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

Ming Liu
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- TSSA physics with Froward sPHENIX
- Dark photons and Dark Higgs Search at Fermilab
- J-PARC possibility?

Outline

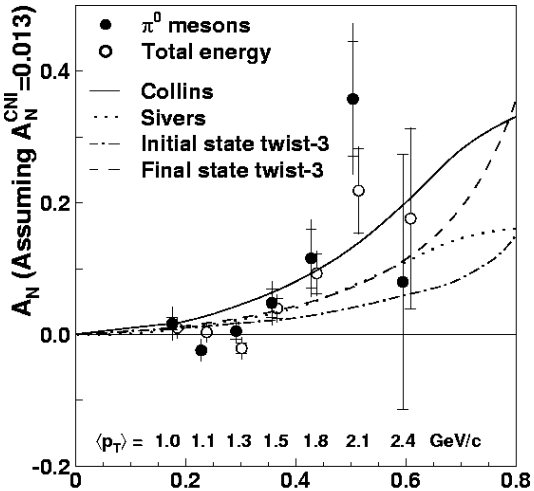
- Transverse spin physics at RHIC
  - A few key questions
  - TMD, Twist-3 etc.
  - Jet TSSA and forward sPHENIX

- Dark particle search at Fermilab
  - Dark photon and dark Higgs
  - E-1067 Dimuon beam-dump experiment at Fermilab (120GeV)
  - J-PARC (30GeV) opportunity?

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

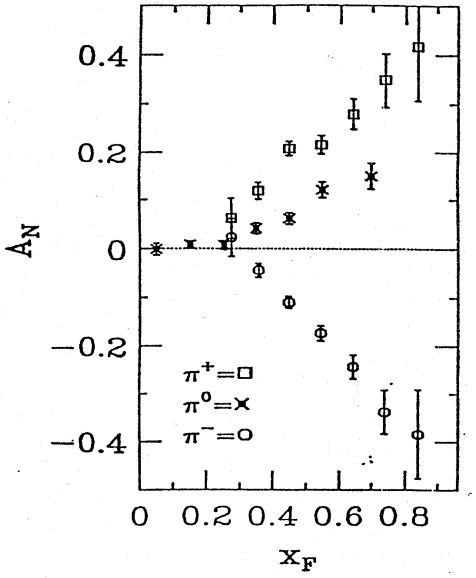
Large Transverse Single Spin Asymmetry (SSA) in forward hadron production persists up to RHIC energy.

RHIC 200 GeV CMS



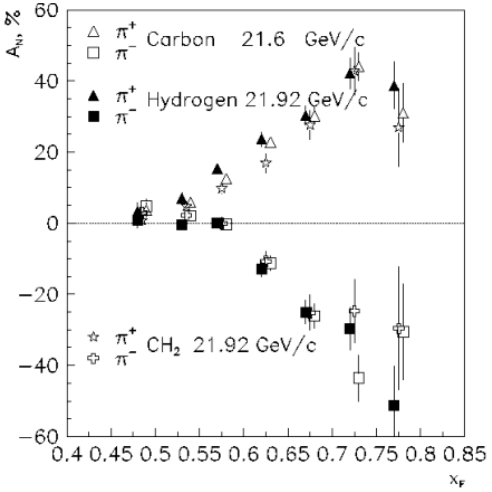
PRL (2004)

00 GeV beam



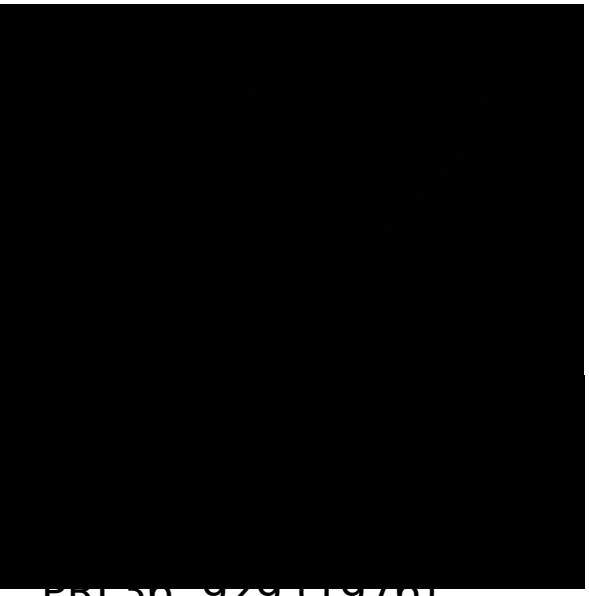
PLB261, 201 (1991)
PLB264, 462 (1991)

AGS 22 GeV beam

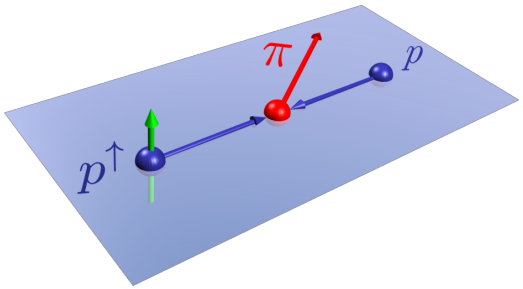


PRD65, 092008 (2002)

ZGS 12 GeV beam



PRL36, 929 (1976)



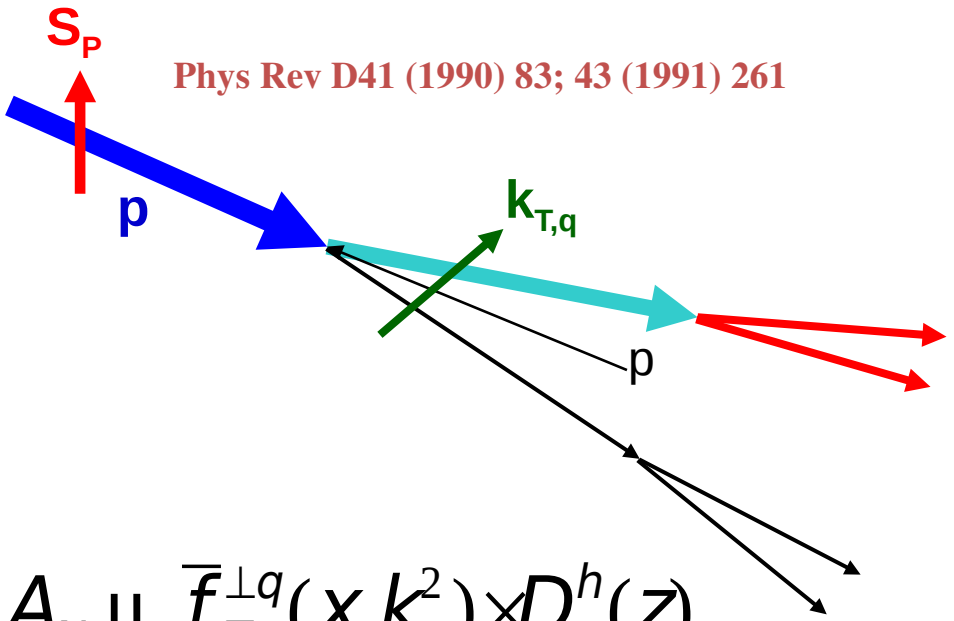
Sivers, Collins, Twist-3 ….

Non-Perturbative cross section → Perturbative cross section

Study the Physics via Hard Scatterings at RHIC

(i) Sivers mechanism:

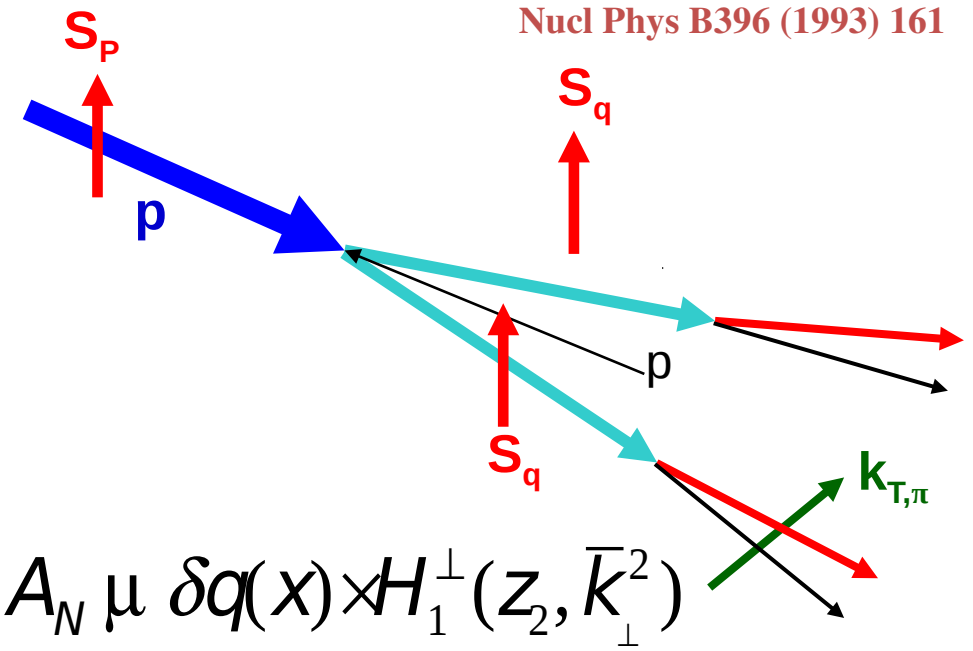
correlation between proton spin & parton k_T



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

(ii) Collins mechanism:

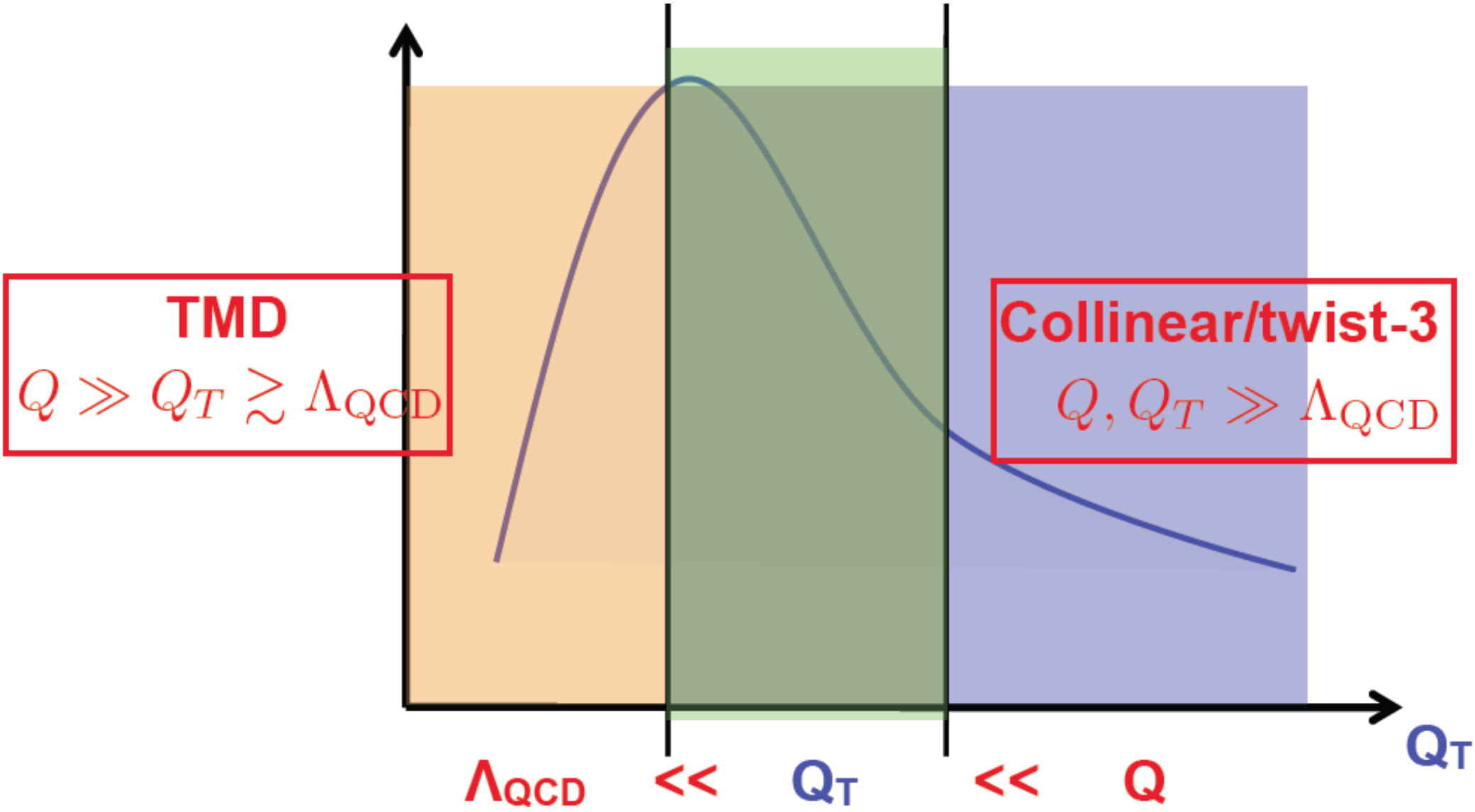
Transversity × spin-dep fragmentation



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

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

TMD and Collinear Twist-3



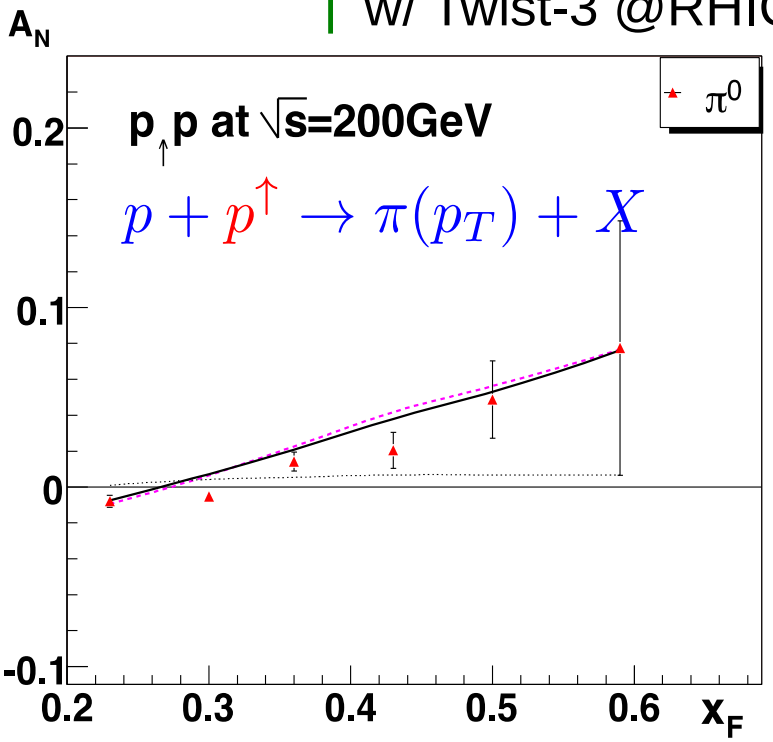
Test the Universality of QCD Descriptions

Are TMD and Twist-3 really consistent?

