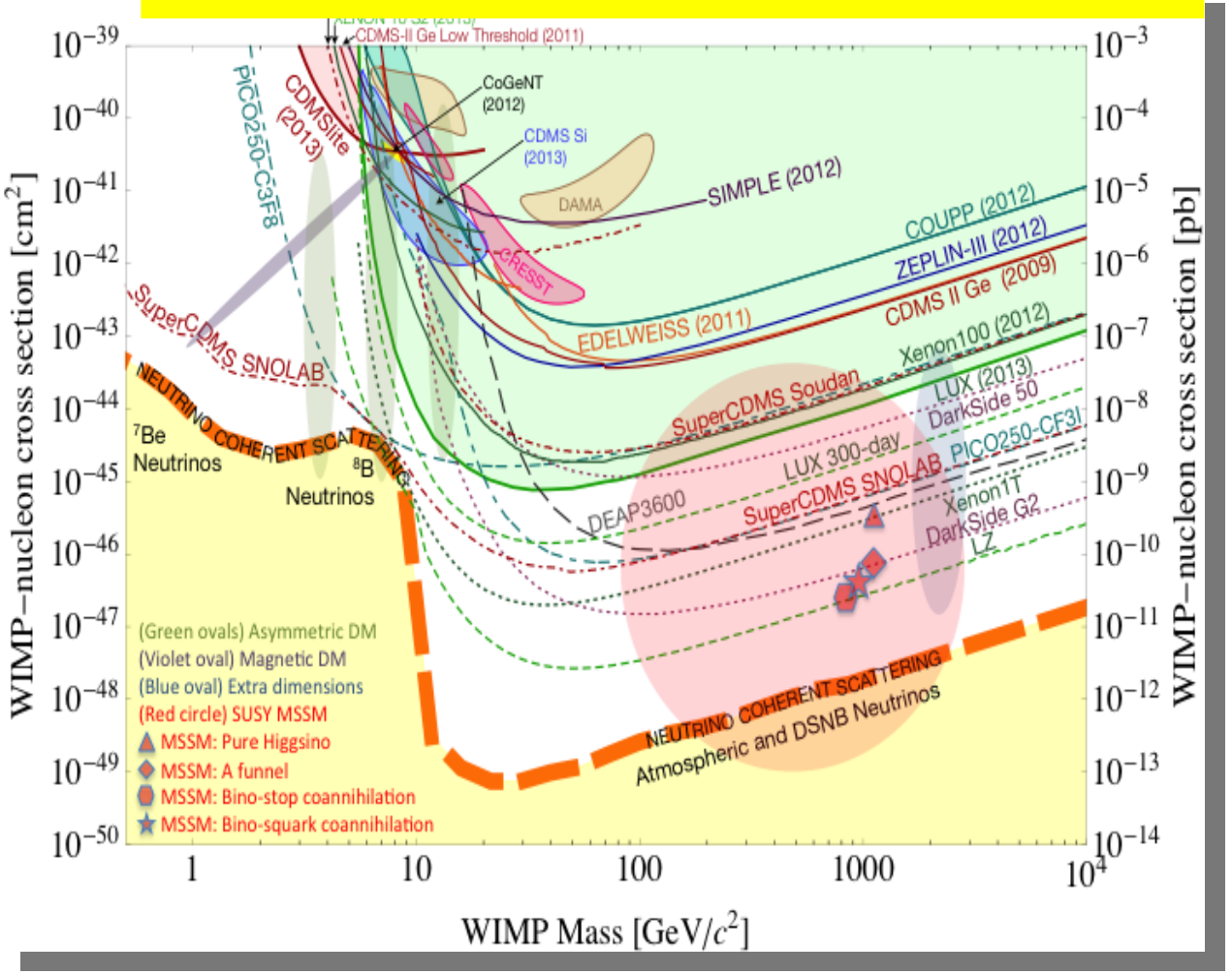
"Sub-GeV" low mass weakly-interacting dark particles become very interesting!

Mass: *O(MeV ~ GeV)*

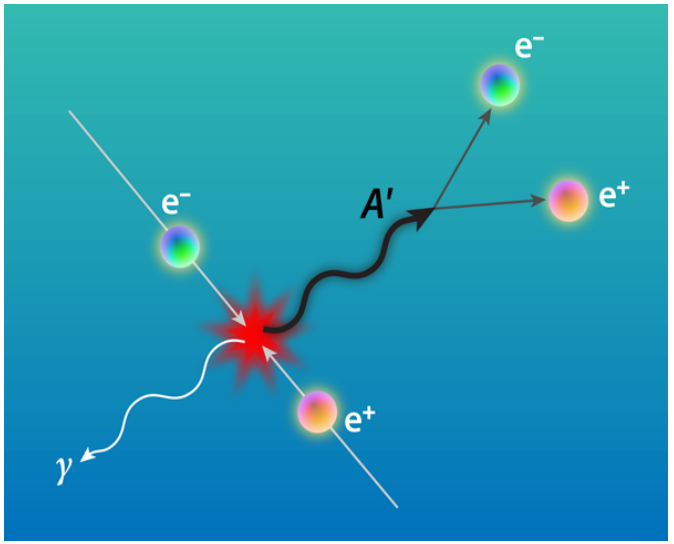
- In particular, high-intensity colliders (B-factories) and fixed target experiments (Fermilab, JLab, LHC) offer an ideal environment to probe these new ideas.

Montgomery's talk at CIPANP2015
"a vision of nuclear and particle physics"

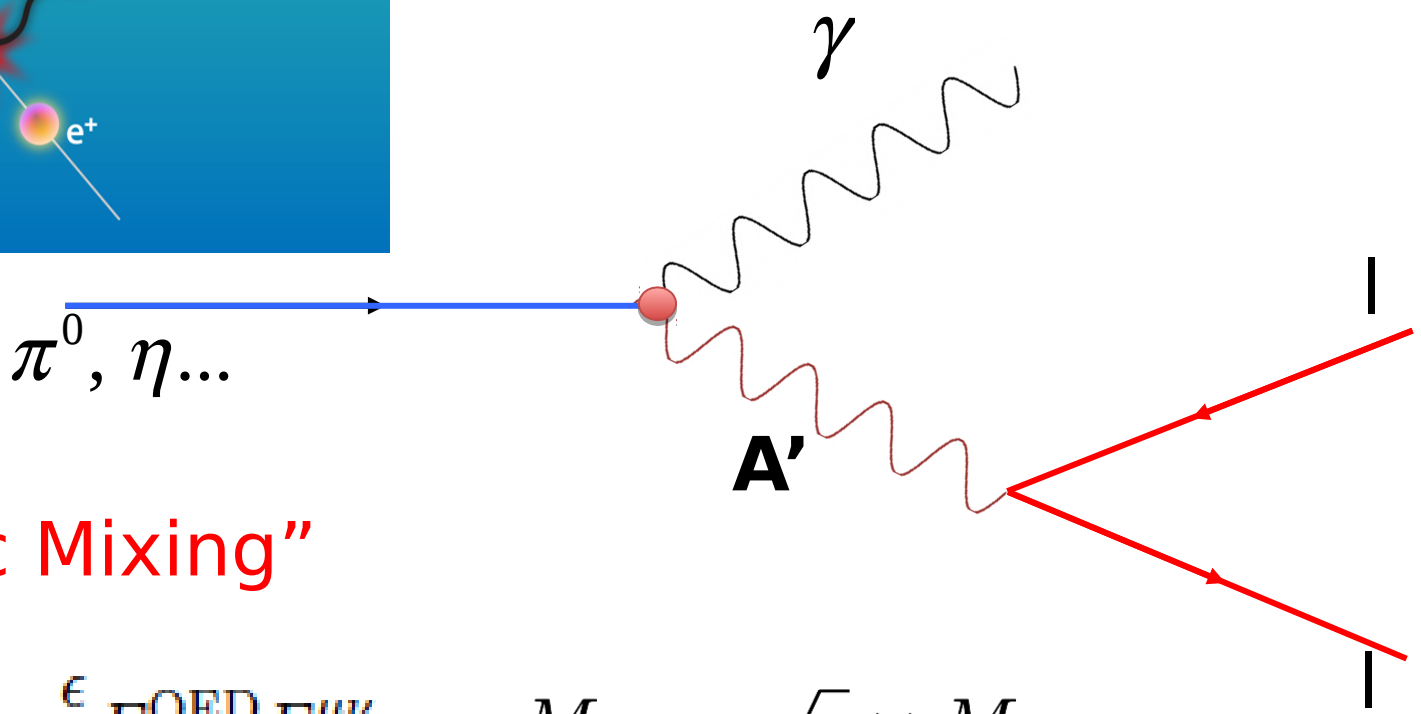
- Imaginable space for these experiments is rapidly disappearing
- the "natural" theory space is also disappearing.
- I like to think that Dark Matter is on solid ground, maybe not!!!



Accelerator Based Direct Search for Dark Photons
B-factories, RHIC, LHC, Jlab, BES-III etc



B. Holdom, Phys. Lett. **B 166** (1986) 196
J. D. Bjorken et al, arXiv:0906.0580



"Kinetic Mixing"

$$\mathcal{L}_{\rm mix} = -\frac{\epsilon}{2} F^{\rm QED}_{\mu\nu} F^{\mu\nu}_{\rm dark} \qquad M_{A'} \sim \sqrt{\epsilon} \times M_Z$$

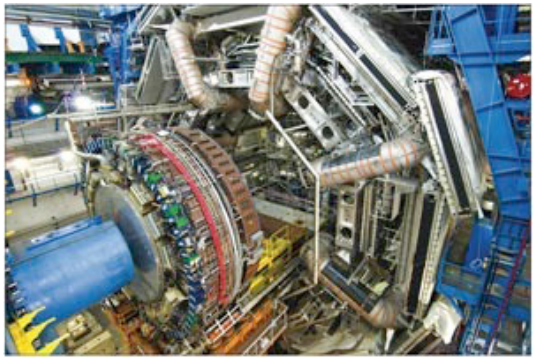
Very Active Field

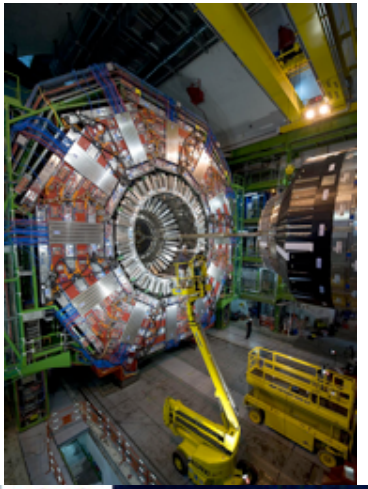
Ongoing A' Searches

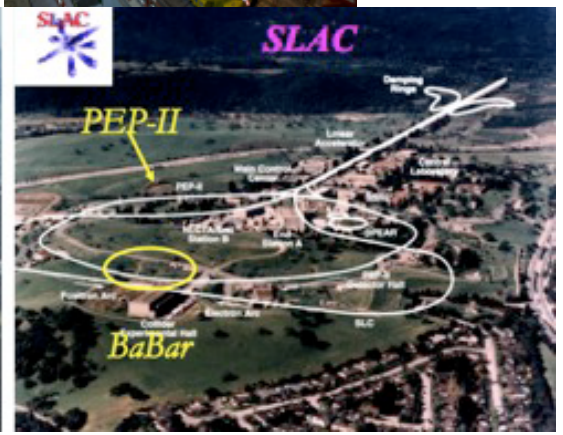
- KLOE-2@DAϕNE(ϕ→ϕA' followed by A'→e+e-)
- HADES@GSI (p+p, p+^{93}Nb, p+^{40}Ar, ^{84}K+^{35}Cl production: π^0,η, Δ decay followed by A'→e+e-)
- BaBar@SLAC (e+e-→Υ→γA' with A'→μμ)
- WASA@COSY (π^0 decay)
- PHENIX@RHIC (π^0 decay)
- A1@MAMI (e on ^{181}Ta)
- ATLAS and CMS @LHC
- SeaQuest @ FNAL
- milliQ@SLAC: invisible search
- APEX@JLab (e on ^{181}Ta)
- HPS@JLab (e on ^{184}W)
- DarkLight @ JLab ERL (e-p elastic scattering below π threshold)