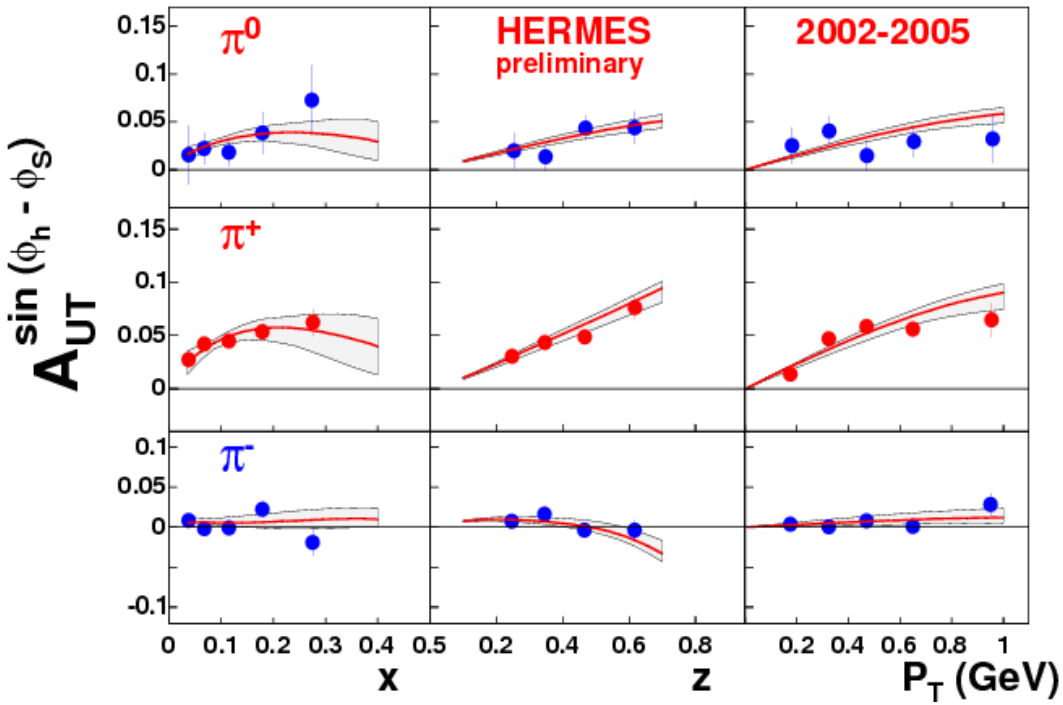
$$gT_{q,F}(x,x) \stackrel{?}{=} -\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{\rm SIDIS}$$

Kang, Qiu, Vogelsang, Yuan(2011)

p+p Sivers-Like
w/ Twist-3 @RHIC



SIDIS Sivers
w/ TMD @HERMES



“Hot Topics” 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

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

  - 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

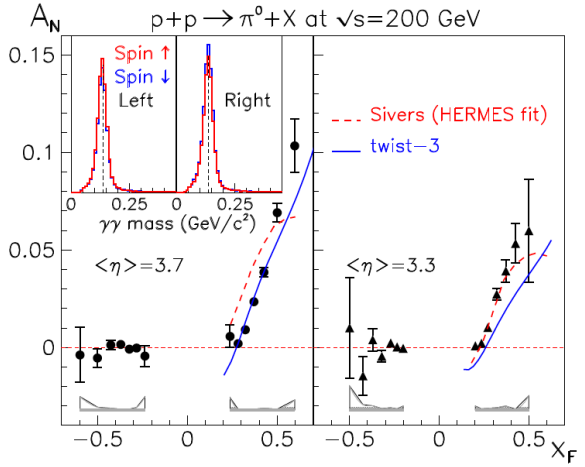
$$T_{q,F}(x,x) = -\int d^2k_\perp \frac{|k_\perp^2|}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{\mathrm{SIDIS}}$$

A Surprise: A_N Sign Mismatch?

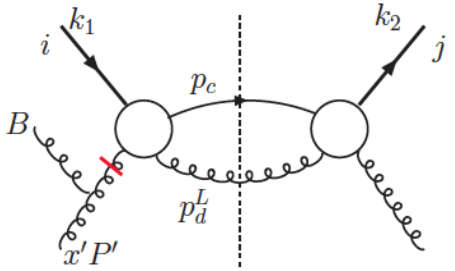
First attempt to check the "Universality of QCD description of TSSA"

Kang, Qiu, Vogelsang, Yuan PRD 2011

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

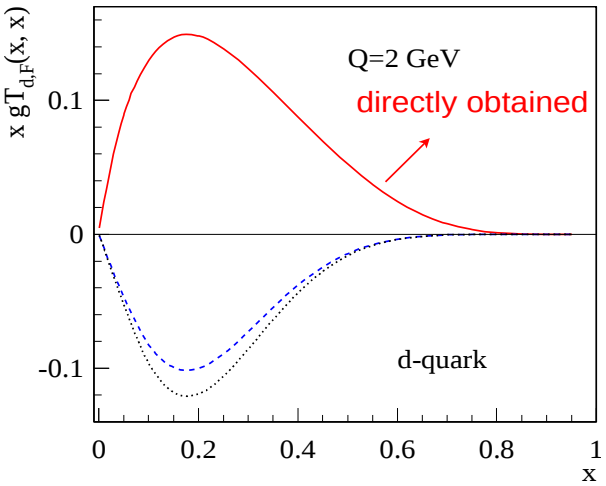


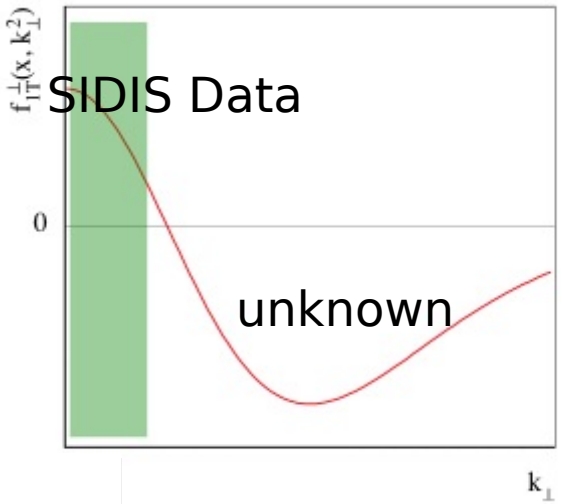
$$gT_{q,F}(x,x) = -\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x,k_\perp^2)\Big|_{SIDIS}$$



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

A possible solution? Kang, Prokudin PRD (2012)





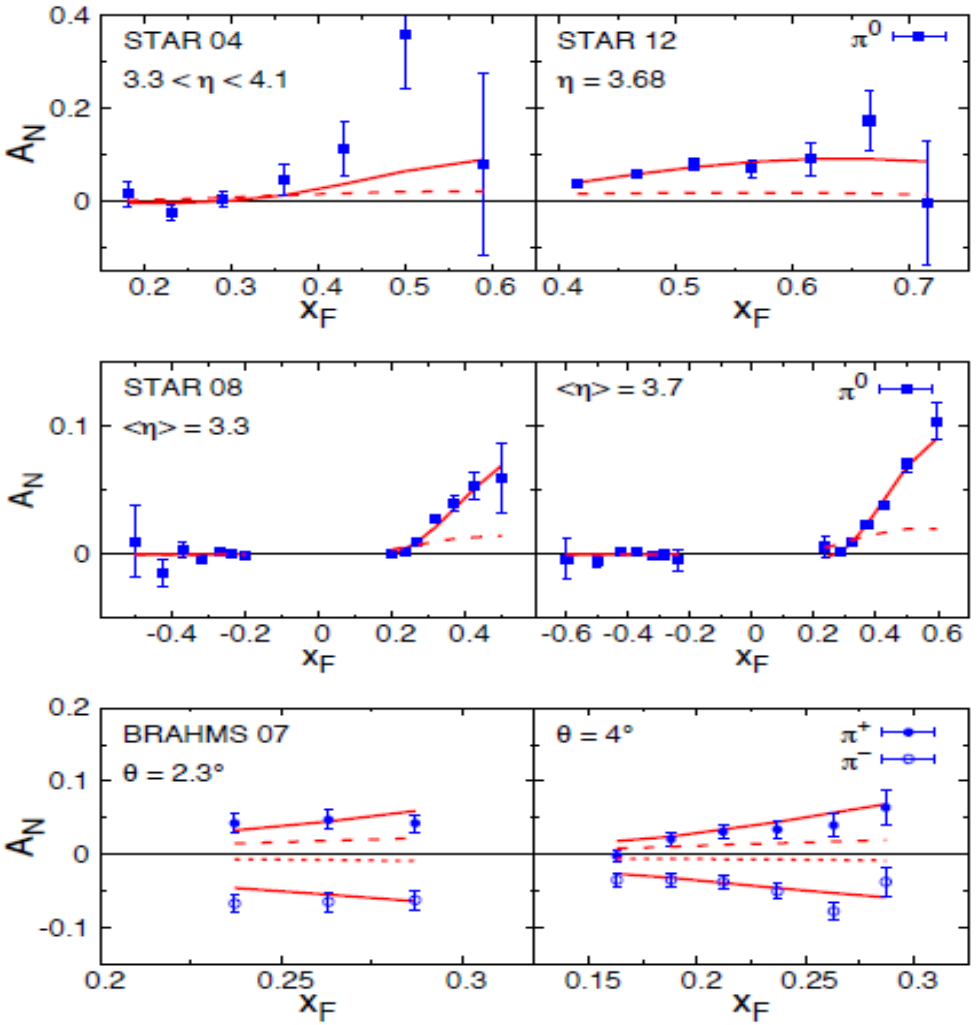
Collins dominates?

Need more data to check other possibilities!

Could "Collins effect" be the Solution?

A_N from twist-3 fragmentation functions

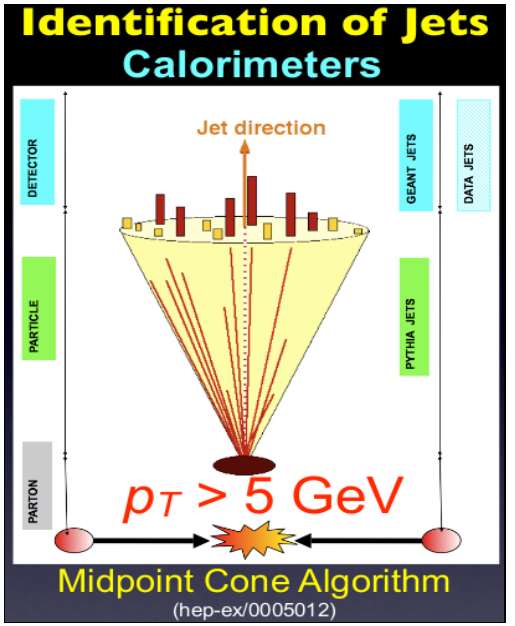
(Kanazawa, Koike, Metz, Pitoniak, arXiv:1404.1033)

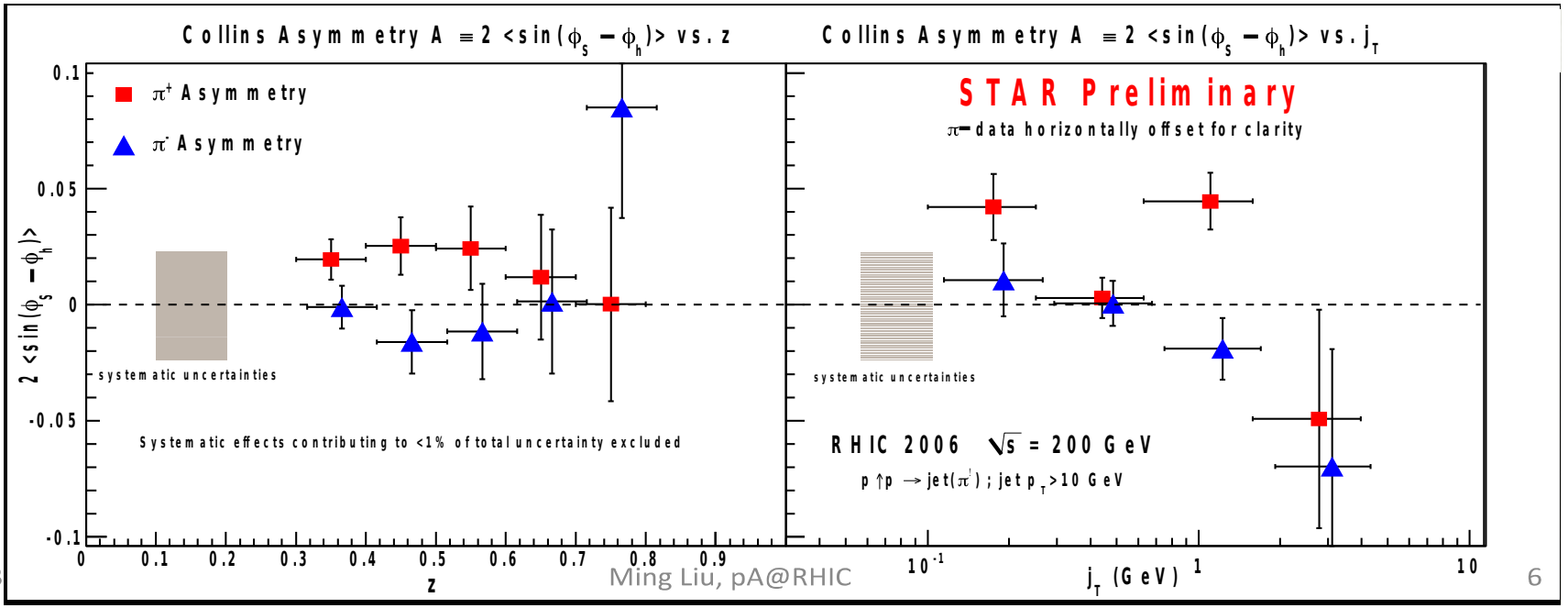


good fit of A_N mainly due to the new twist-3 fragmentation function

Collins Asymmetry inside Jets

- Significant non-zero spin asymmetry observed @RHIC





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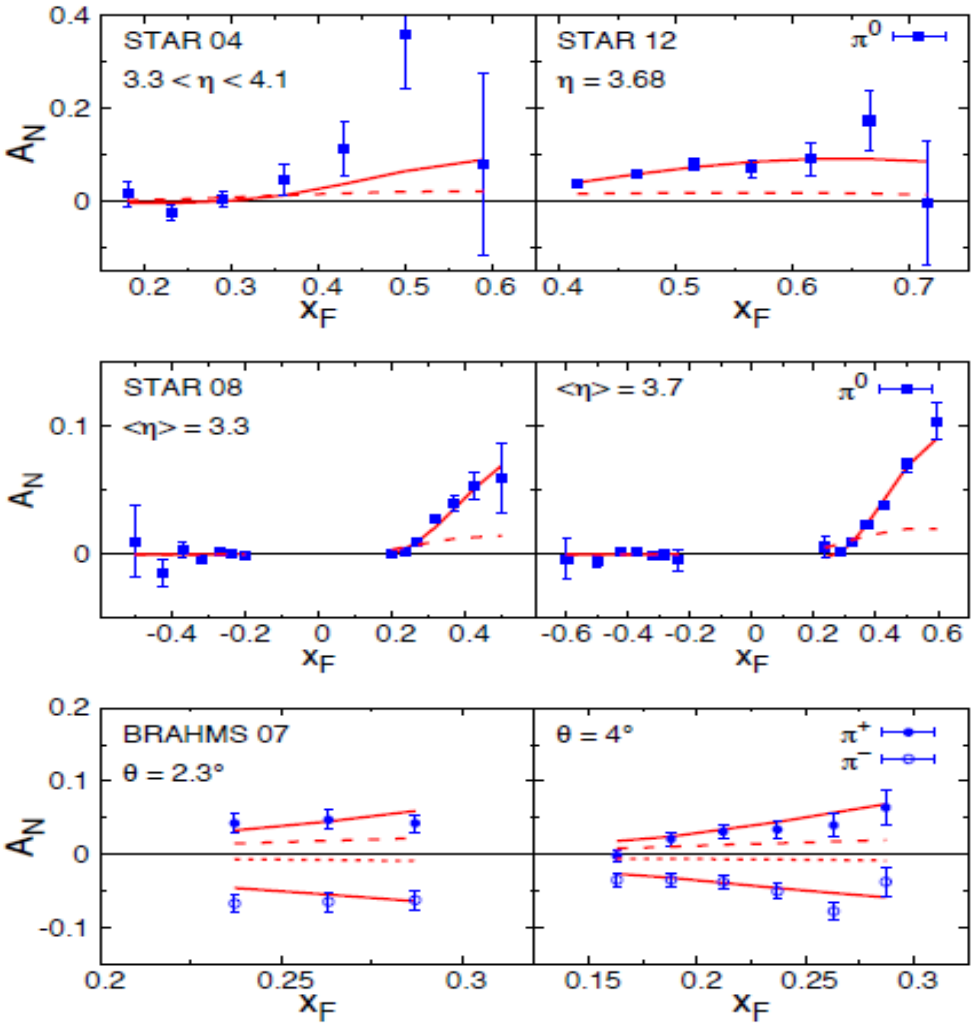
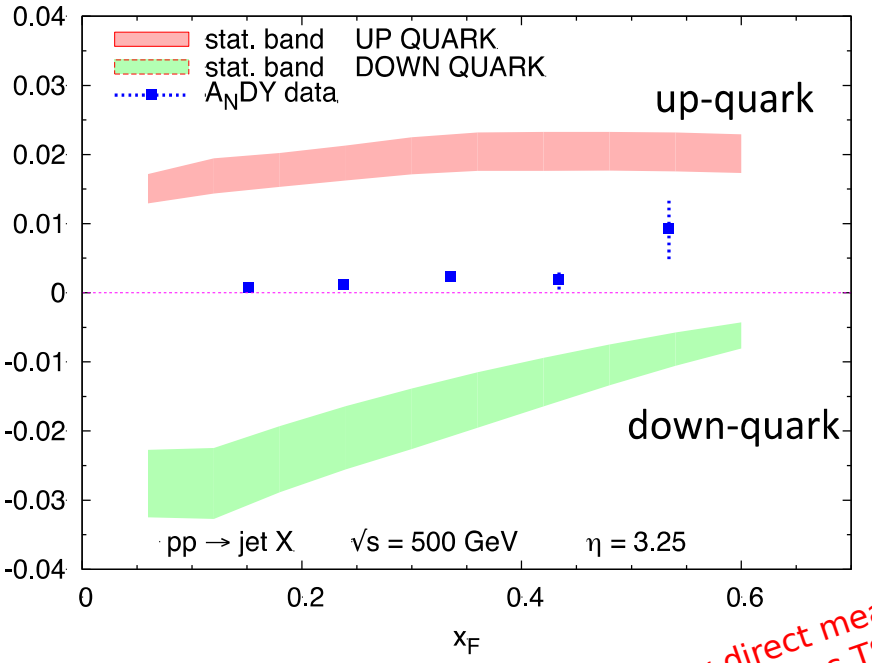
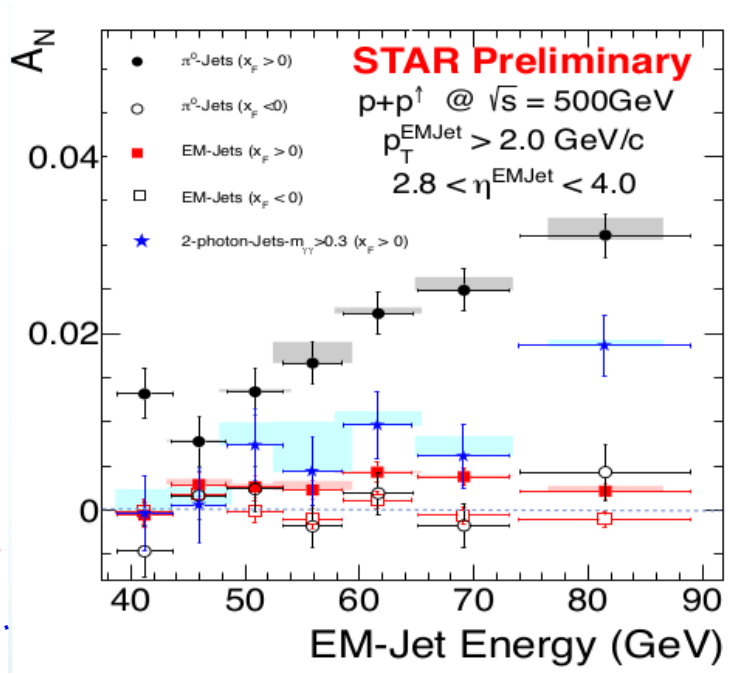


good fit of A_N mainly due to the new twist-3 fragmentation function

AnDY inclusive Jet TSSA and STAR Jet Collins

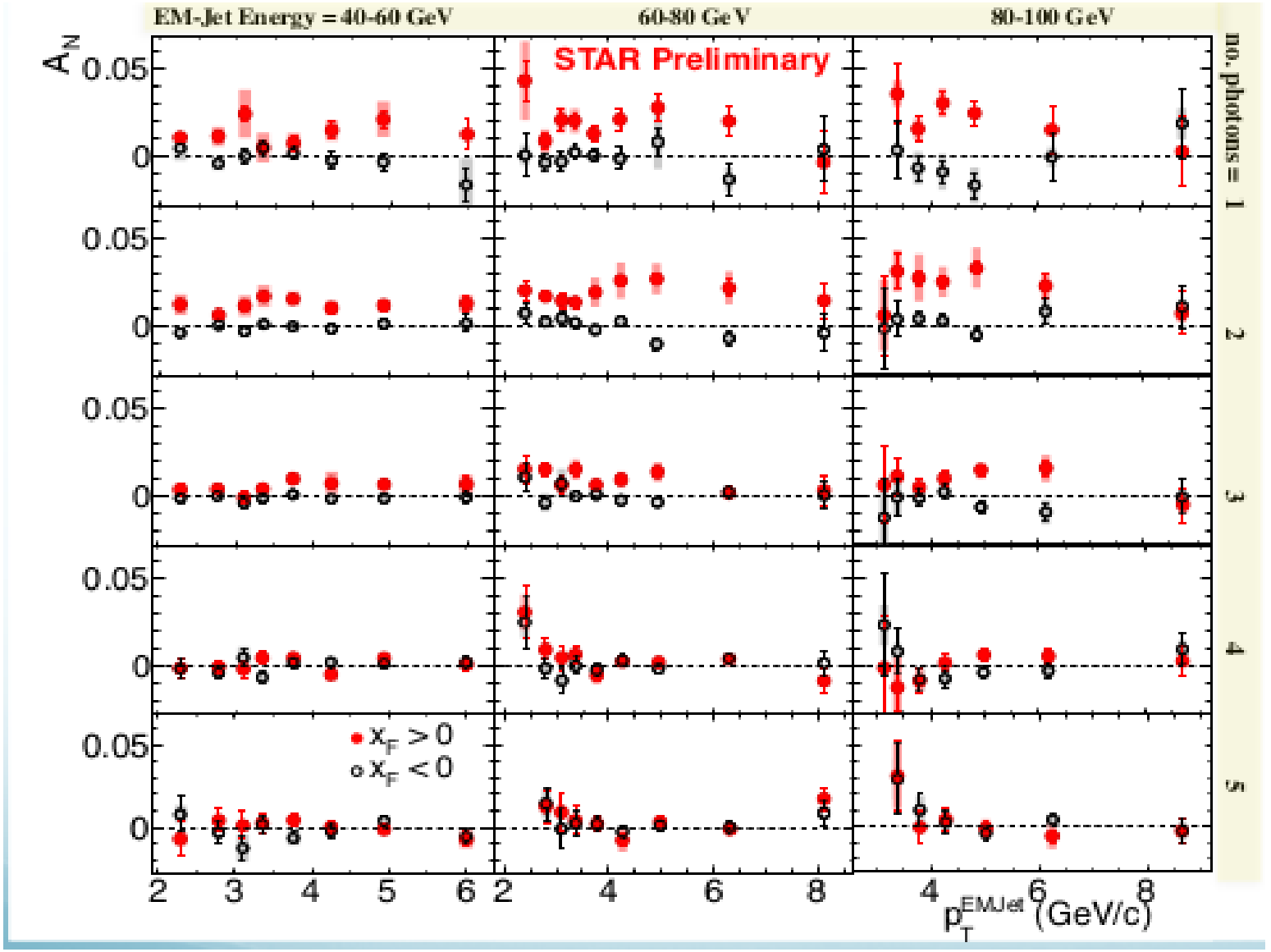
- AnDY Jet TSSA
  - Very small, u and d cancellation?
- STAR jet pi0 Collins TSSA
  - Small for jetty type