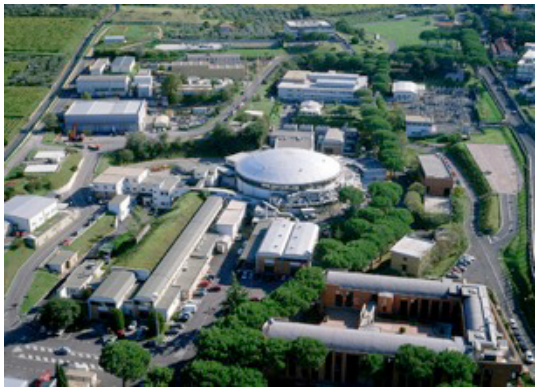
Courtesy: R. Milner at the Fundamental Interactions Town Meeting, Chicago, Sept. 28-29, 2014

The search is on … **J-PARC?**



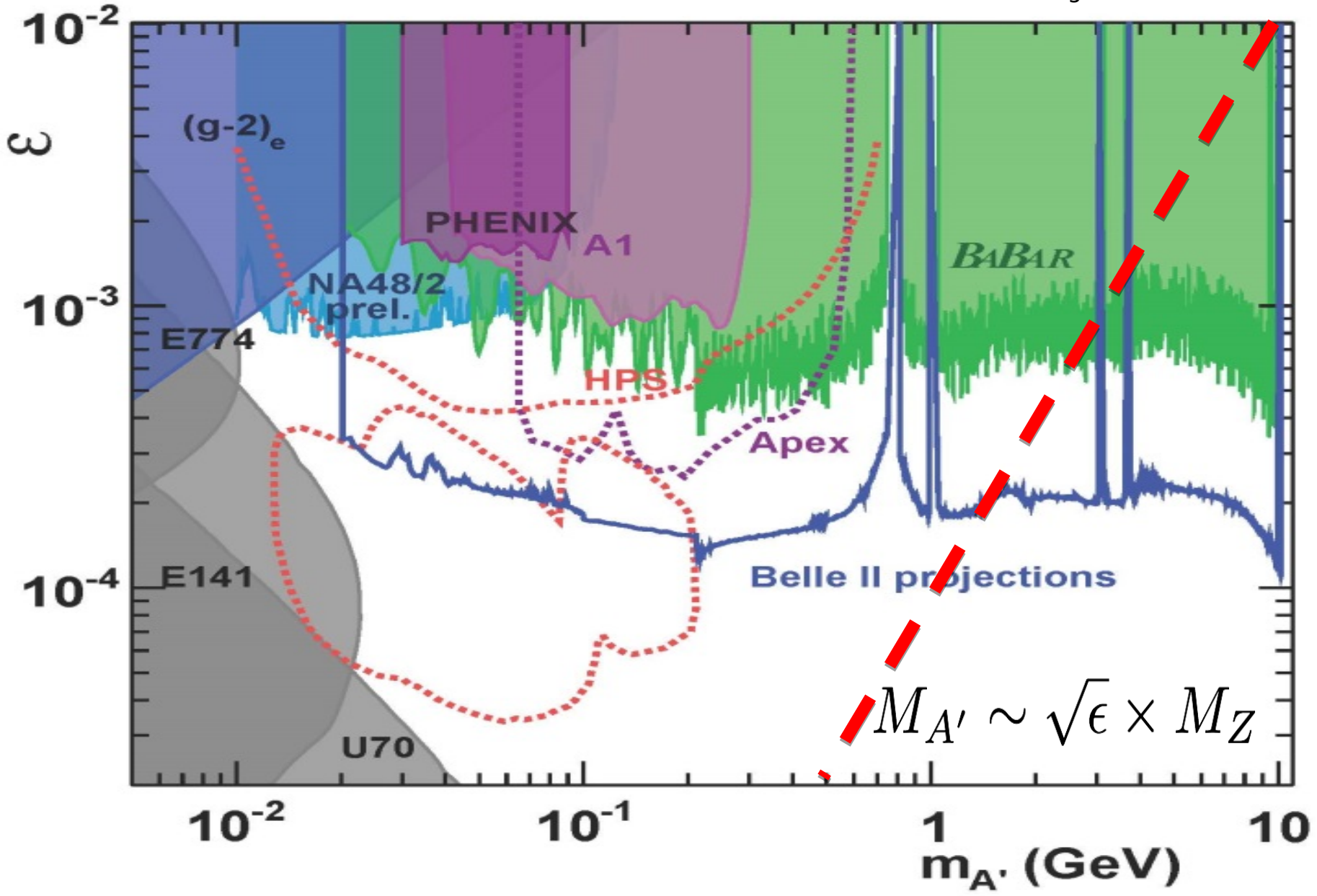






Current Limits on Dark Photon Search

R. Essig et al arXiv:1309.5084



Letter of Intent for a Direct Search for Dark Photon and Dark Higgs Particles with the SeaQuest Spectrometer in Beam Dump Mode

Co-Spokespersons: Ming X. Liu (LANL) and Paul E. Reimer (ANL)

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R.-S. Guo, G. Wang
National Kaohsiung Normal University, Taiwan

LOI submitted to Fermilab PAC on May 20, 2015

A joint experimental and theoretical collaboration (most E906/E1039 + new members)

Phase-I: (2017-2019)

1. Addition of a new displaced dimuon trigger to tag long-lived downstream decayed dark photons (dark Higgs).
2. Parasitic data taking with E1039 in 2017-2019;
   - A short dedicated run (up to ~1 month) if needed.
3. POT 1.44×10^{18}

Phase-II:(2020+)

4. Dedicated runs later with EMCal/HCal upgrades, $e^{+/-}$ and $h^{+/-}$ capabilities.
5. Cover the full parameter phase space allowed by beam energy and luminosity
6. POT: >> 1.4×10^{18}

Phase-II request will be presented to PAC at a later time.

Endorsed by Fermilab Director and PAC! 07/15/2015

The PAC "... recognize exciting opportunity brought by P-1067 to search directly for a da photon and dark Higgs and " ... believe that P-1067 offers exciting physics prospects and recommends the Laboratory to grant th modest request."

Fermilab

Nigel S. Lockyer
Directorate
TEL 630.840.3211
Lockyer@fnal.gov

July 15, 2015

Ming Liu
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dear Ming,

Thank you very much for your presentation: *"P-1067 LOI: Direct Search for Dark Photon and Dark Higgs"* at the June meeting of the Fermilab Physics Advisory Committee (PAC). The Committee explicitly mentioned its appreciation of the carefully prepared presentations for this meeting.

Future initiatives were an important topic at the meeting. Excerpts on your LOI from the PAC report are attached. As you can see, the committee *"... recognizes the exciting opportunity brought by P1067 to search directly for a dark photon and dark Higgs in high-energy proton□nucleus collisions using existing SeaQuest Spectrometer."* The PAC noted that in the LOI the collaboration requests approval for inclusion of the new elements in the detector needed to make a dark sector trigger, and approval of parasitic data collection during E-1039 running. The committee *"... believes that P-1067 offers exciting physics prospects and recommends the Laboratory to grant these modest requests."* The PAC also suggests *"A proposal for a dedicated experiment, or a parasitic experiment with electron and hadron calorimeters, should be based on the results obtained with this first phase."*

I accept the PAC recommendations, and wish you good luck in implementing a dark sector trigger.

Sincerely,

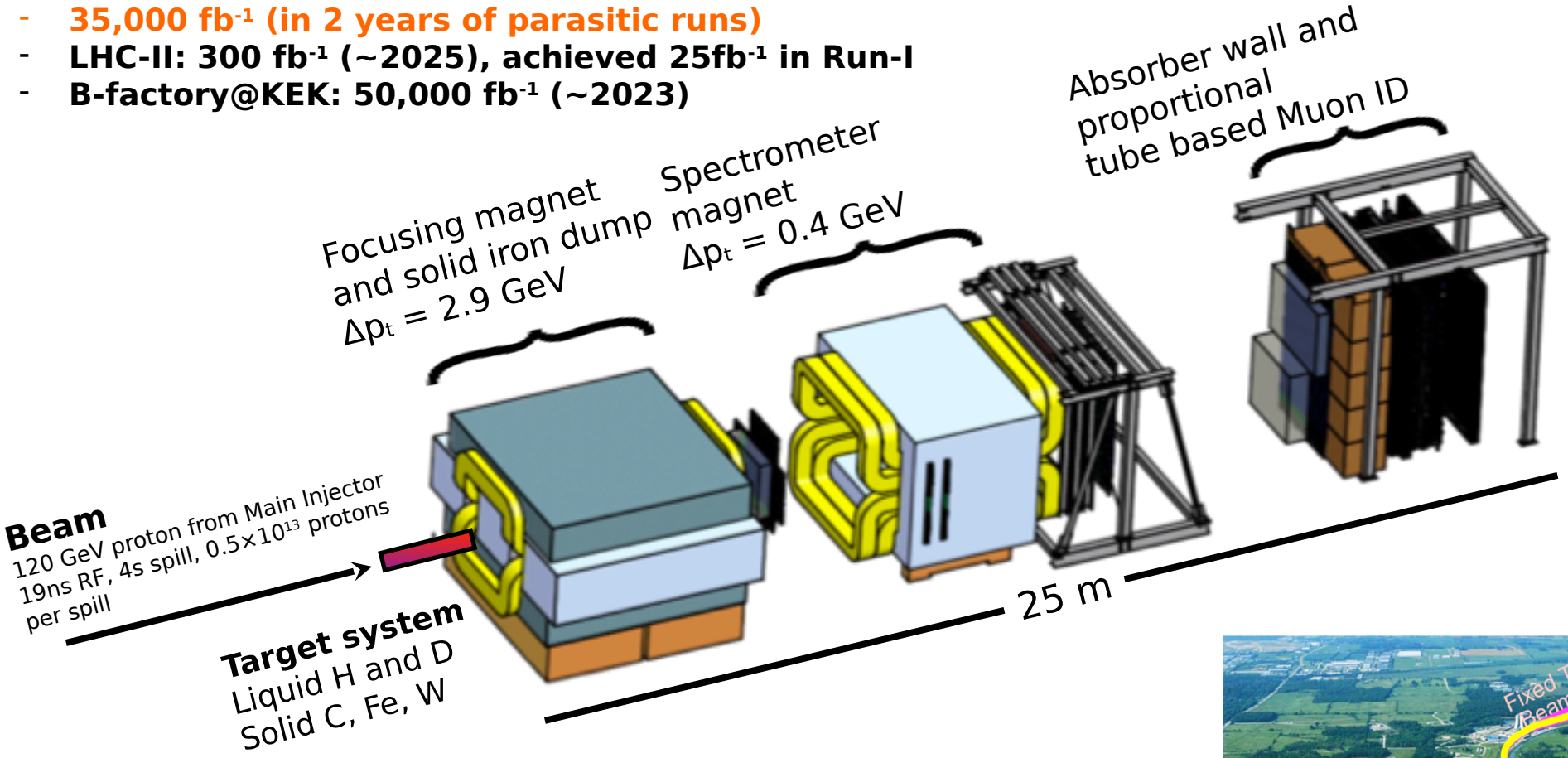
Nigel S. Lockyer
Director of Fermilab

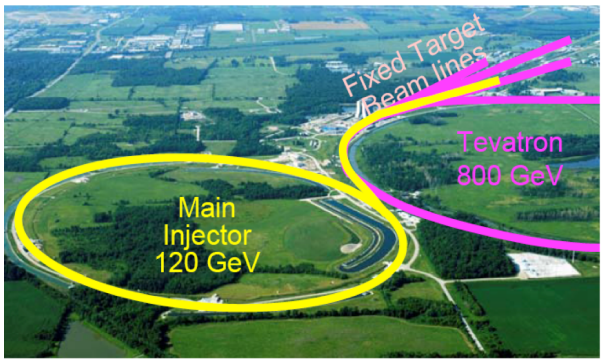
cc: D. Bortoletto, G. Bock, P. Reimer, J. Shank, S. Geer, P. McBride, D. Geesaman, J. Lykken, T. Meyer, A. Stone

Intensity Frontier at Fermilab: 120 GeV Beam

World's highest intensity high energy proton beam:
"beam dump mode" @SeaQuest/E906