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

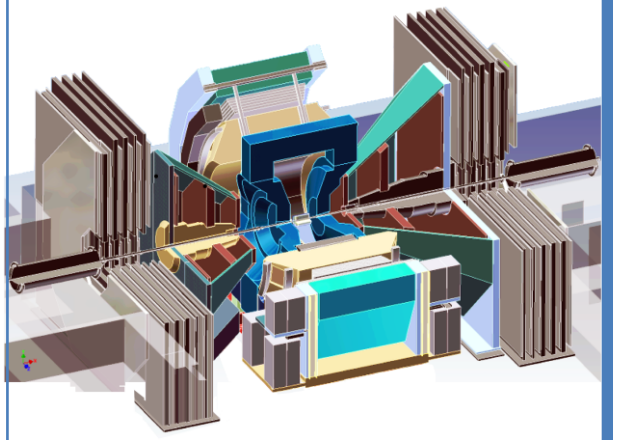
STAR: EM-Jet TSSA

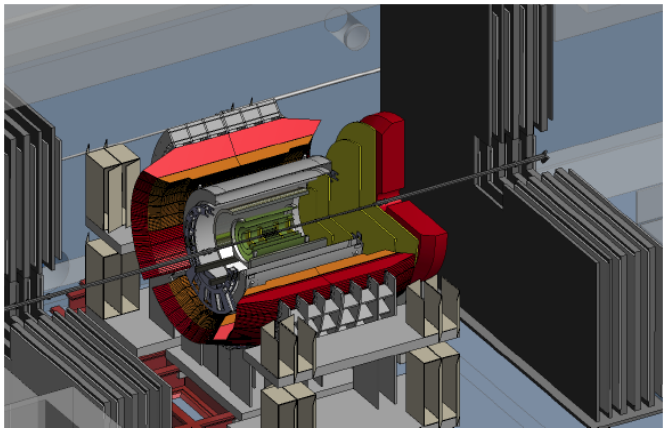


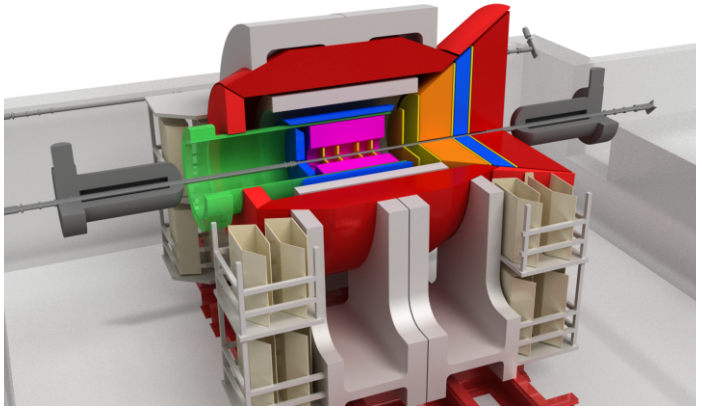
PHENIX -> Forward/sPHENIX->ePHENIX

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







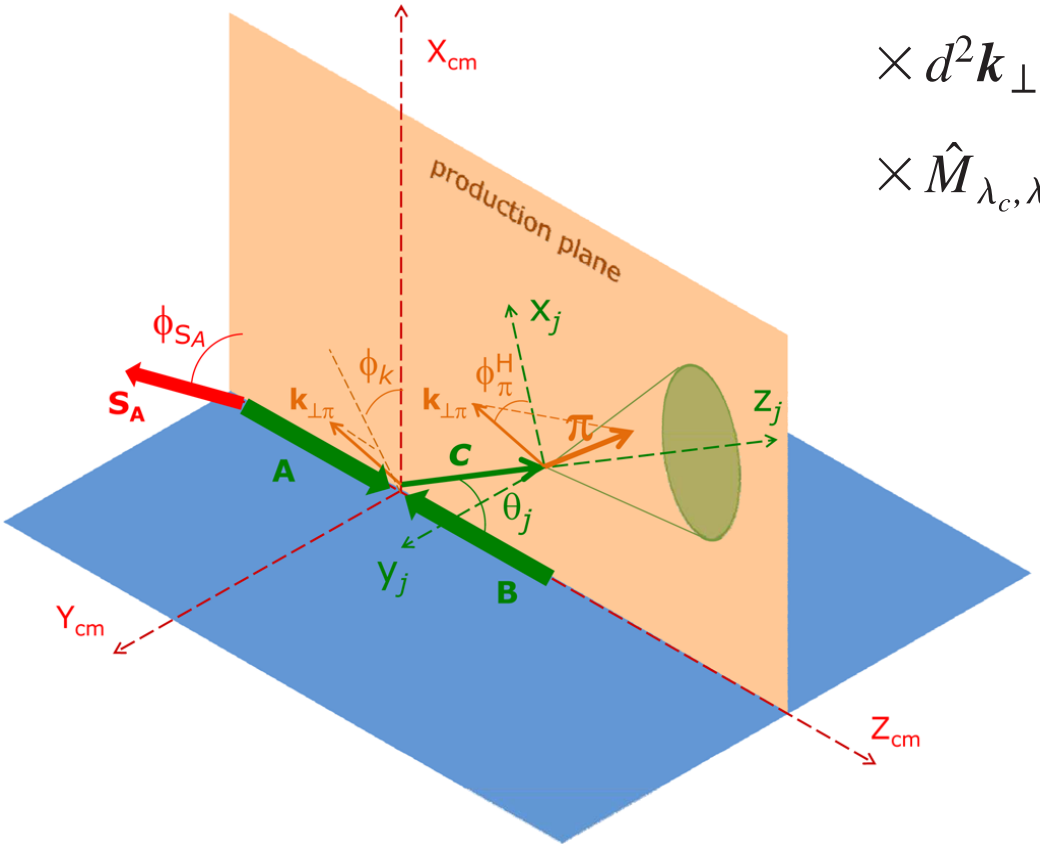
~2000 2017→2020 ~2025 Time

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

eRHIC: e+p, e+A

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

eng Yuan, PRL 100, 032003 (2008)
mberto 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
- Hadron P_h , PID
- Beam polarization

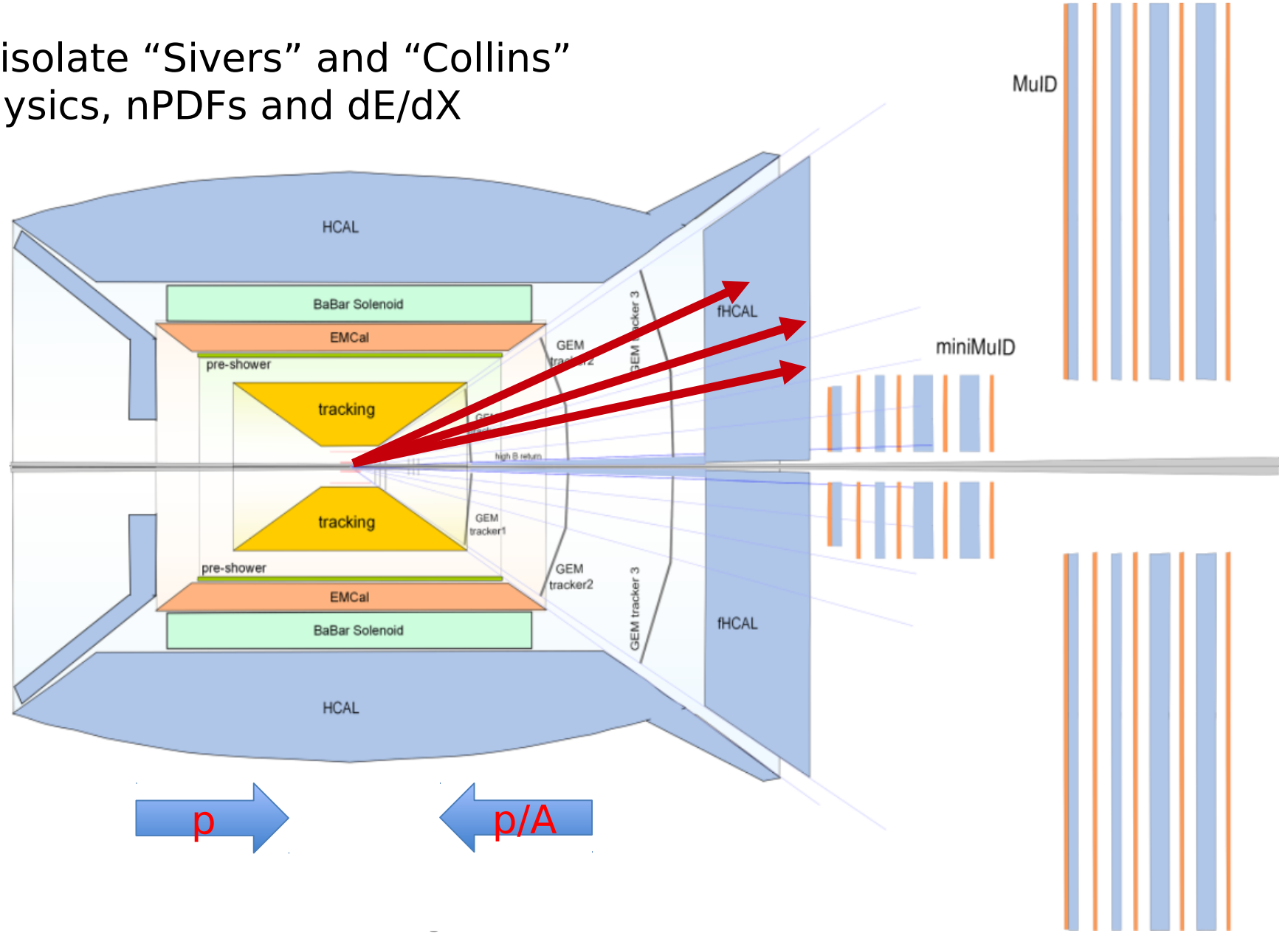
$A_N^{\sin\phi_{S_A}}$ → "Sivers-like"

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

Forward sPHENIX

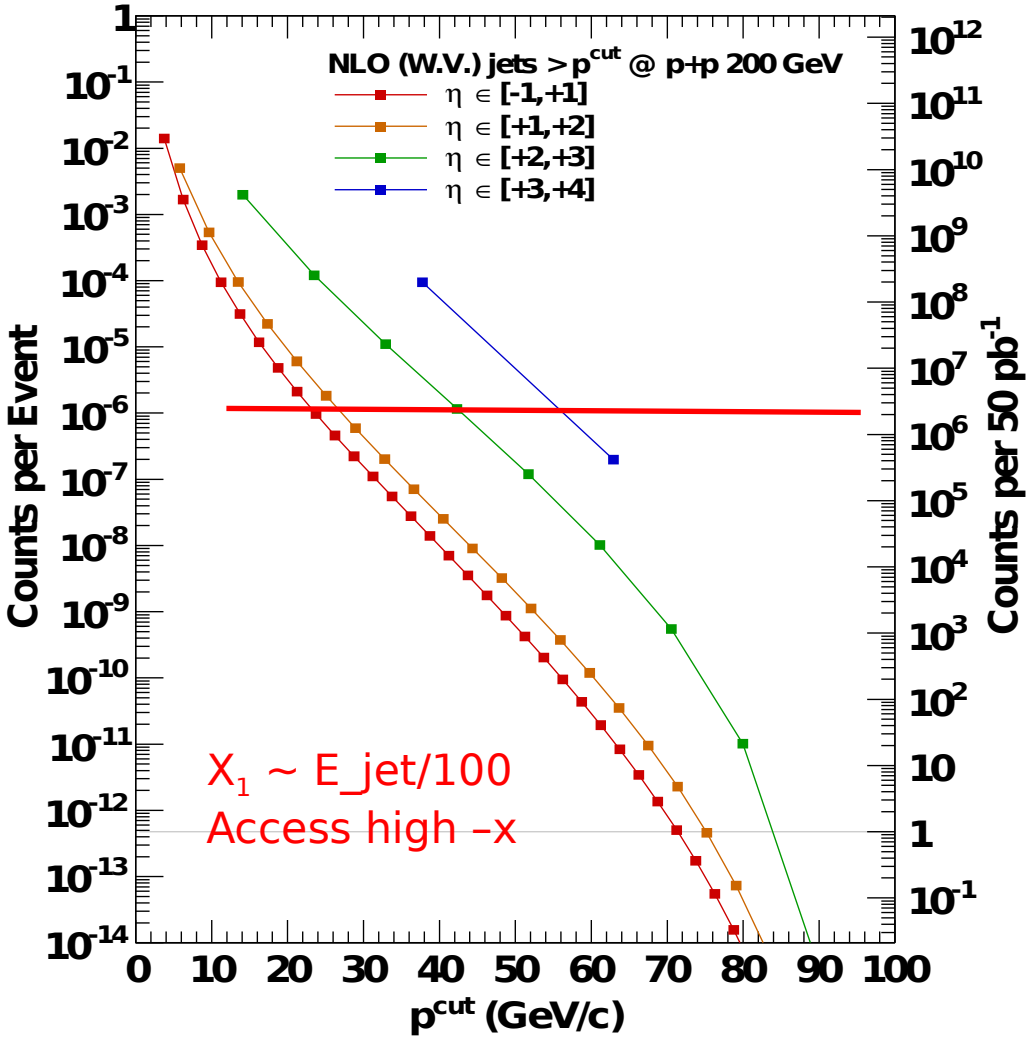
-1 < eta < 4

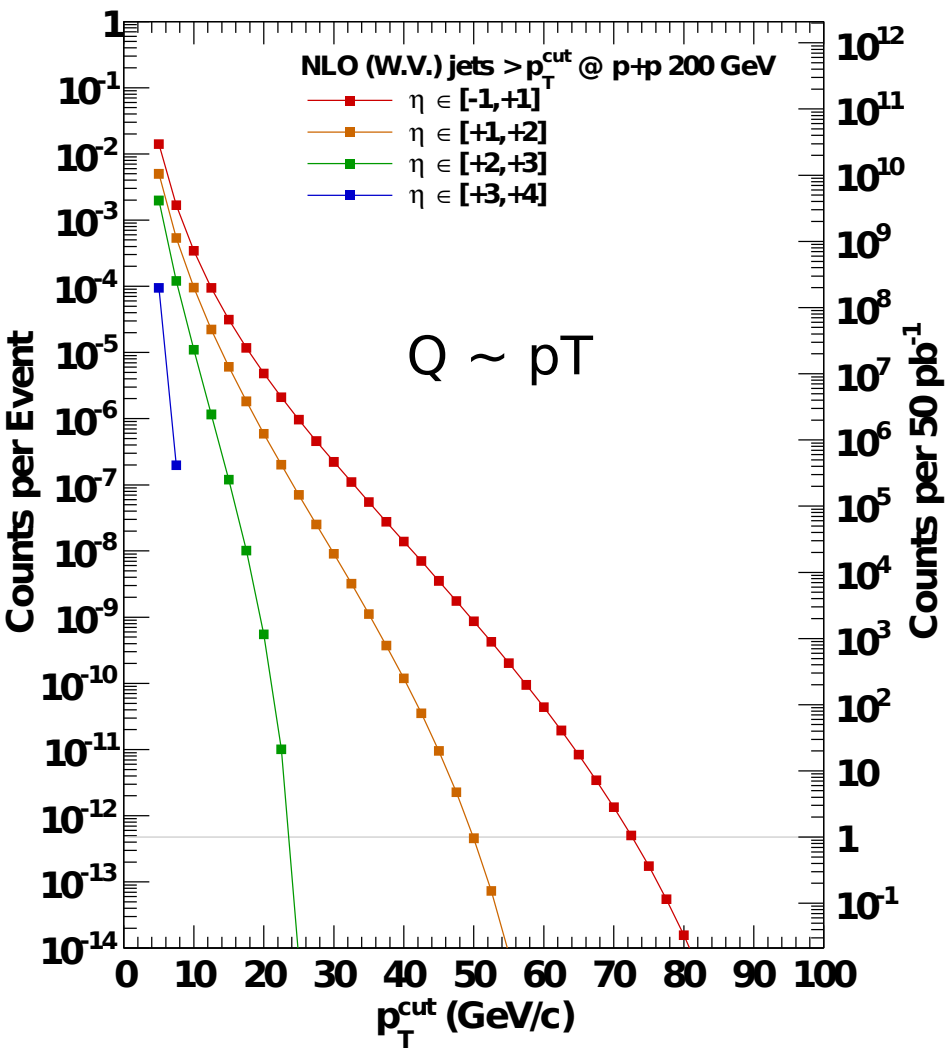
- Clearly isolate “Sivers” and “Collins”
- CNM physics, nPDFs and dE/dX