- **35,000 fb^{-1} (in 2 years of parasitic runs)**
- **LHC-II: 300 fb^{-1} (~2025), achieved 25fb^{-1} in Run-I**
- **B-factory@KEK: 50,000 fb^{-1} (~2023)**

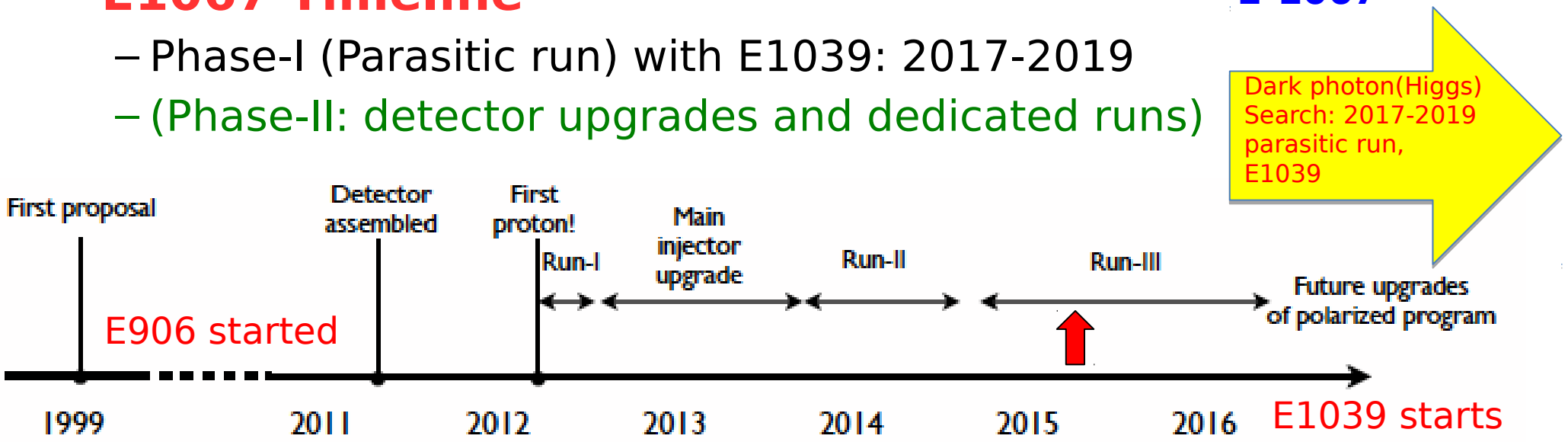




- Capture most beam in beam dump mode: p+Fe collisions!
- Parasitic run mode possible with other experiments, E1039/E1027

Schedule of SeaQuest Experiments

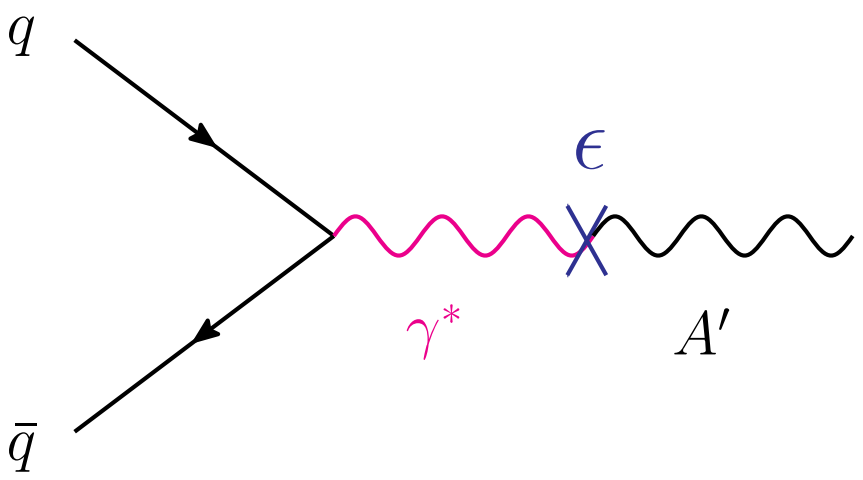
- E906 complete data taking in summer 2016
  - E906 targets are located ~1.3m upstream of the beam-dump
- E1039 will replace current E906 targets with a polarized NH_3 target.
  - No change to E906 spectrometer setup
  - Target/trigger installation: 2016 - 2017
  - Data taking: 2017 – 2019
- **E1067 Timeline**
  - Phase-I (Parasitic run) with E1039: 2017-2019
  - (Phase-II: detector upgrades and dedicated runs)



Direct Productions of Dark Photons and Dark Higgs in p+Fe at Fermilab

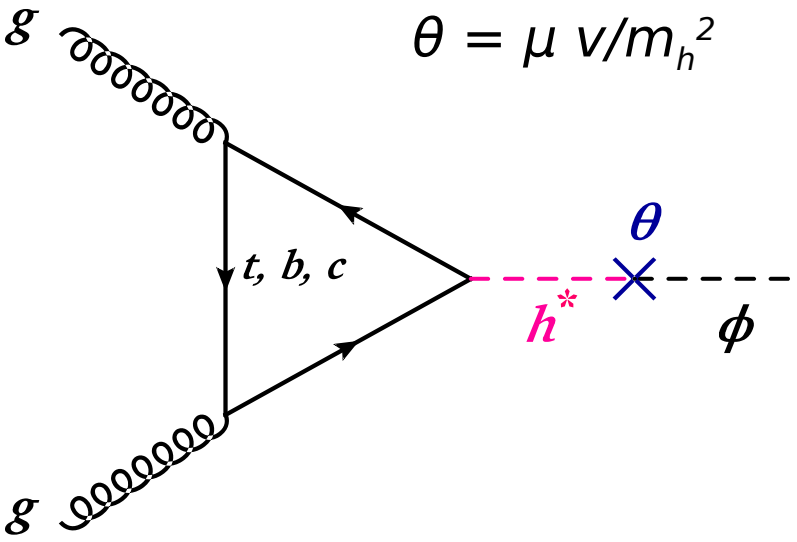
Photon portal: "vector"

$$\mathcal{L}_{\rm mix} = \frac{\epsilon}{2} F^{\rm QED}_{\mu\nu} F^{\mu\nu}_{\rm Dark}$$



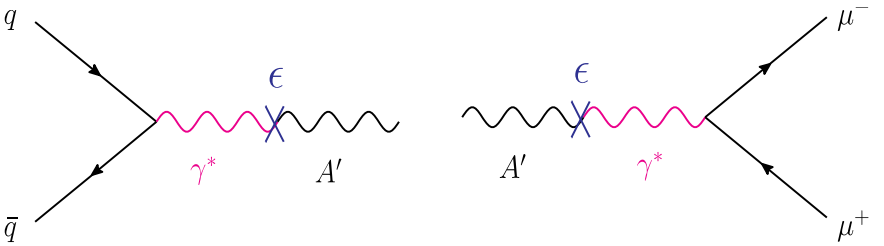
Higgs portal: "scalar"

$$\mathcal{L}_{\rm mix} = \mu\phi\left|H^\dagger H\right|$$

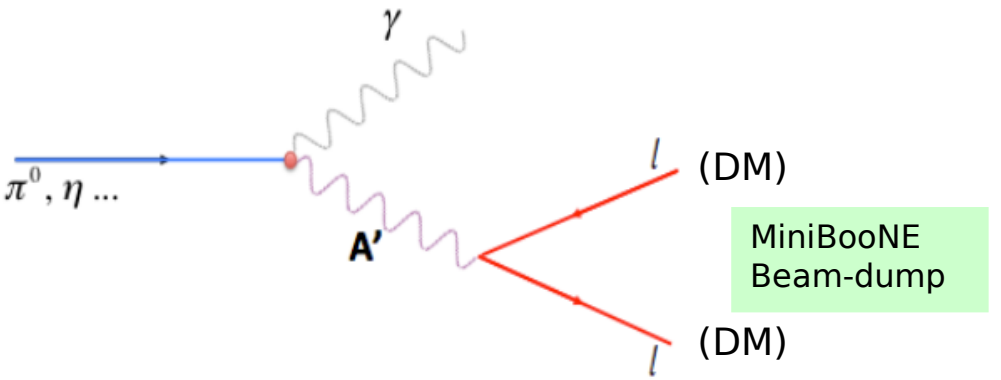


Dark Photon Search in Dimuon Channel at SeaQuest in Beam Dump Mode (p+Fe)

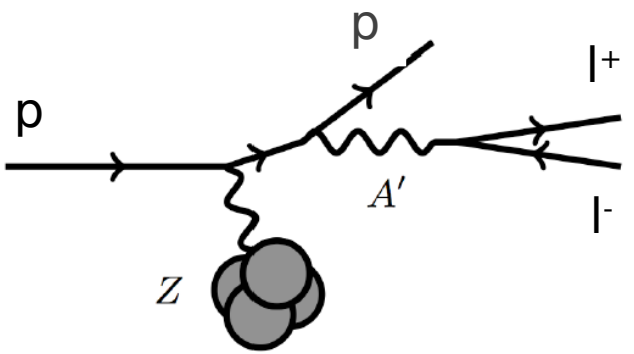
1. Drell-Yan like



2. π^0, η, … decay



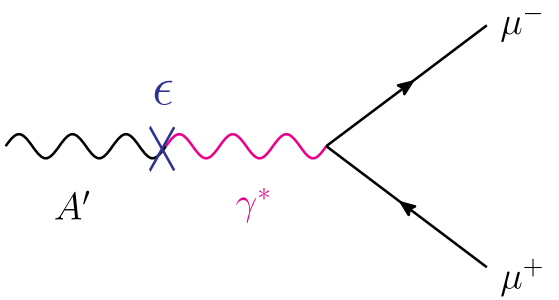
3. Bremsstrahlung



Dark Photon Decay Modes

"Minimal" Decay:

- Dark photon is the lightest in the dark sector;
  - SM final state particles only

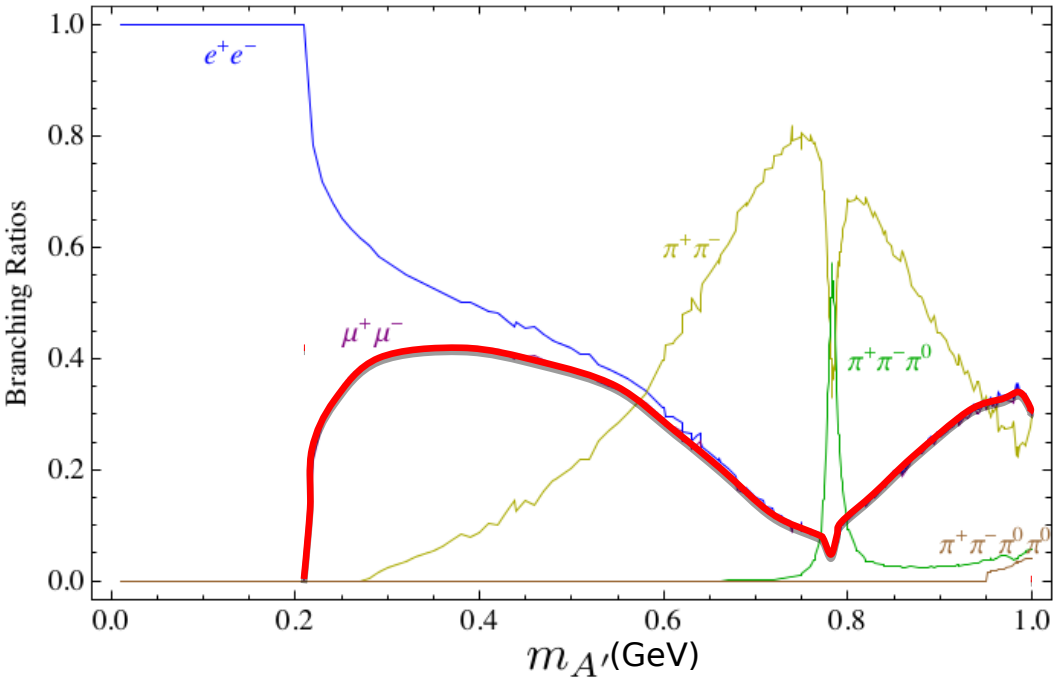


$$\Gamma(A' \to f + \bar{f}) = C\frac{\epsilon^2 m_{A'}}{3} e_f^2 \alpha_{\rm em} \left(1 + \frac{2m_f^2}{m_{A'}^2}\right) \sqrt{1 - \frac{4m_f^2}{m_{A'}^2}},$$

D. Curtin, et al, arXiv: 1312.4992

Long proper decay length: $L_0 \sim$ *O(1m)*

$$L_0 \sim \frac{1}{\epsilon^2 \times m_{A'}}$$



"General" Decay:

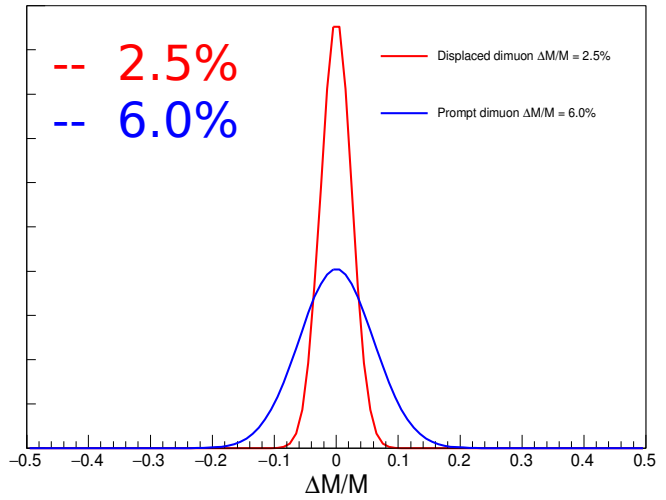
- Decay into other dark particles, dominant channel if allowed
  1. Dark -> Dark
  2. Dark -> SM particles

Proposed Experimental Measurements

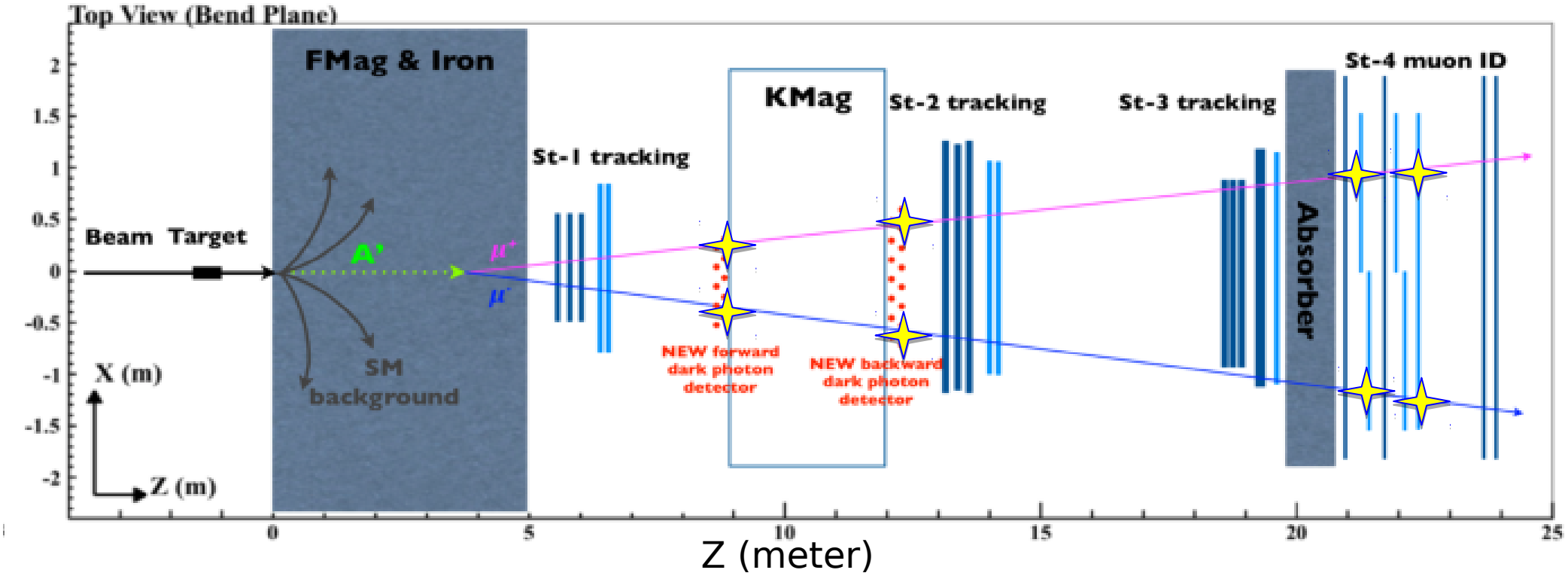
- Dark photon trigger upgrade
  1. Add a fine-granularity scintillating strip based trigger/tracking to tag dimuons from the same decay Z-vertex
  2. A new trigger for events with displaced down-stream dimuons

- Unique signals
  1. Displaced dimuon decay vertex for long-lived particles
  2. Invariant mass peak in dimuon mass spectrum

- Beam time
  1. Run parasitically with E1039 (2017-2019)
  2. Possible dedicated runs later with upgraded ($e^{+/-}$, $h^{+/-}$)



Dimuon mass resolution



Z (meter)

A New High-Granularity Displayed Dimuon Vertex Trigger

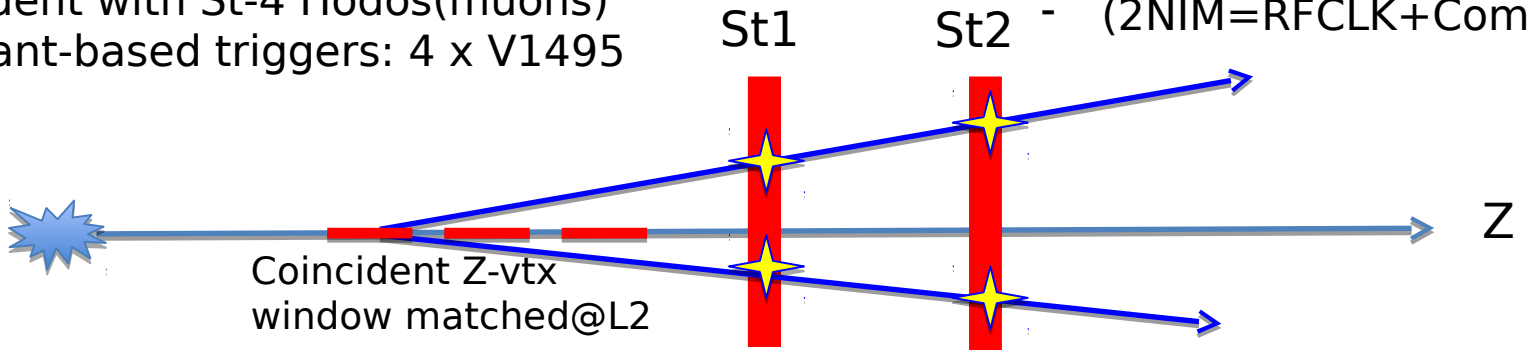
High rejection power, very low rate, << 1 kHz(E906 DAQ limit)

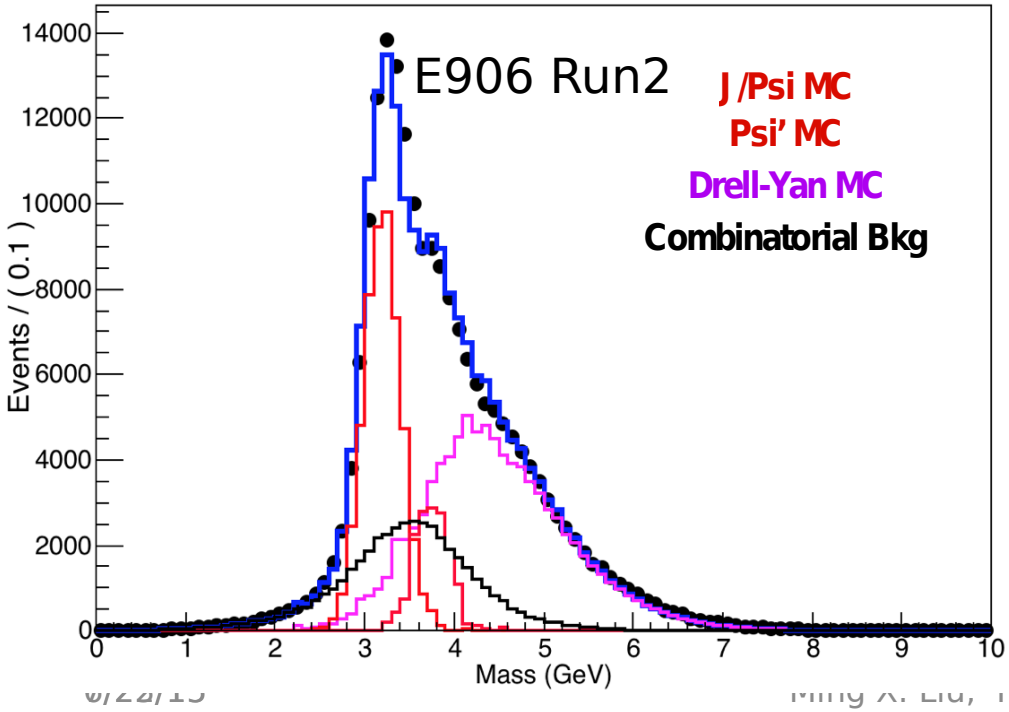
Y-Plane Trigger:

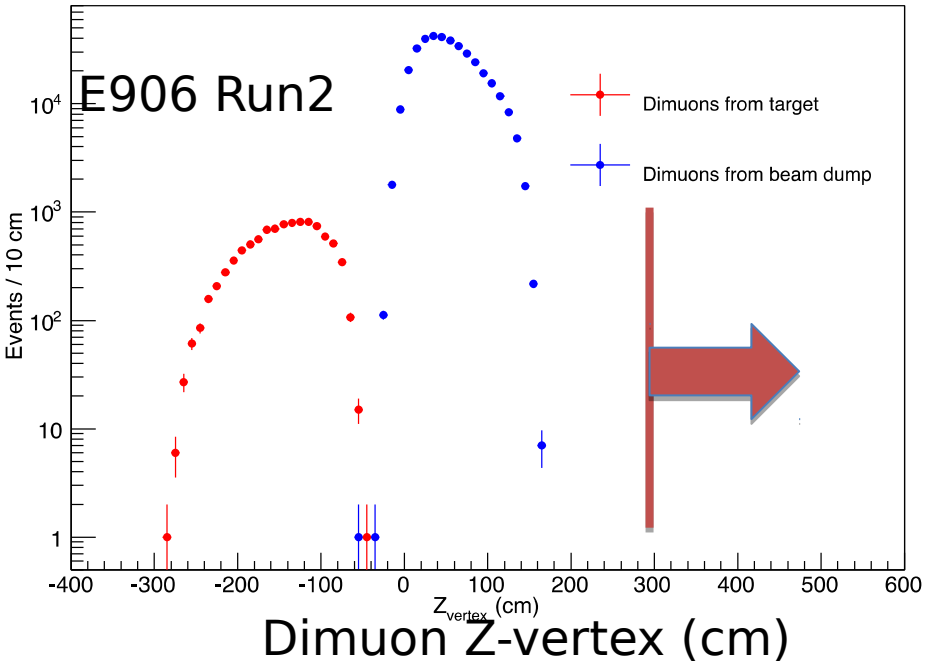
- A quadrant panel: 40 x 40 cm^2, 1cm thinck
  - 40 x 1cm x 40 cm scintillating strips, SiPM readout
- Straight line projection, 30cm Z-vertex resolution
- Displaced z-vertex, mostly low mass < 3GeV
- Coincident with St-4 Hodos(muons)
- Quadrant-based triggers: 4 x V1495

Y-channels per quadrant:

- 1x V1495
- 40(St1) + 40(St2) + 8x2 (St4-Y1,2) = 96
- 96+64 = 160 possible
  - 72+72+16 = 160 (possible)
  - (2NIM=RFCLK+ComSTOP)







Dimuon Z-vertex (cm)

Search Mode (1): Long-lived Dark Photons

Reconstructed dimuons with downstream Z-vertex:

3m < Z-vertex < 6m

- Low trigger rate, << 1kHz
- SM background free
- Dimuon mass peak

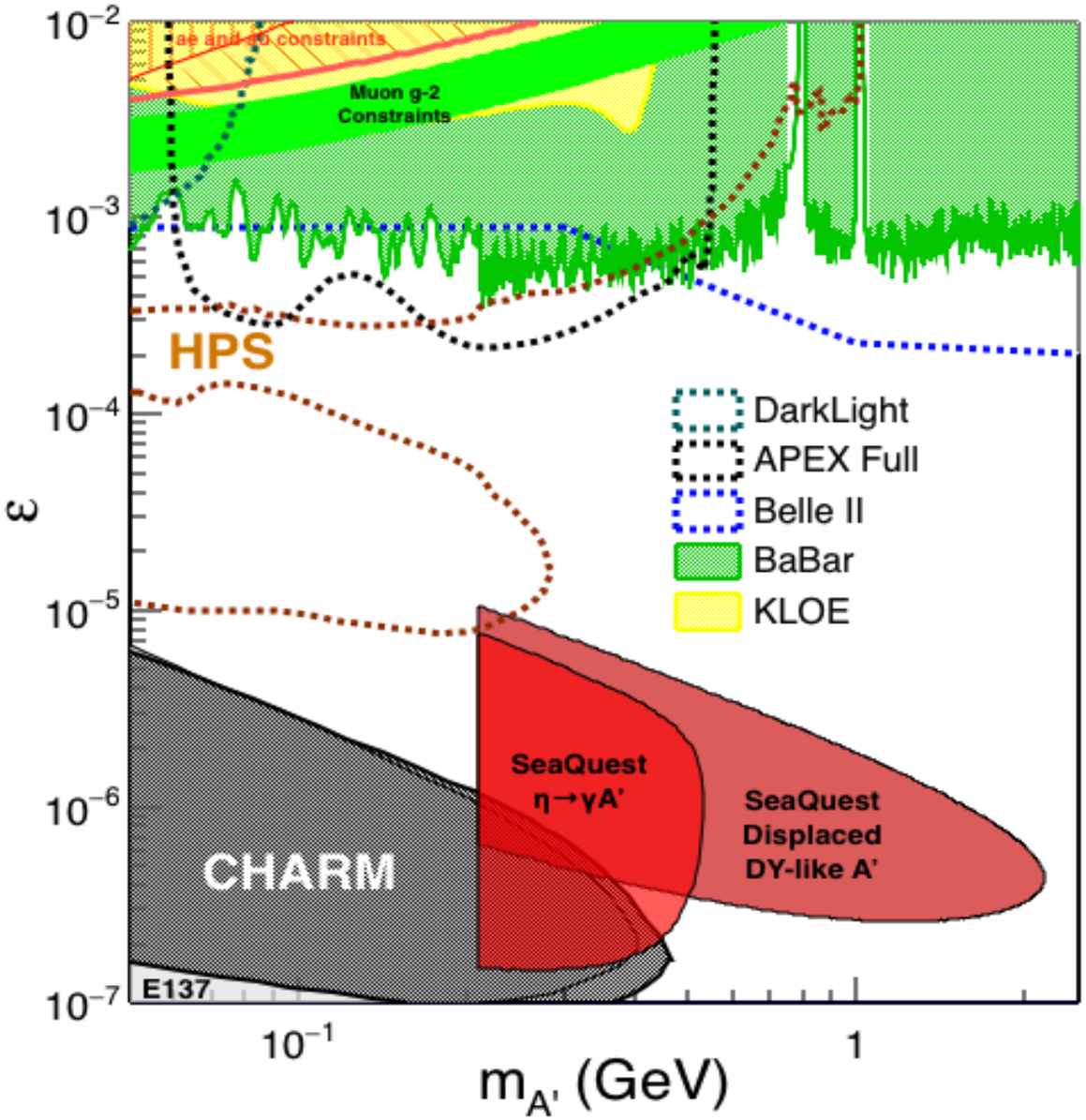
- 5×10^{12} ppp (current E906)
- 200 days

1.4×10^{18} POT (recorded)

- 4 events contours (2-sigma)

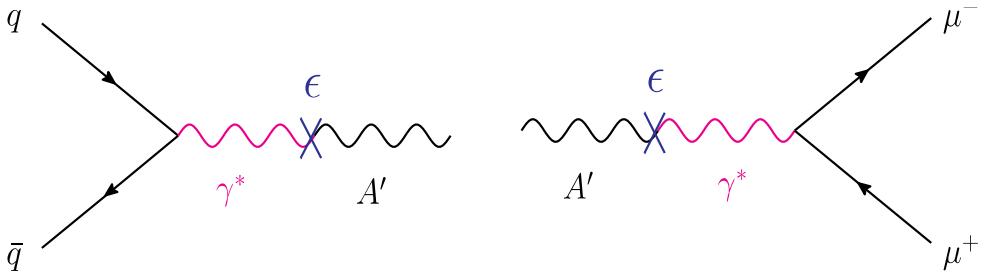
2-sigma (95%) exclusion plots

Excellent coverage of uncharted region!



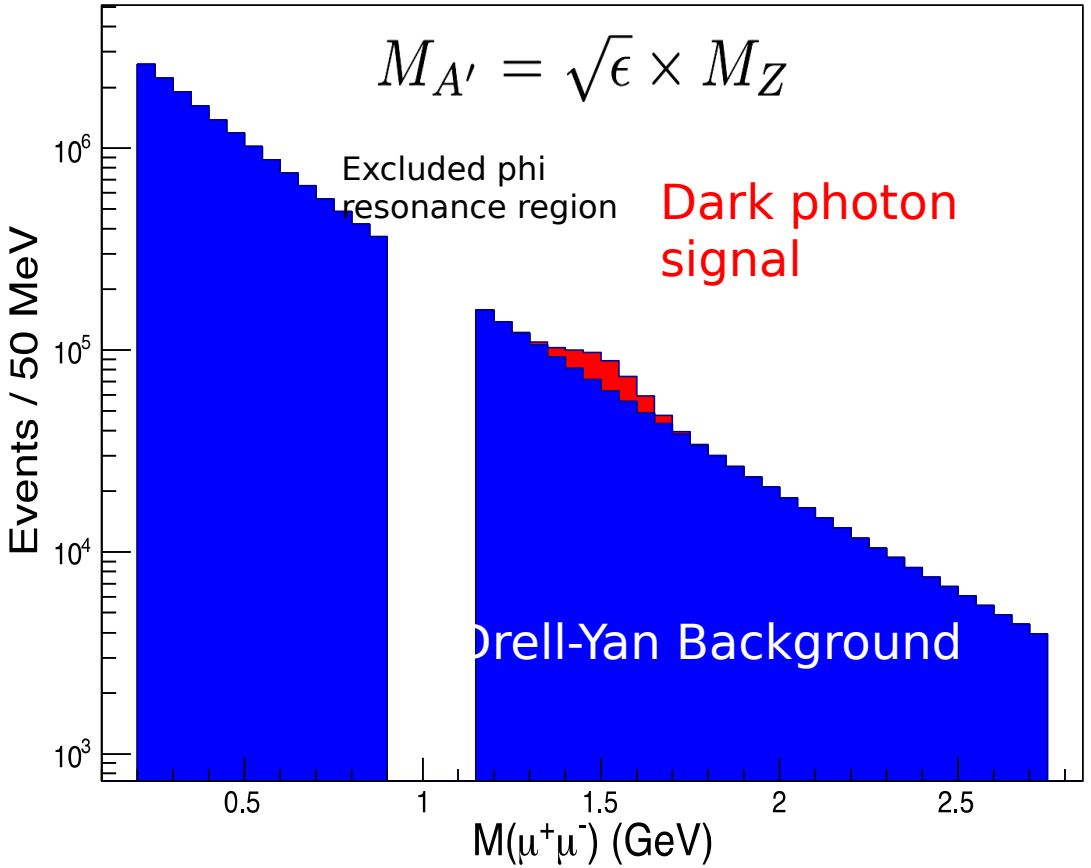
Search Mode (2): "Prompt" Dark Photons vs Drell-Yan

Z-vertx < 3m



Expected Drell-Yan like signal and backgrounds:

$$\frac{d\sigma}{dx_F}(p+p\to A'+X)=\sigma_0^{A'}\sum_q e_q^2 q(x_1)\bar{q}(x_2)\frac{x_1x_2}{x_1+x_2}$$



$$\sigma_0^{A'}=\frac{4\pi^2\alpha_{em}\epsilon^2}{N_c m_{A'}^2},\quad x_1=\frac{x_F+\sqrt{x_F^2+4m_{A'}^2/s}}{2},\quad x_2=\frac{-x_F+\sqrt{x_F^2+4m_{A'}^2/s}}{2},$$

$$sig=S/\sqrt{(S+B)}$$

$$sig\sim\epsilon^2\times\sqrt{N_{DY}\times M/\sigma_M^{Det.}}$$

Work in progress
Further optimization possible

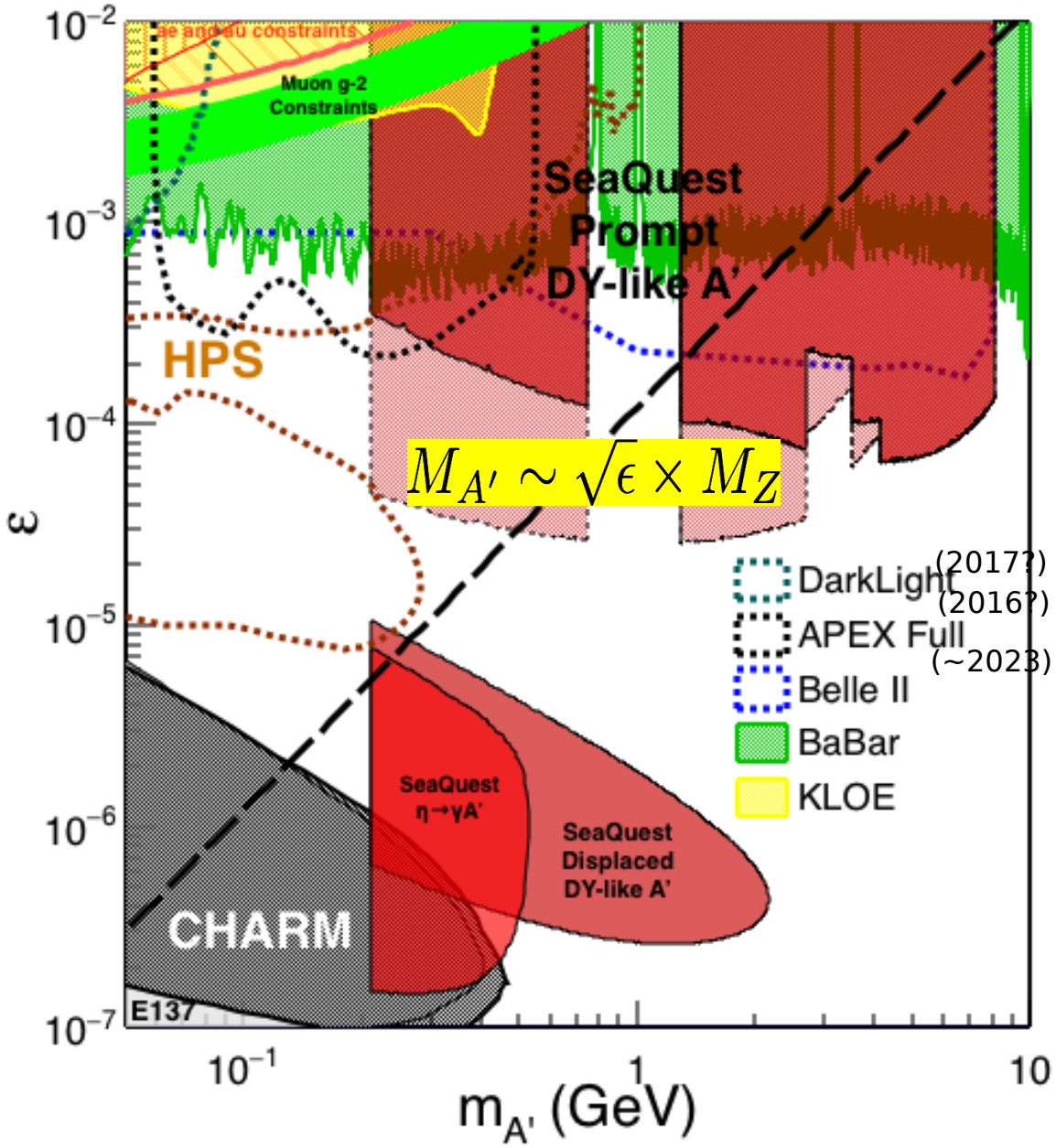
Dark Photon Sensitivity: Summary

POT:1.4x10^{18} (parasitic w/ E1039)