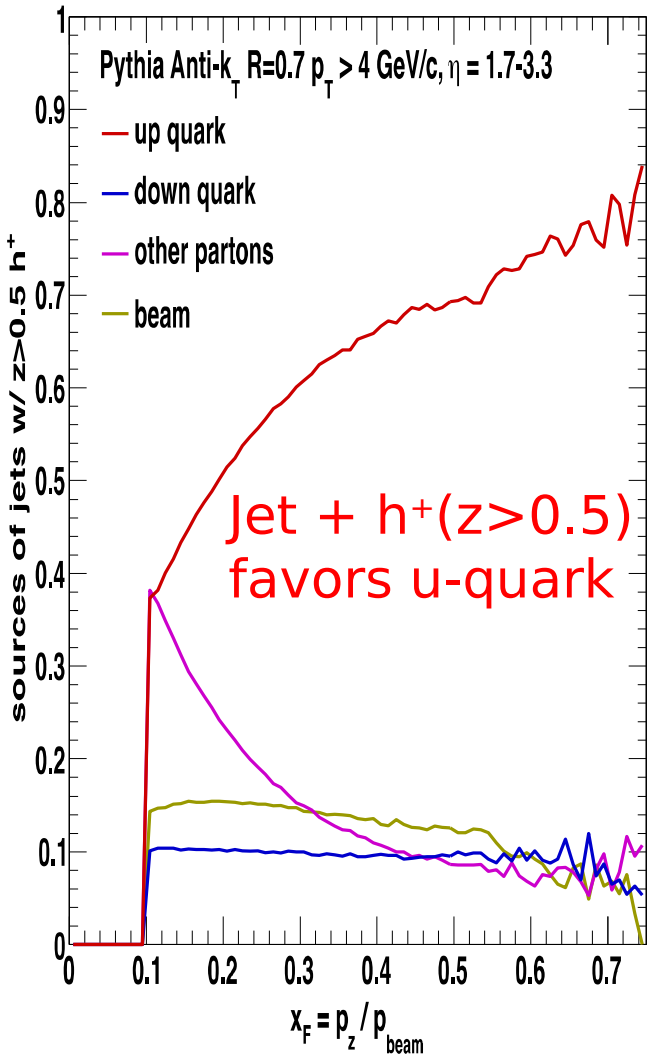
Jet Production Rates @NLO

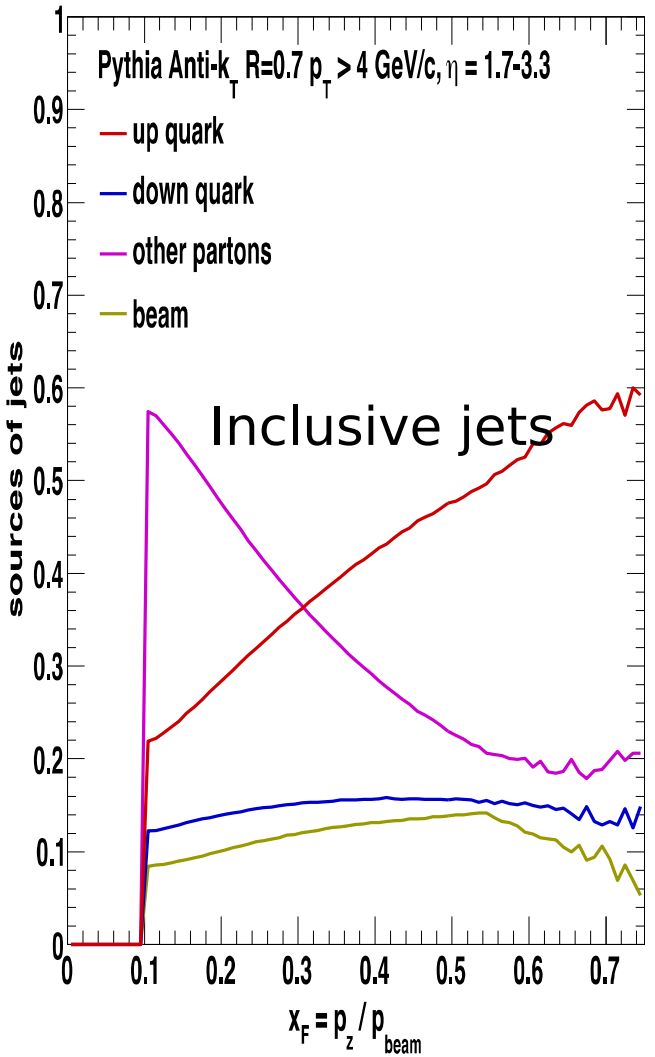
200GeV p+p: Lumi = 50pb^{-1}

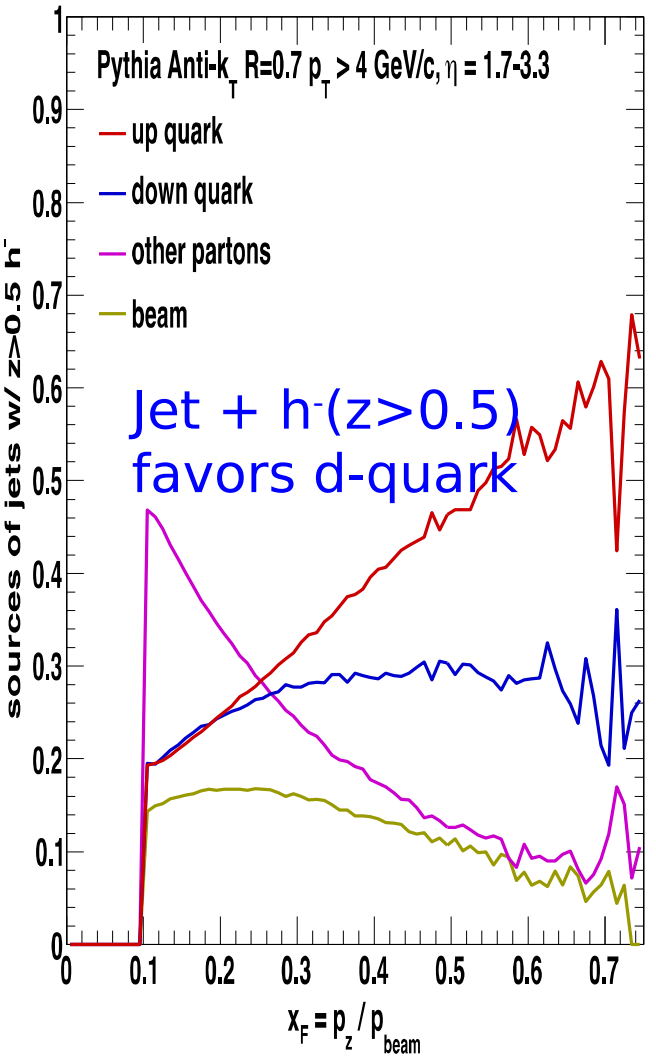




Jet Quark-Flavor Tagging with Charged Hadrons





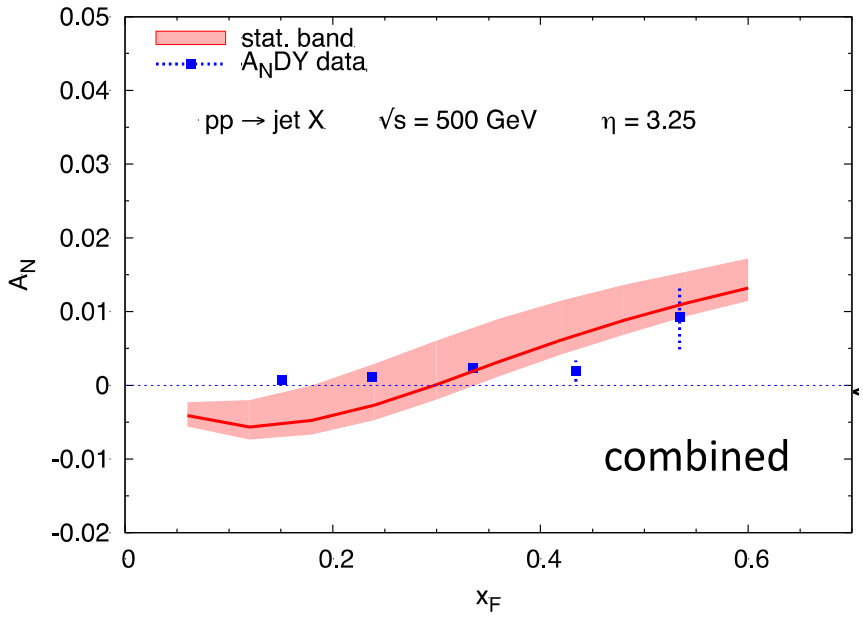


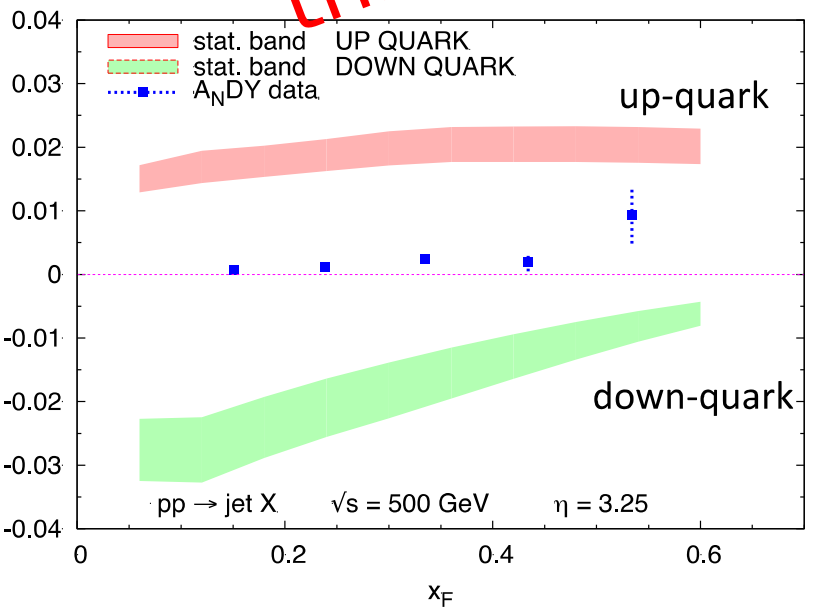
Flavor Tagged Jet SiversAsymmetry

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

We can do this!

Directly use Sivers function from SIDIS fit

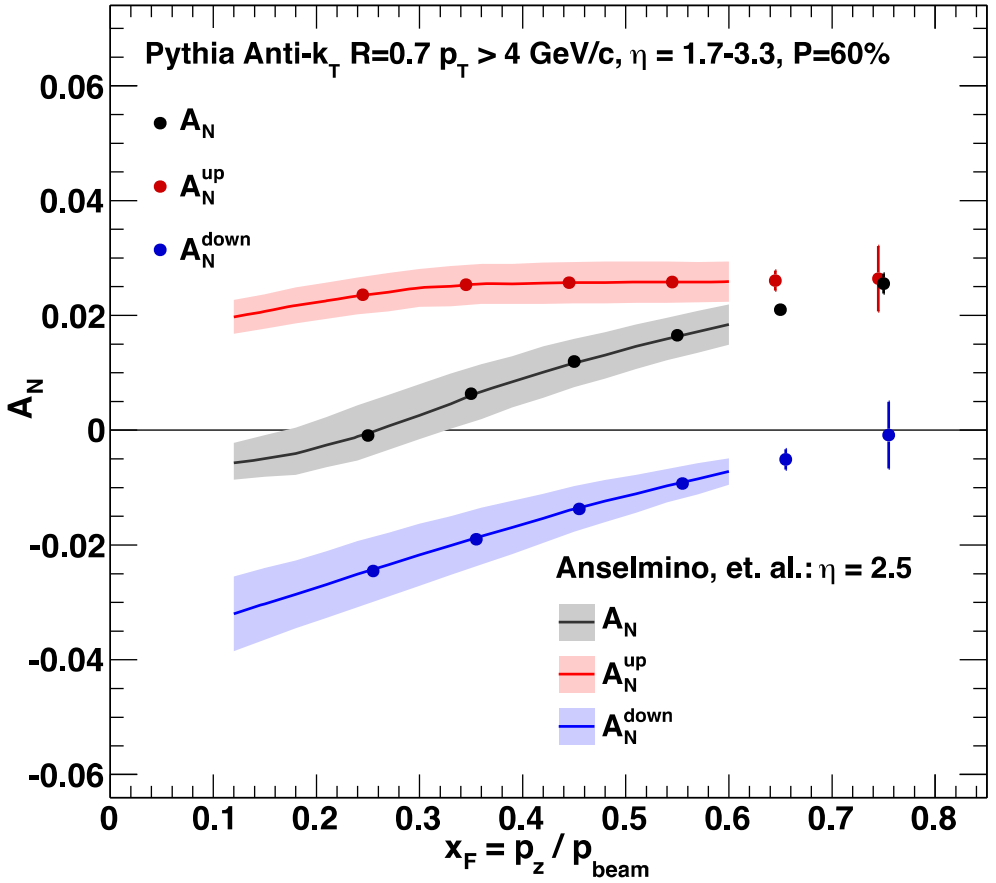




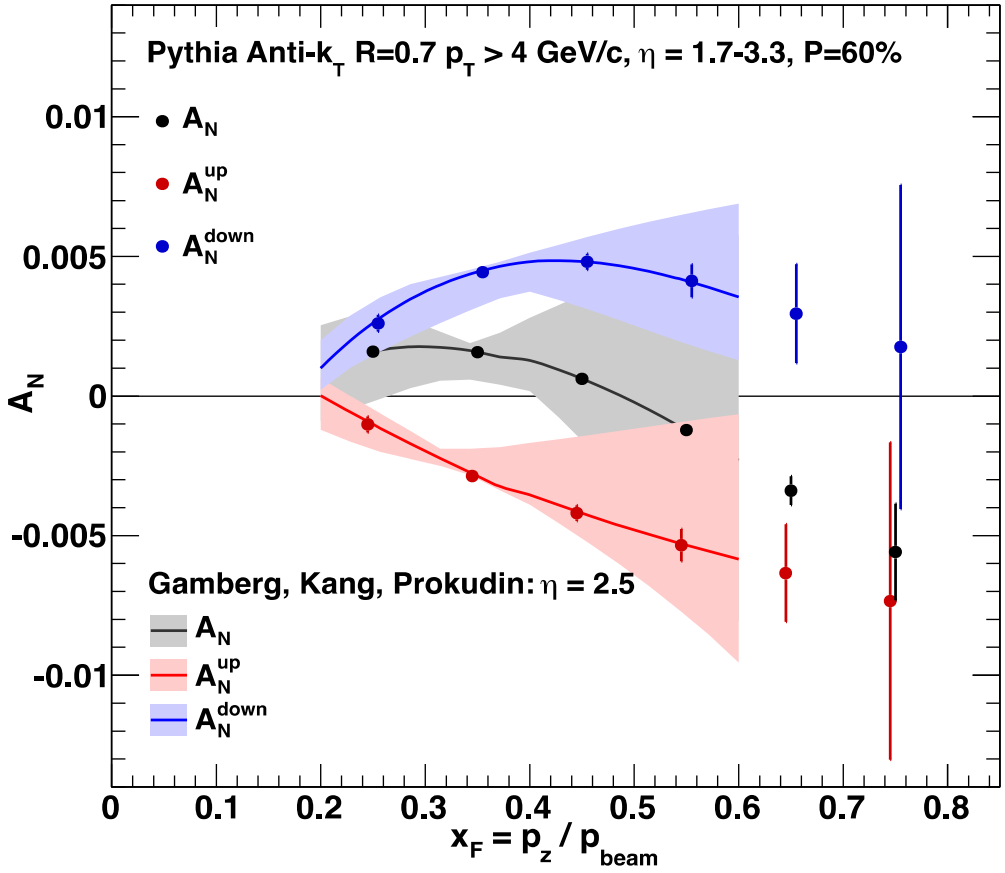
Jet TSSA: Test Process Dependence

- Change of sign in flavor-tagged Jet TSSA

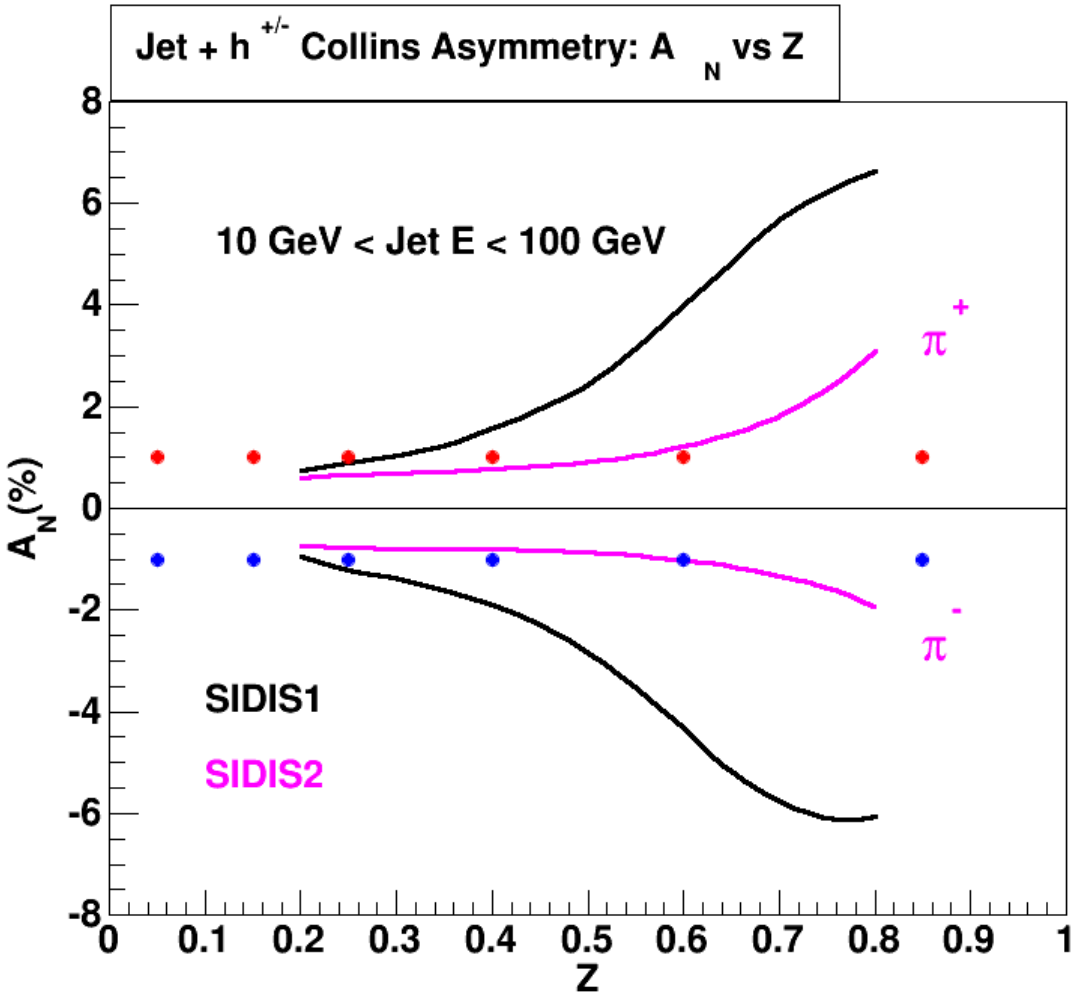
Naïve DIS Fit Sivers



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



Hadron Collins Asymmetry in Jets



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

Collins asymmetry on proton

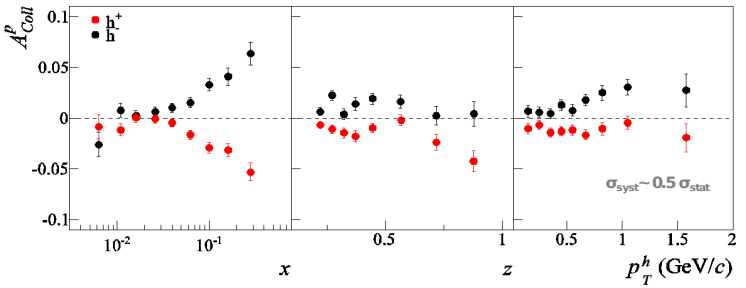
COMPASS

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

Observations and Comments

- Twist-3 and TMD Parton Model
  - Color gauge approach
  - Works reasonably well in their own kinematic domains
- Quark sector: good knowledge
  - Quark Sivers and Collins functions
  - Twist-3 quark-gluon correlation functions
- Gluon sector: largely unknown
  - Gluon Sivers function(s)??
  - Twist-3 tri-gluon correlation functions
- Next experimental steps for p+p
  - Heavy quark probe!
    - Directly access the color charge coupling to quark and anti-quark
  - Multi probes in a wide kinematic range
    - Drell-Yan, W/Z, direct-photon etc.
- It is all about the color dynamics in hard scattering
  - TSSA @RHIC-SPIN
  - p/d+A @RHIC
  - Jlab-12, EIC...

PHENIX -> Forward/sPHENIX->ePHENIX

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

Current PHENIX	*f*/*s*PHENIX	An EIC detector
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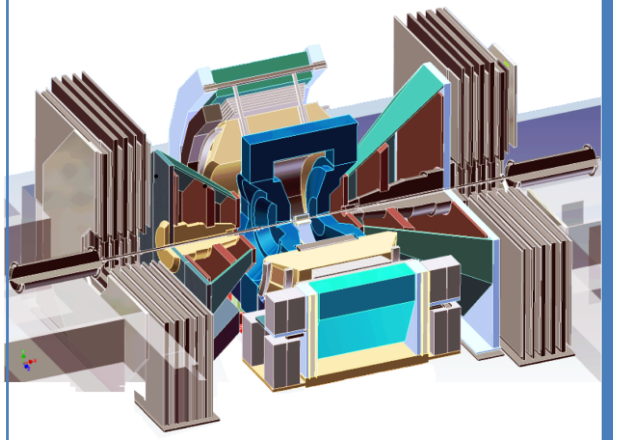
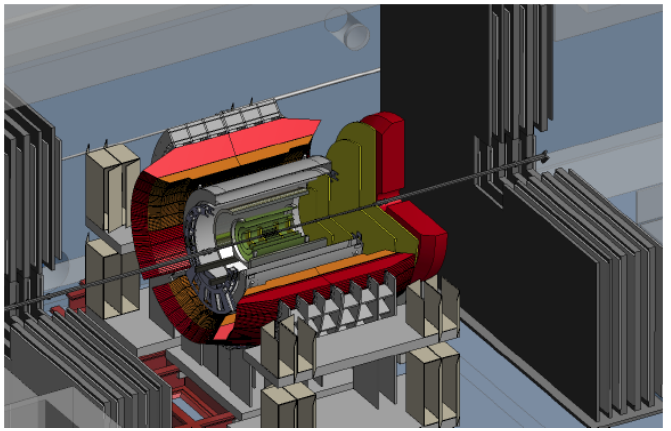
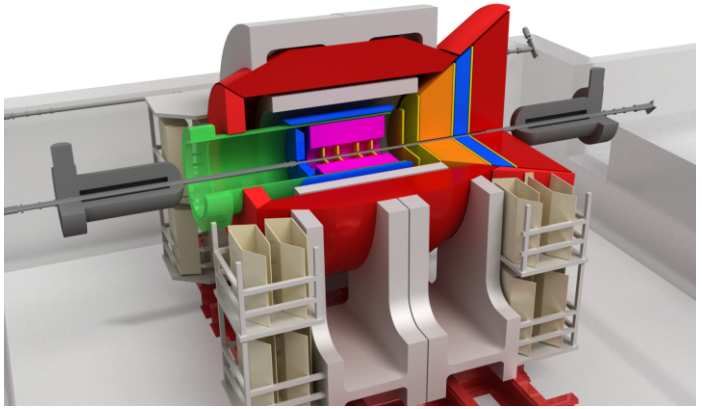






~2000 2017→2020 ~2025 Time

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

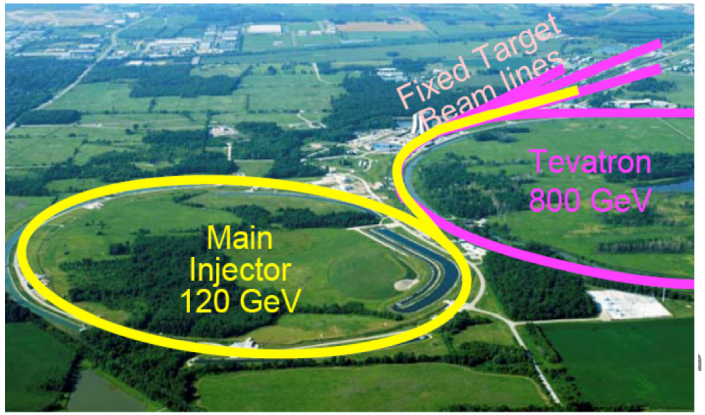
eRHIC: e+p, e+A

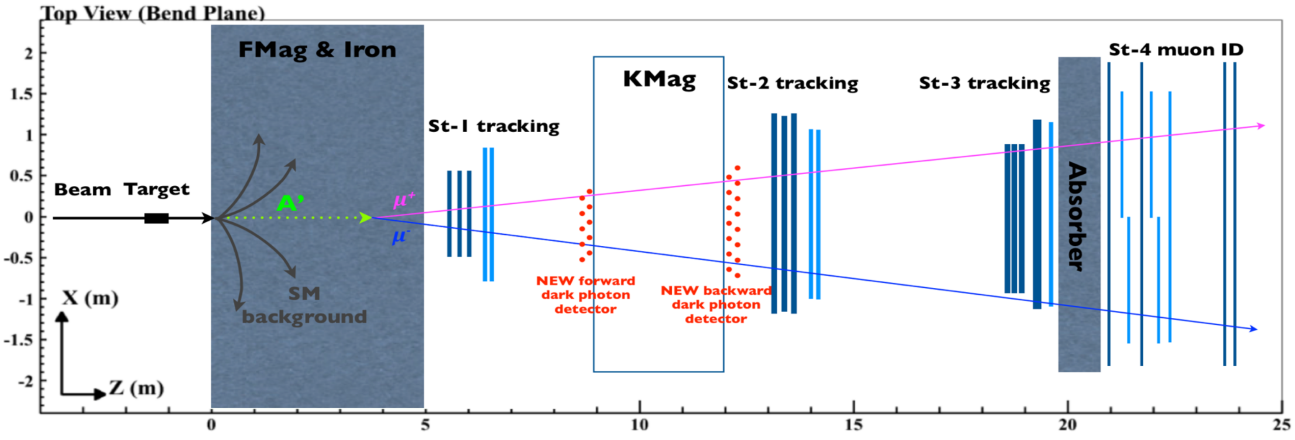
Topic-II: Dark Matter Search at Fermilab

- Dark photons
- Dark Higgs
-
- J-PARC possibility?

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

E-1067 Collaboration





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)

Collaboration:

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LOI submitted to Fermilab PAC on May 20, 2015

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

Phase-I: (focus of this presentation)

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:

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!

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

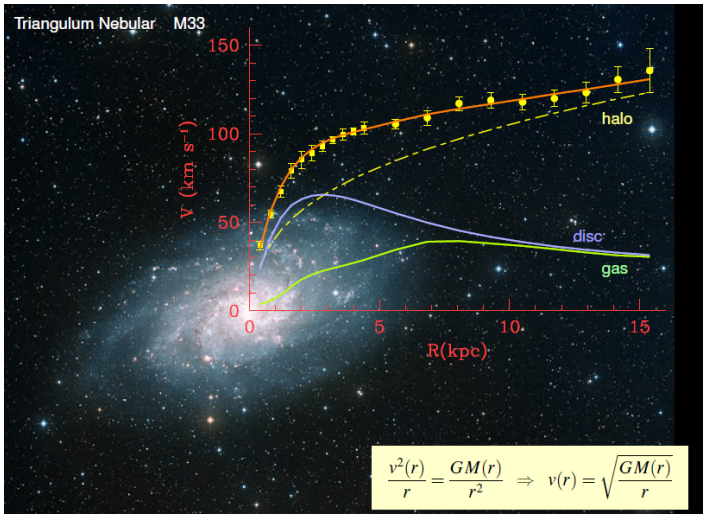
Sincerely,

Nigel S. Lockyer
Director of Fermilab

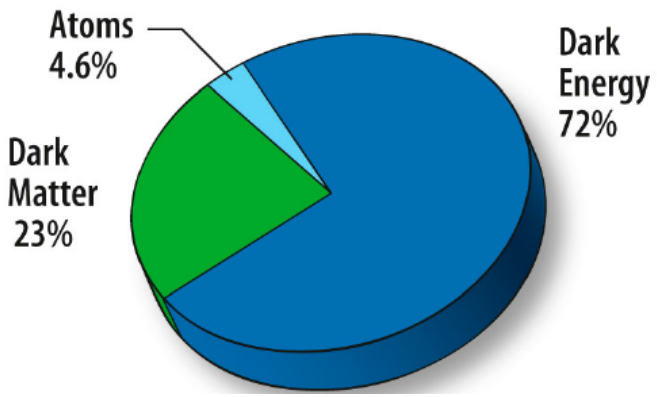
cc: D. Bortoletto, G. Bock, P. Reimer, J. Shank, S. Geer, P. McBride, D. Geesaman, J. Lykken, T. Meyer, A. Stone

Dark Matter?