Signals considered:
- Drell-Yan like
- Eta decays
- Bremsstralung

Covers a wide range of unexplored parameter phase space

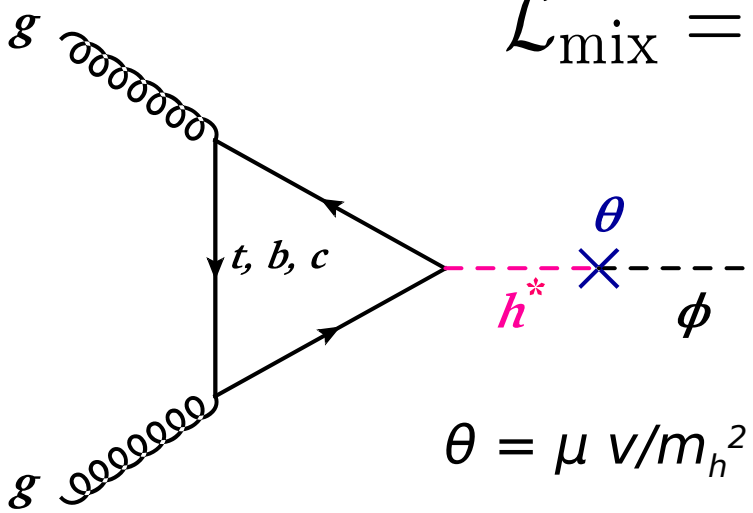
- Displaced dimuons
  - Minimal SM background
- Prompt dimuons
  - Excellent coverage over BELLE-II projection
  - Possible dedicated runs later to fully restore mass < 3GeV (Phase-II)
- ***Phase-II with upgrades***
  Access below 200MeV with di-electrons (add EMCal)



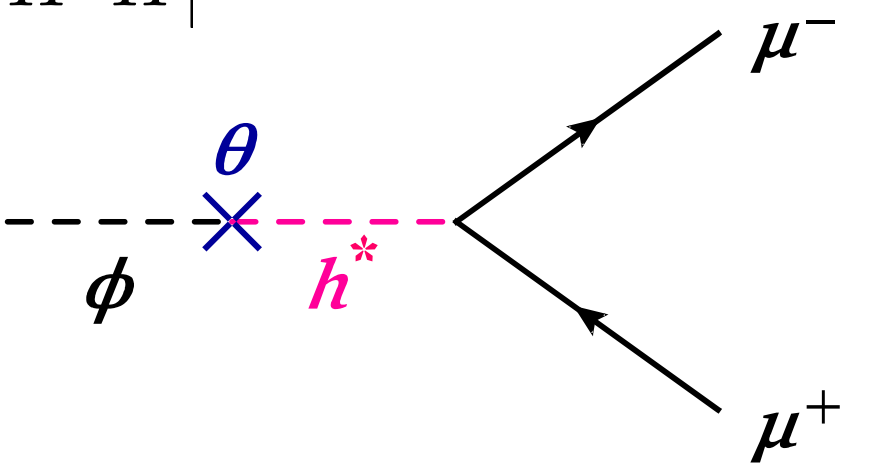
Dark Higgs Search at SeaQuest

$$\mathcal{L}_{\rm mix} = \mu\phi|H^\dagger H|$$

Y. Zhang et al, arXiv:1502.06983



$\theta = \mu\, v/m_h^2$



D. Curtin et al arXiv:1312.4992

$$\sigma(p+p\to\phi+X) = \int_0^1 \frac{dx}{x} g(x) g\left(m_\phi^2/(xs)\right) \frac{\alpha_s^2 G_F m_\phi^2}{288\sqrt{2}\pi s}$$

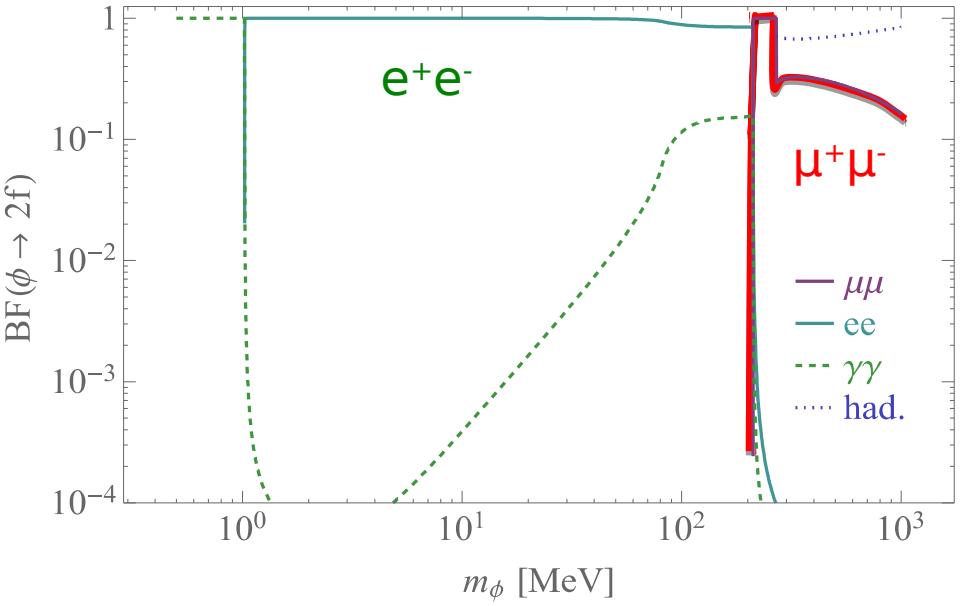
Phase-I:

High-mass: $\mu^+\mu^-$ and hadrons

Advantage of using hadron beams with muon probes over electrons

Phase-II:

Low-mass: e^+e^-, <200MeV possible

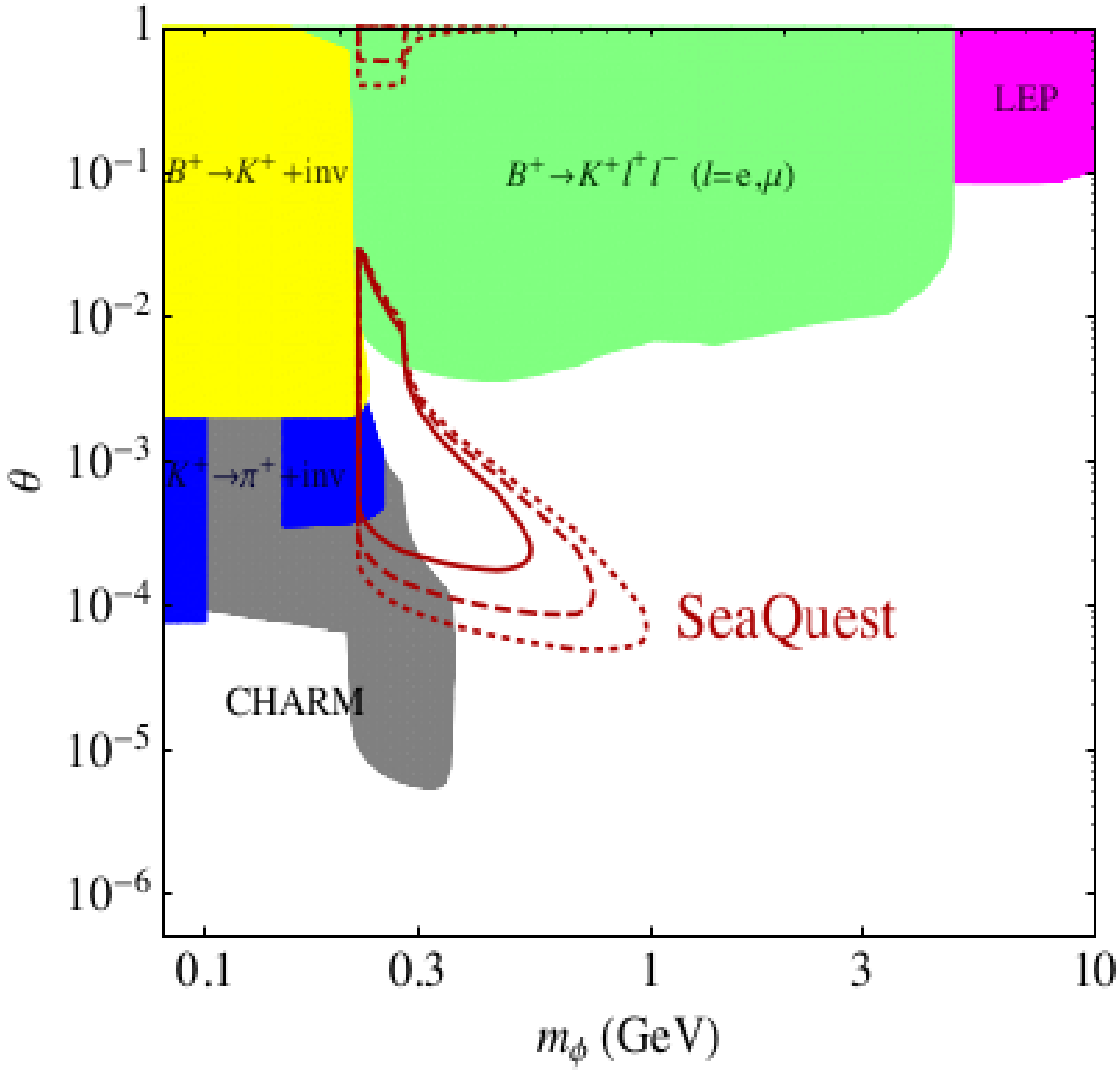


SeaQuest Dark Higgs Sensitivity

POT:1.4x10^{18} (Phase-I)

Y. Zhang (2015)

- Dimuons with downstream displaced decay vertices
- Limited sensitivity to "prompt" large mixing case due to small cross-section
- Dark Higgs or dark photons?
  - Dimuon kinematic and angular distributions
- Phase-II
  - Dedicated high luminosity runs optimized for low mass acceptance, mass<3GeV

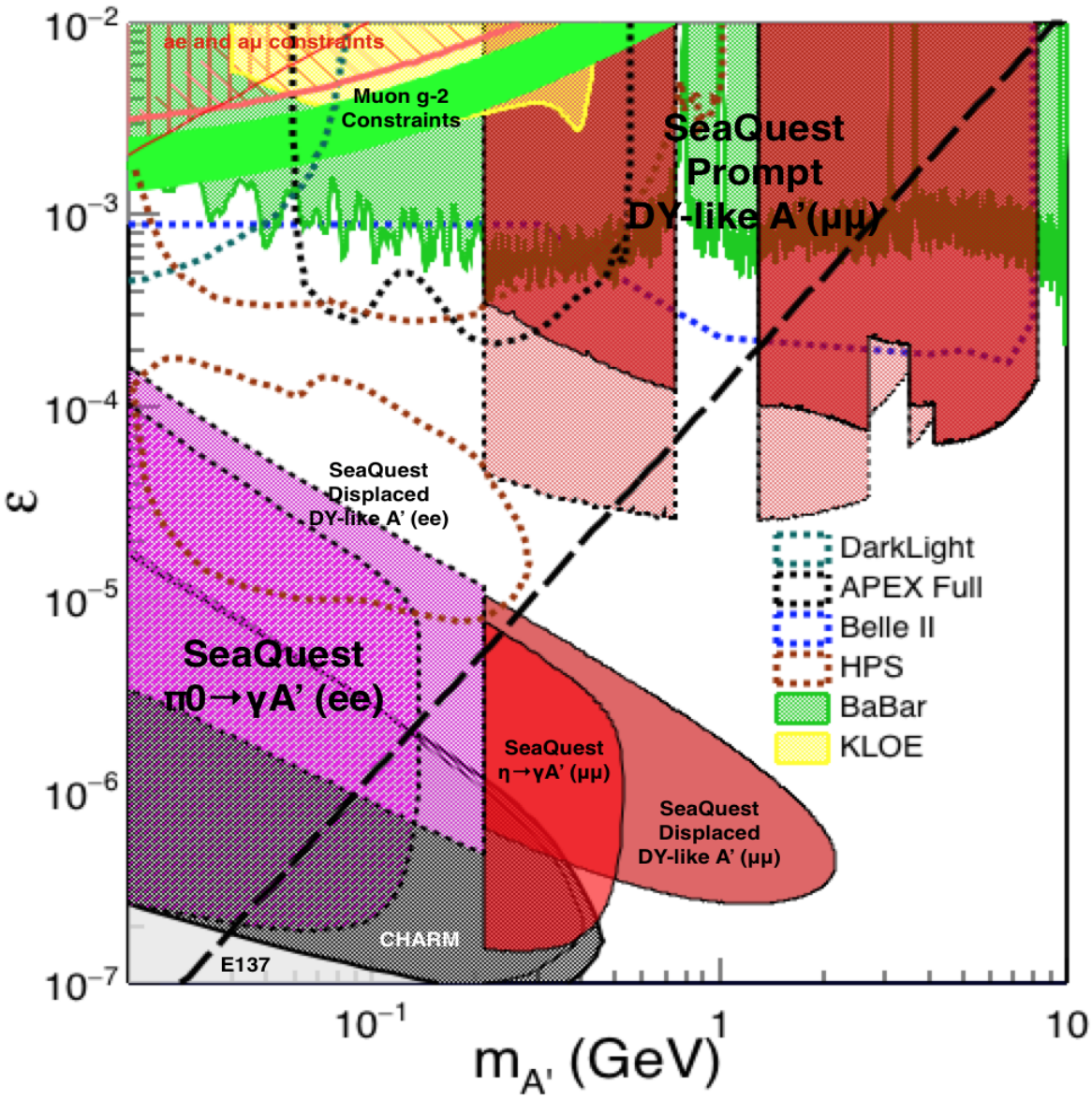


Phase-II: Full Coverage (2020+)

with future detector "EMCal/HCal" upgrades

Projection: POT 1.4 x 10^{18}

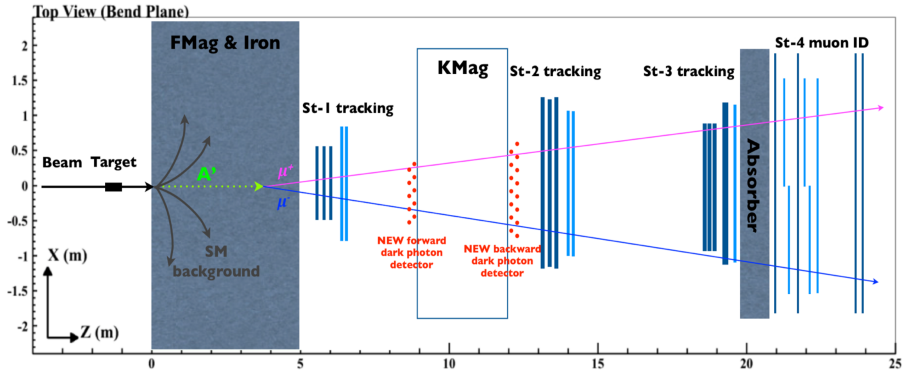
- Detector upgrades
  - EMCal: $e^{+/-}$
  - HCal: $\pi^{+/-}$
  - Recycle from other experiments, RHIC/JLab etc.
- DAQ upgrade
  - 100 kHz
- Timeline of dedicated runs
  - 2019+
- Detector configuration
  - Access low mass region with optimized Fmag settting

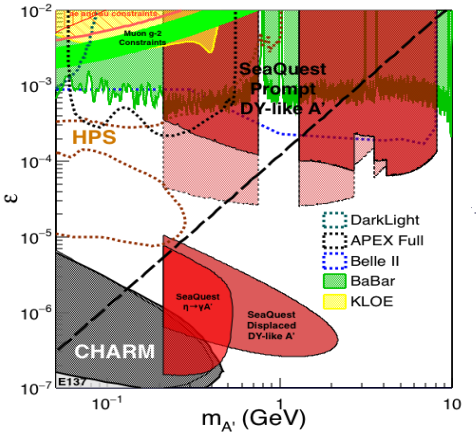


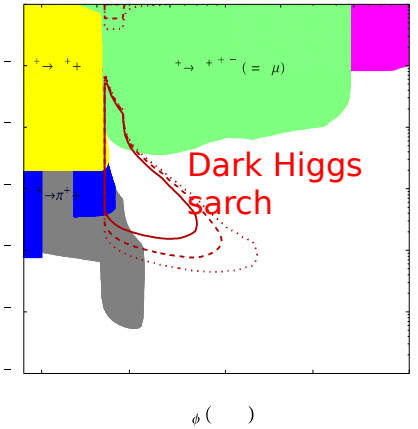
Summary and Outlook

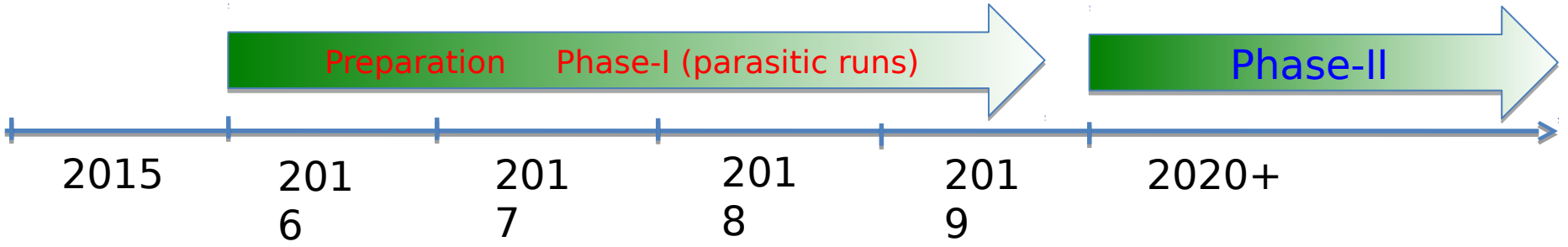
- ***Phase-I (2017-2019+)***
  - ***Great discovery potential!***
  - ***Add a new displayed vertex trigger***
  - ***Early parasitic data taking 2017-2019+***
  - ***POT 1.4 x10¹⁸***

- ***Phase-II (2020+)***
  - ***Possible detector upgrade later, add electrons and hadrons***
  - ***A new dedicated dark matter program at Intensity Frontier!***









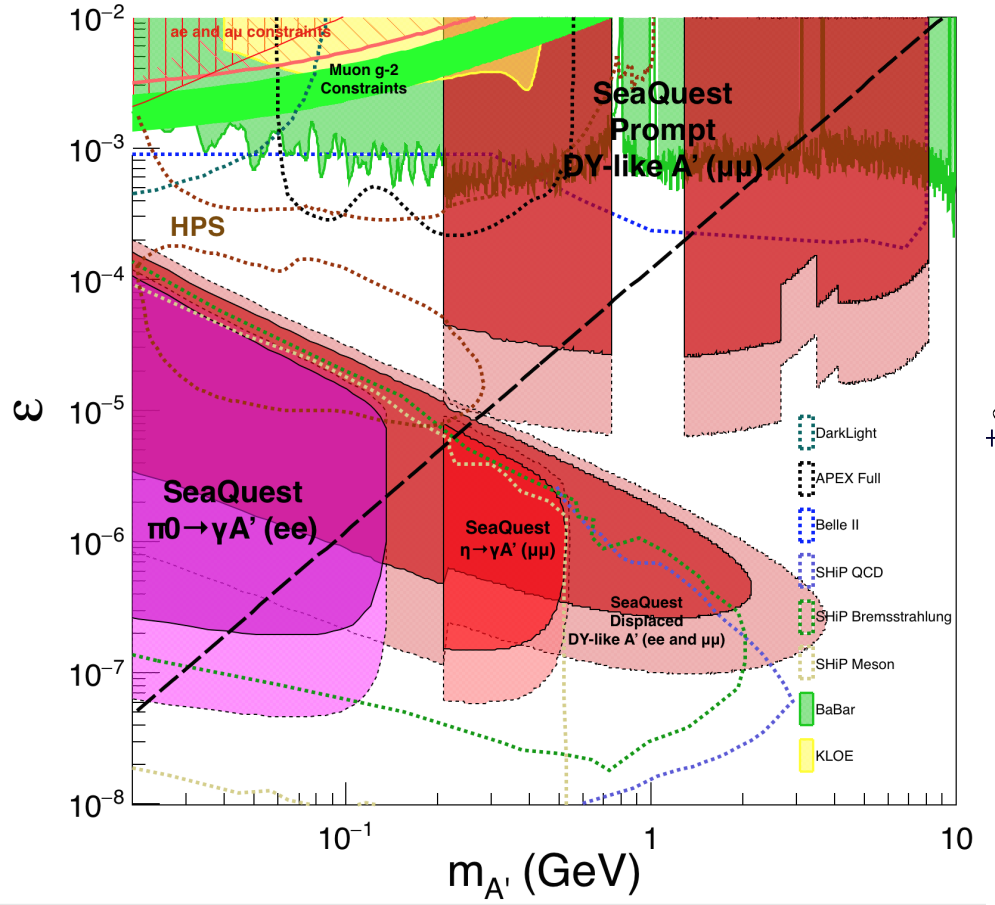
J-PARC Possibility?

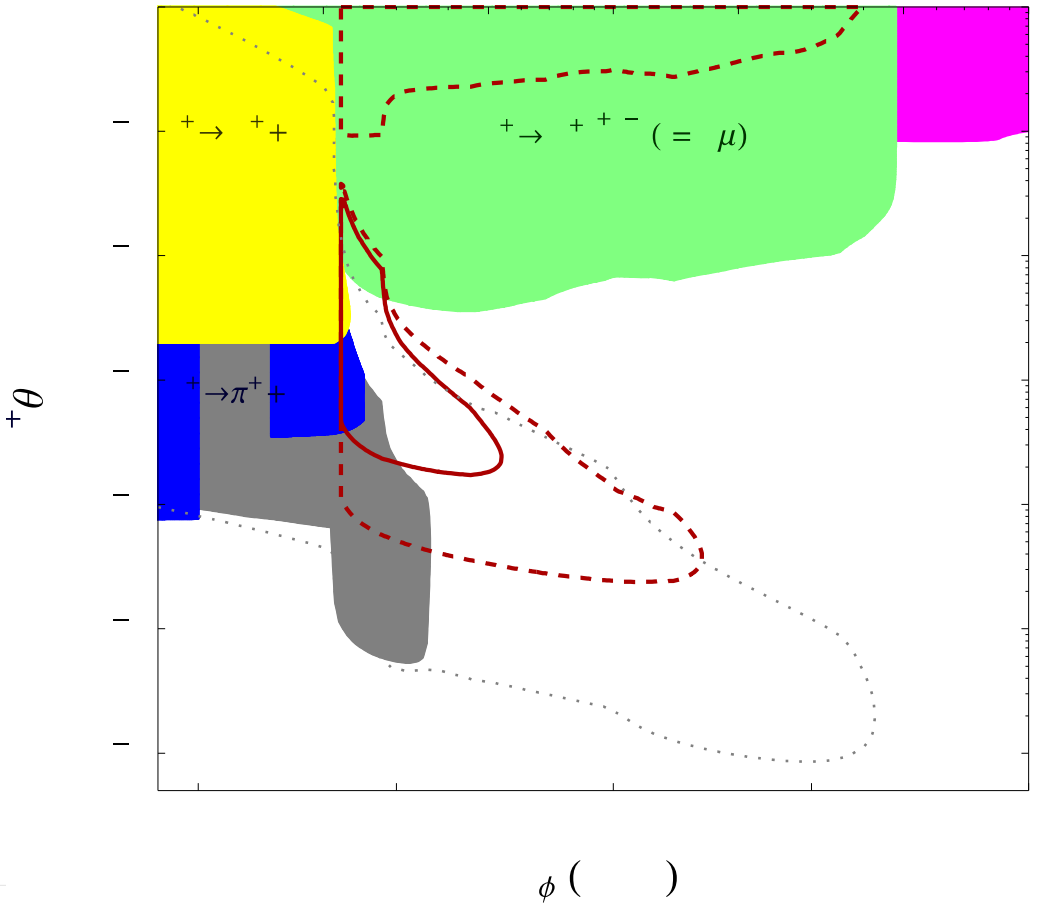
- 30GeV primary beam
  - High luminosity in a beam-dump mode
  - POT ~ 1x10^20?
- Similar setup to E-1067
  - Di-electrons?
  - Di-hadrons?
  - Using/Recycling existing detectors?
- Access different phase space
  - MC study needed