Galaxies' rotation curve



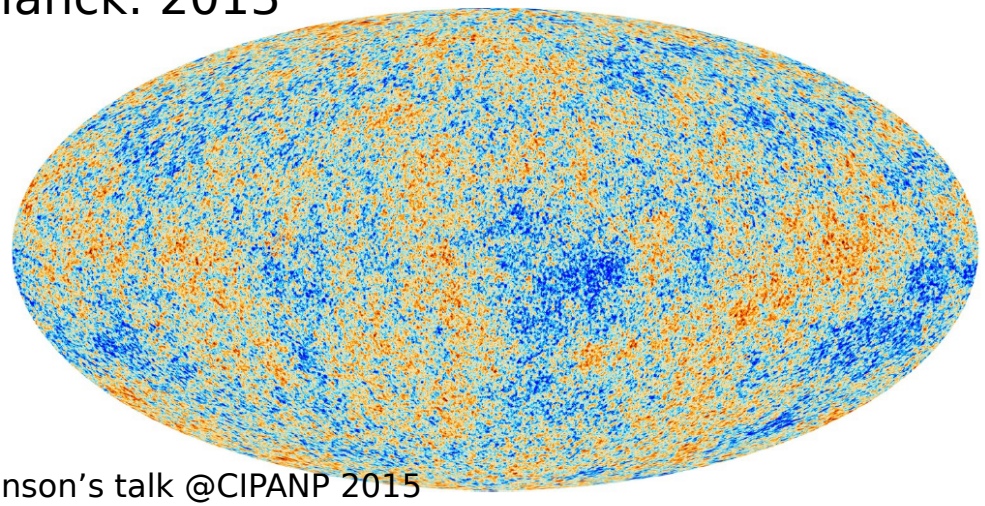
Zwicky, ApJ 86 (1937) 217, V. Rubin et al, ApJ 238 (1980) 471



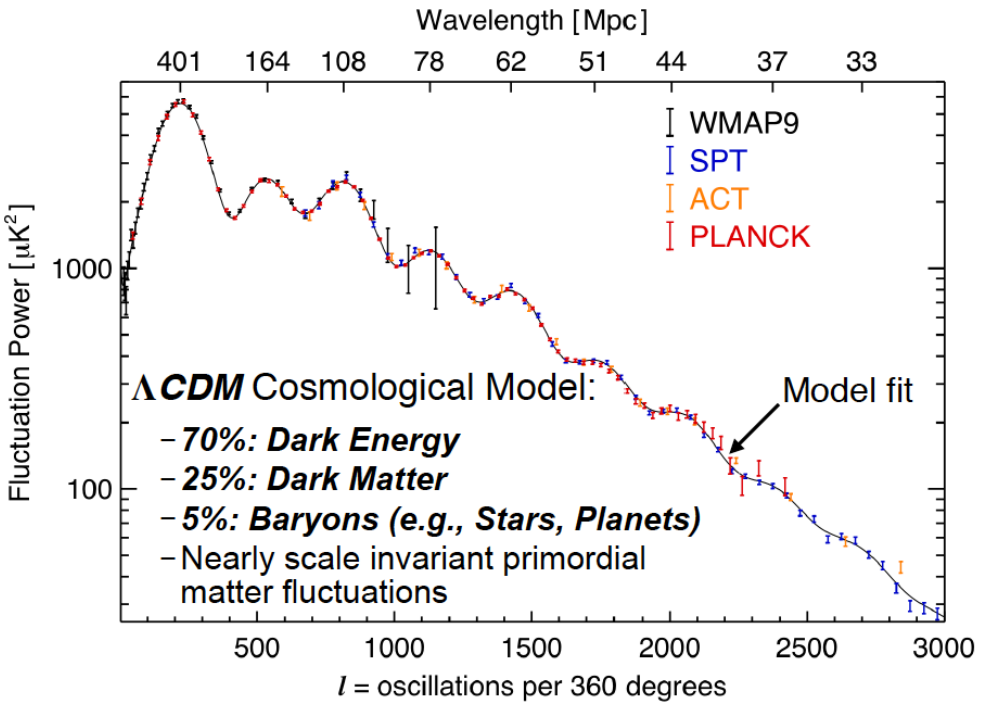
Gravitational lensing (Hubble 2007)

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

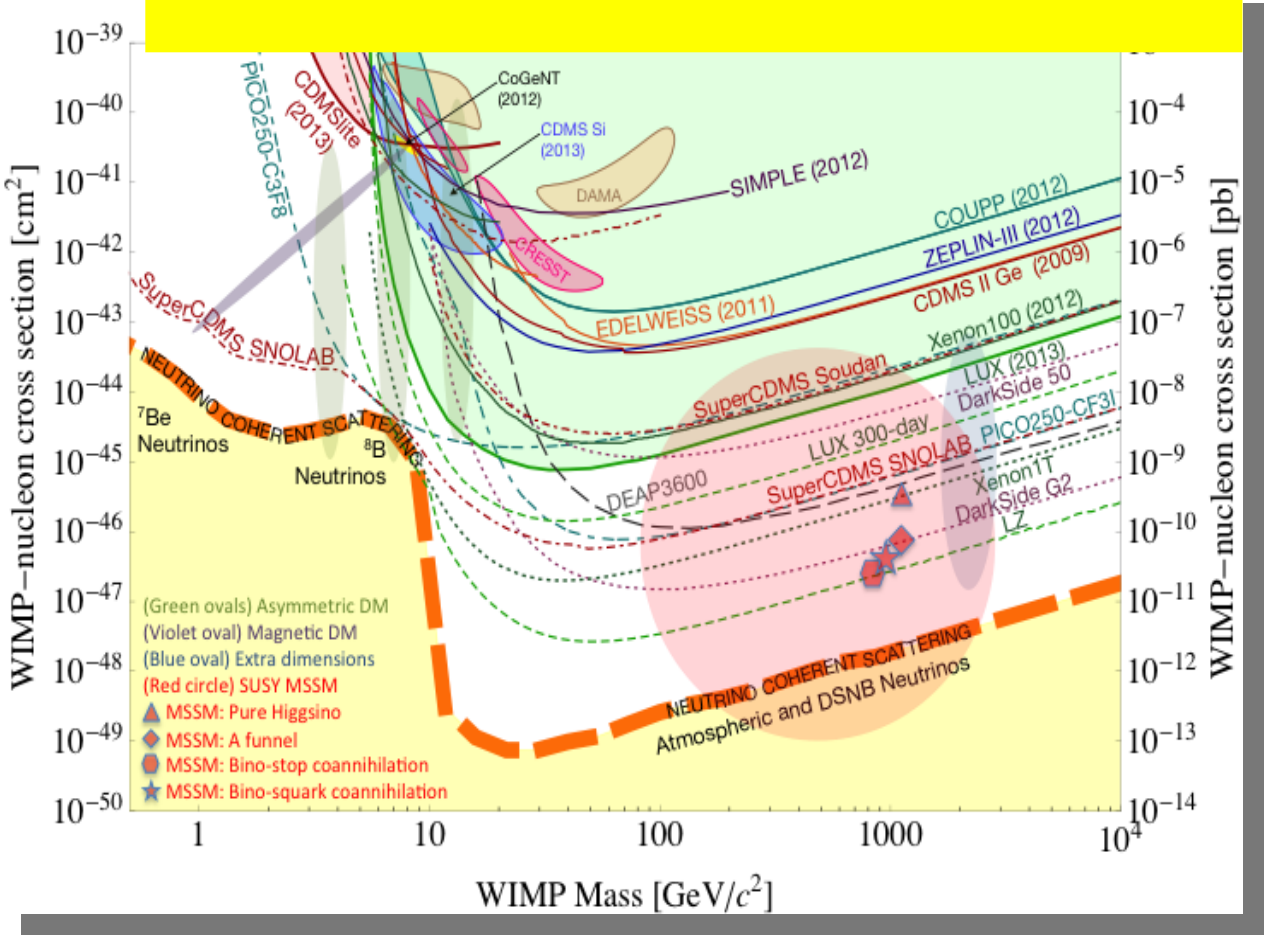
"Sub-GeV" low mass weakly-interacting dark particles become very interesting!

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"

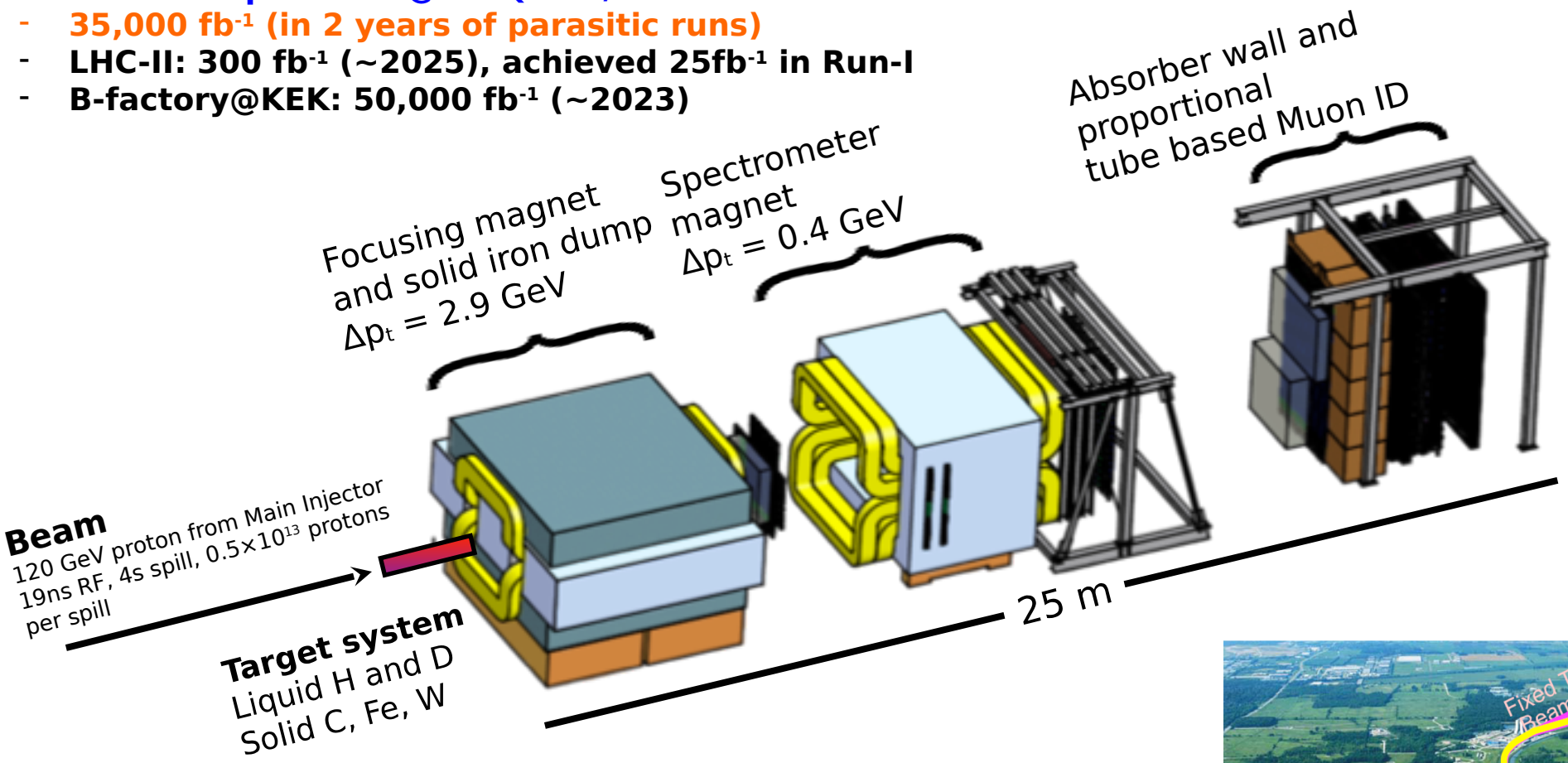
- Imaginable space for these experiments is rapidly disappearing
- the "natural" theory space is also disappearing.
- I like to think that Dark Matter is on solid ground, maybe not!!!

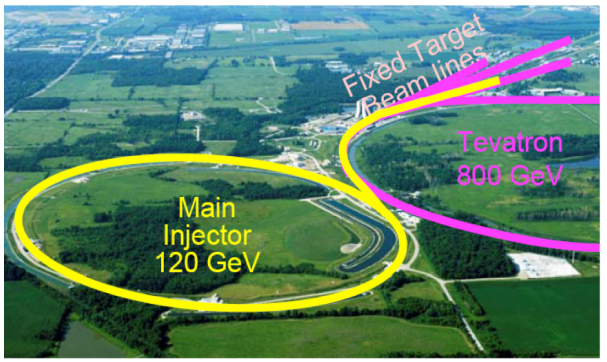


Intensity Frontier at Fermilab: 120 GeV Beam

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)**

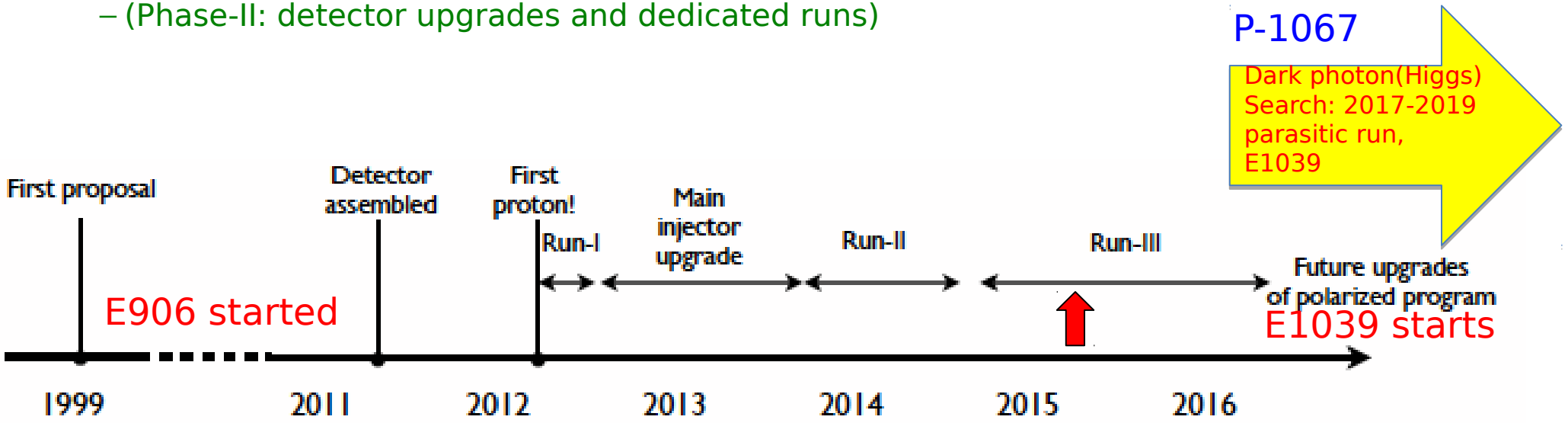




- Capture most beam in beam dump mode: p+Fe collisions!
- Parasitic run mode possible with other experiments, E1039/E1027