Comparison with CERN/SPS SHiP Proposal

120 GeV@FNAL: 2017 -2019
1.4x10^{18} POT, future dedicated runs

400 GeV@SPS: 2025 -2030
4x10^{20} POT

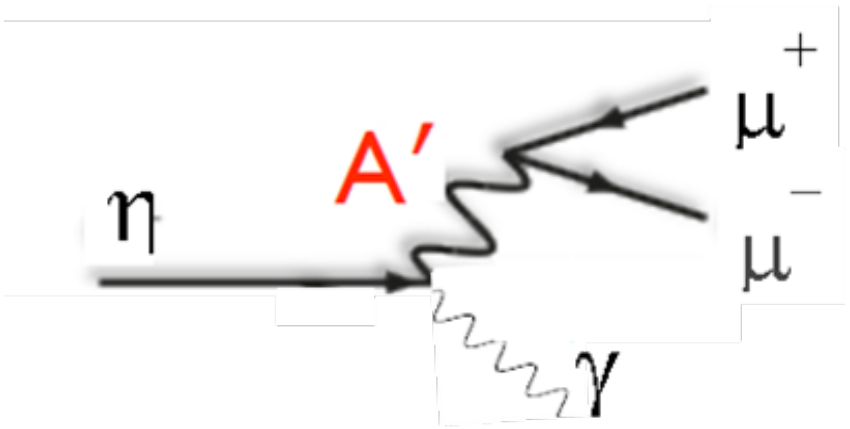




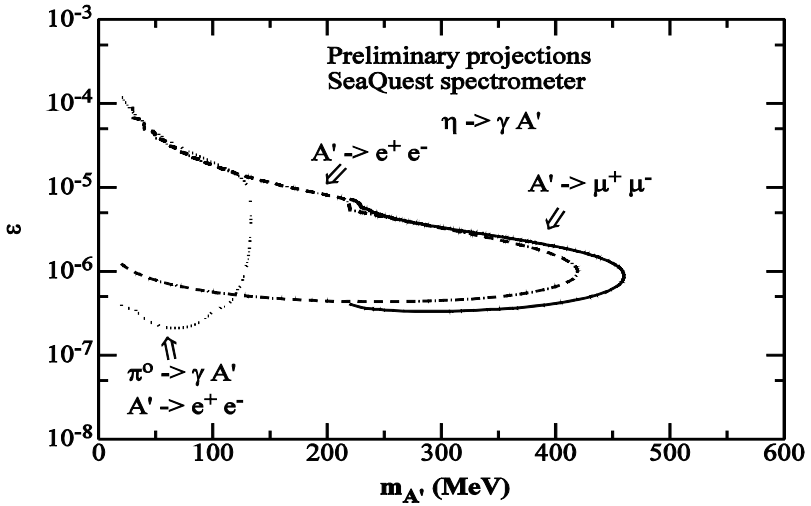
Backup slides

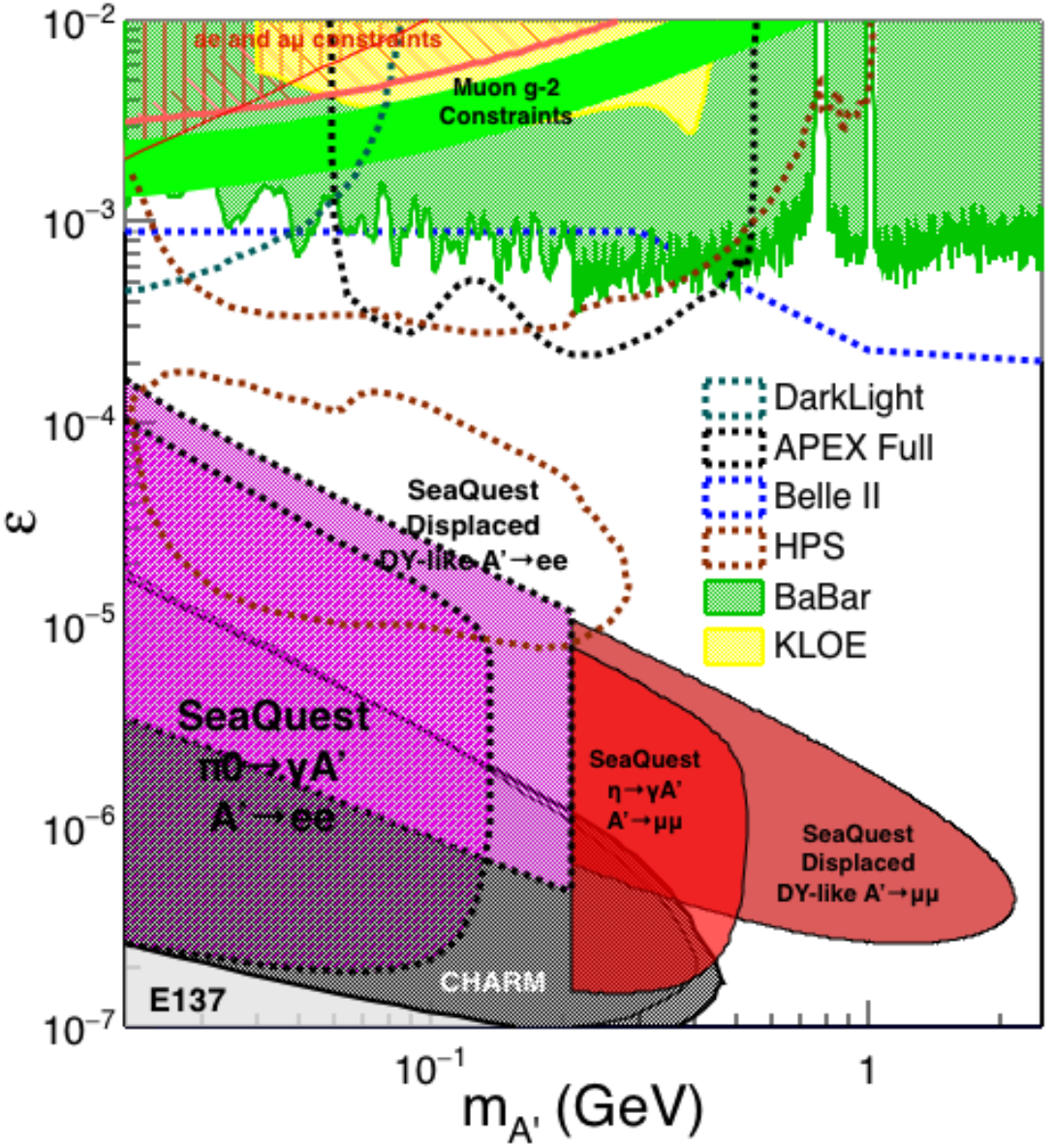
Phase-II: Access Low Mass Region with e^+e^-

with future detector "EMCal" upgrades



S. Gardner, R. Holt et al

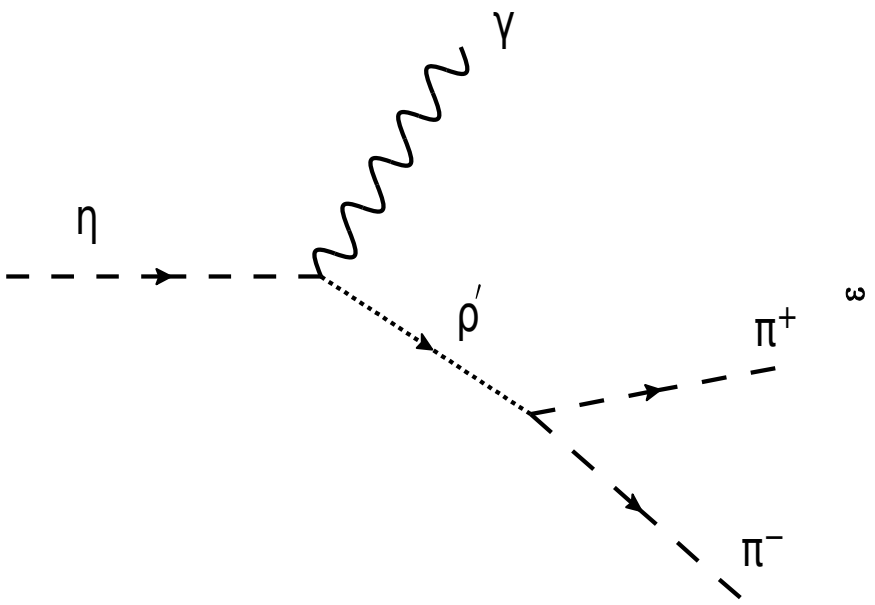




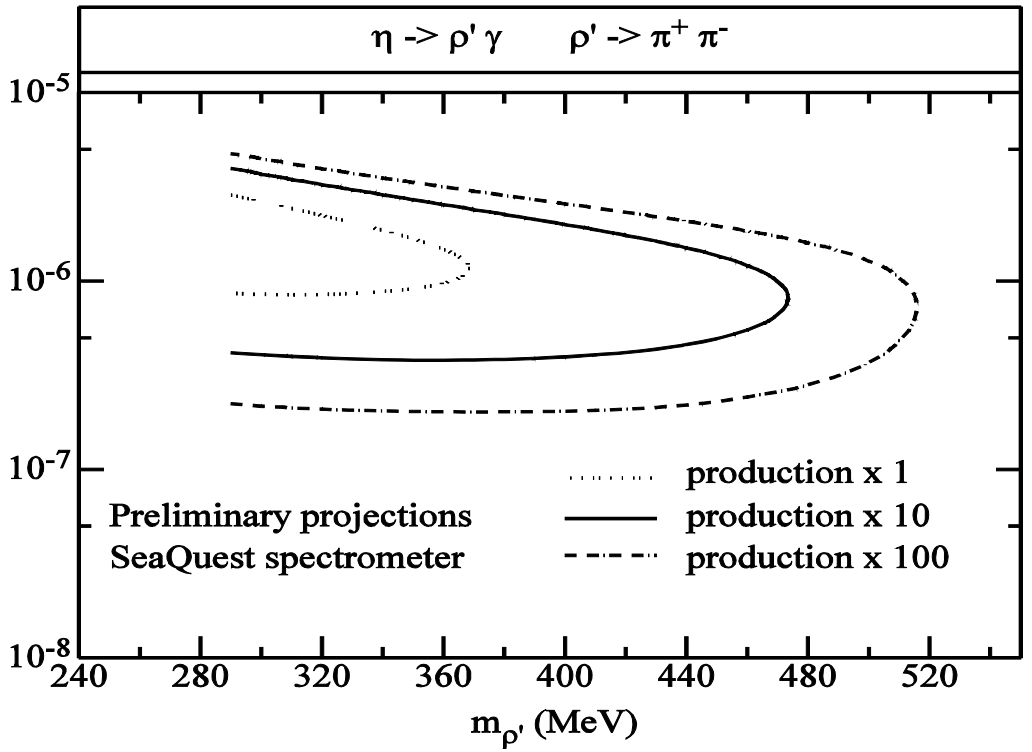
Non Abelian Dark Sector

with future detector "HCal" upgrades

non-Abelian dark sector process



S. Gardner and R. Holt



[Note: Batell, Pospelov, and Ritz, PRD 80 (2009) 095024 for a review re fixed target expts.]
Here we consider a non-Abelian (gluon) portal
[Baumgart et al., JHEP 0904, 014 (2009); Gardner and He, PRD 87 (2013) 116012]
The "shining through walls" design – unique to Seaquest – makes this possible ,
to yield, e.g., via a "minimal" decay….

E906 Run-II and III Performance