Schedule of SeaQuest Experiments

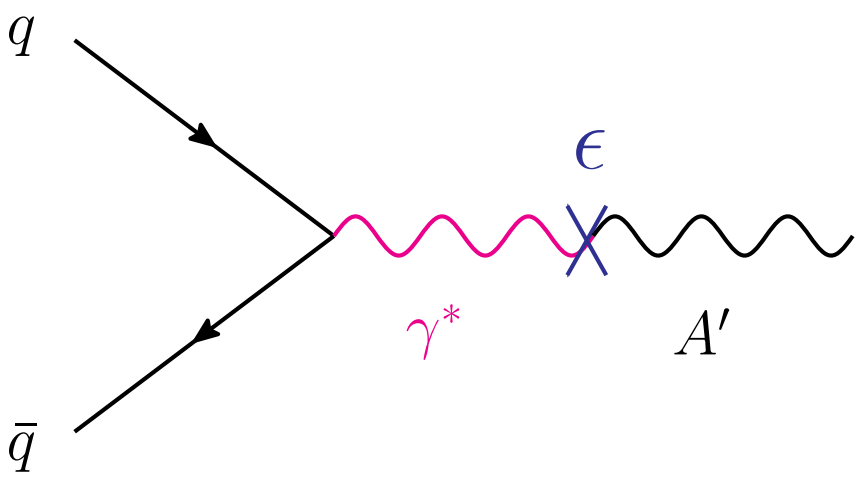
- E906 complete data taking in summer 2016
  - E906 targets are located ~1.3m upstream of the beam-dump
- E1039 will replace current E906 targets with a polarized NH_3 target.
  - No change to E906 spectrometer setup
  - New target located about 3.5m upstream of the beam-dump
- E1039 Timeline
  - Target/trigger installation: 2016 - 2017
  - Data taking: 2017 – 2019
- P1067 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

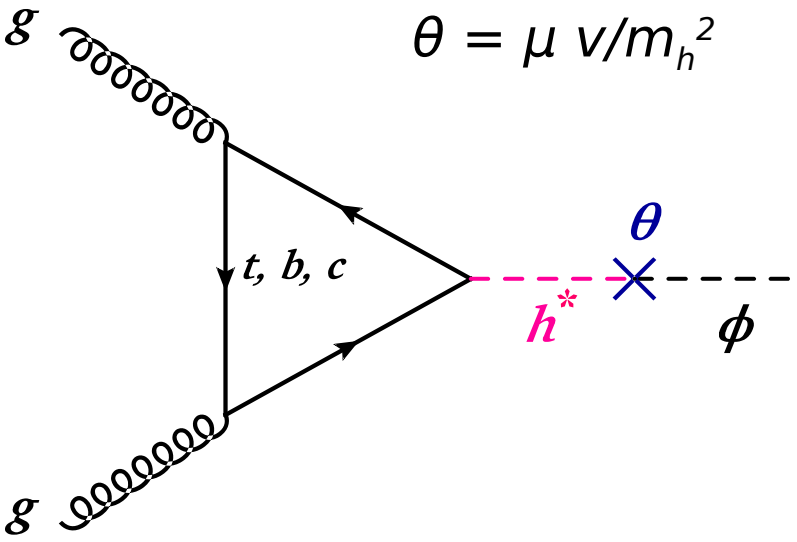
Photon portal: "vector"

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



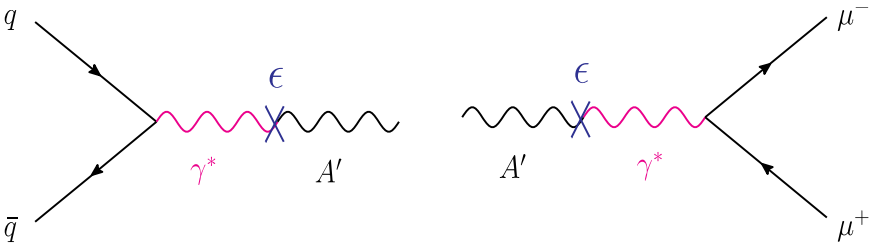
Higgs portal: "scalar"

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

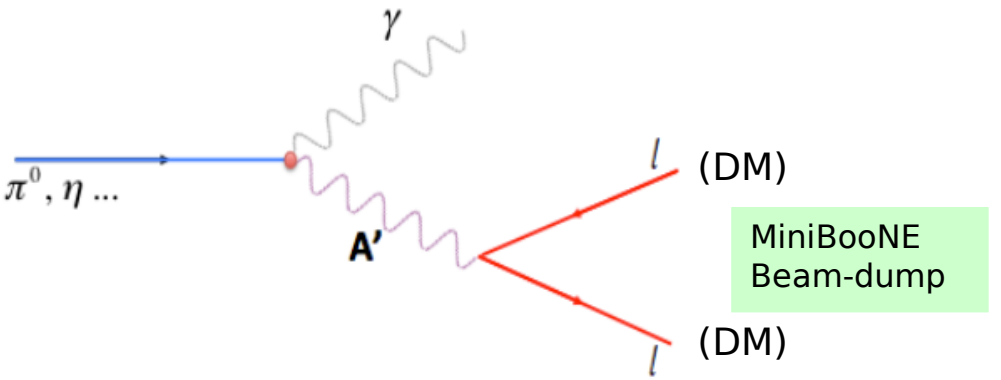


Dark Photon Search in Dimuon Channel at SeaQuest in Beam Dump Mode (p+Fe)

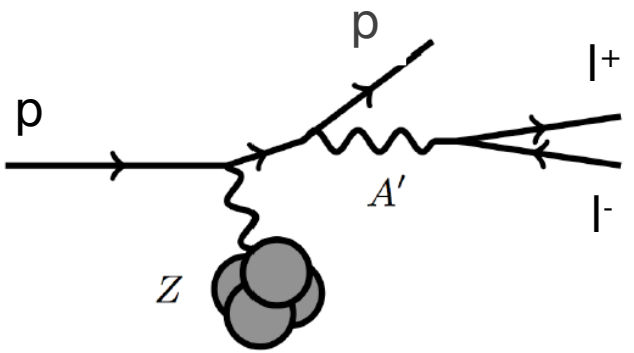
1. Drell-Yan like



2. π^0, η, … decay



3. Bremsstrahlung



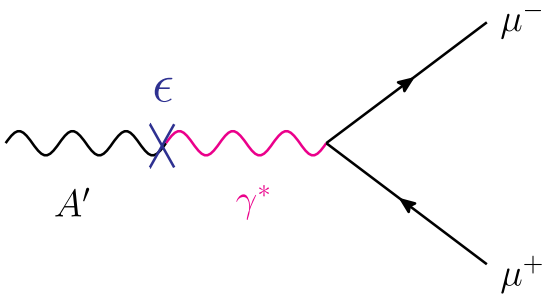
Dark Photon Decay Modes

"Minimal" Decay:

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

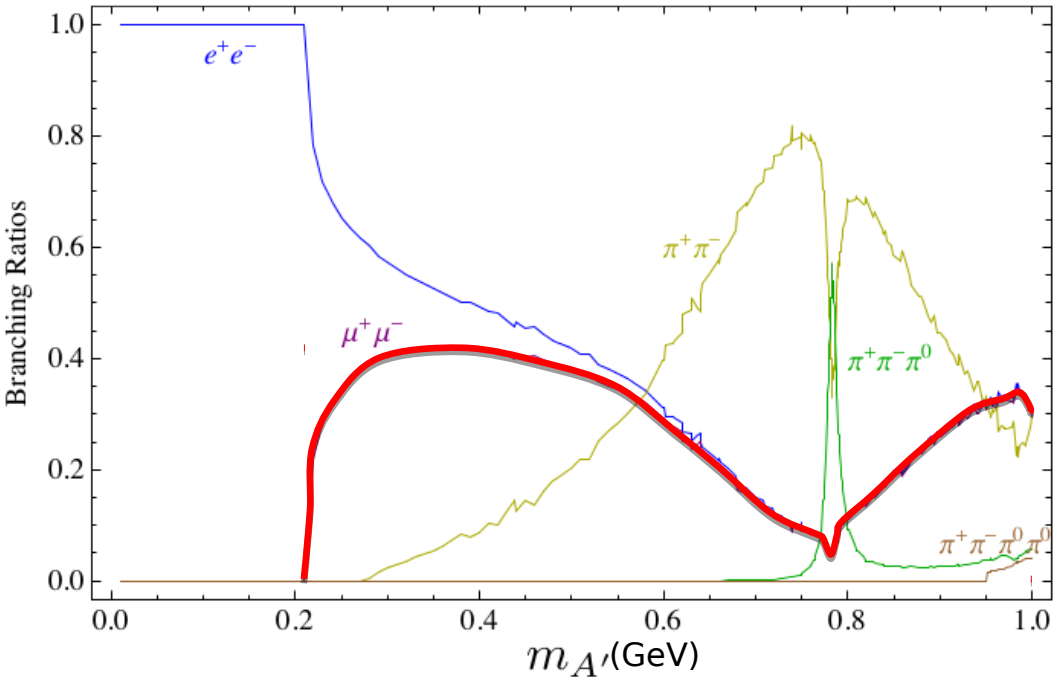
Long proper decay length: $L_0 \sim$ *O(1m)*

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



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

D. Curtin, et al, arXiv: 1312.4992



"General" Decay:

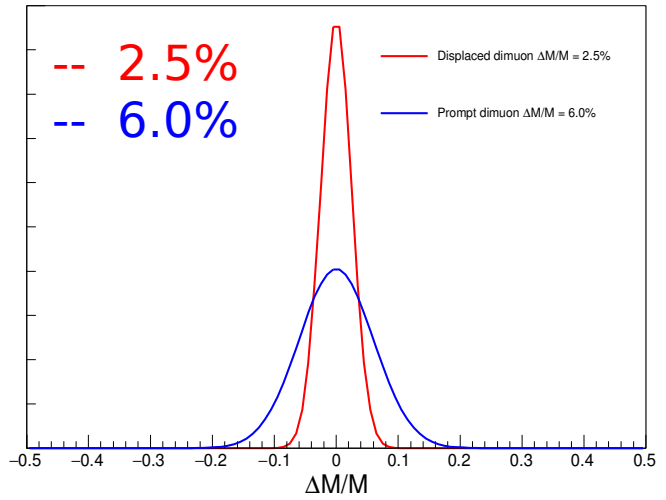
- Decay into other dark particles, dominant channel if allowed
  1. Dark -> Dark
  2. Dark -> SM particles

Proposed Experimental Measurements

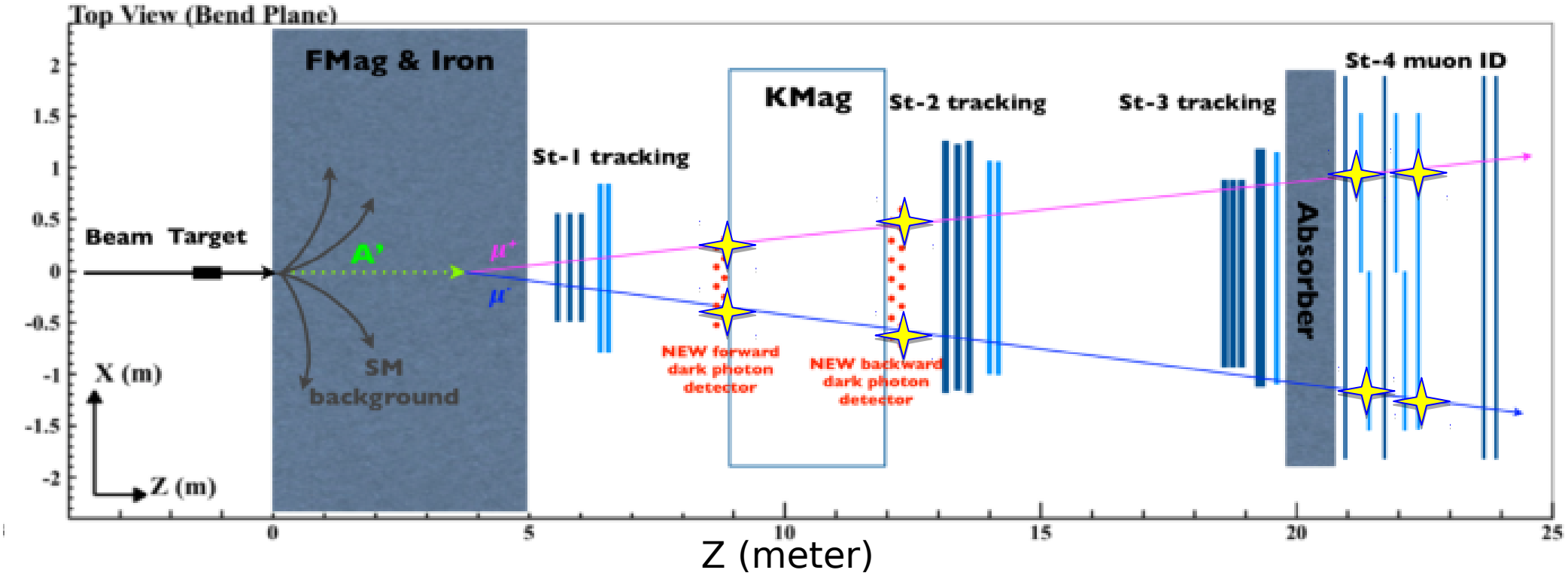
- Dark photon trigger upgrade
  1. Add a fine-granularity scintillating strip based trigger/tracking to tag dimuons from the same decay Z-vertex
  2. A new trigger for events with displaced down-stream dimuons

- 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)

-Plane Trigger:

A quadrant panel: 40 x 40 cm², 1cm thinck

- 40 x 1cm x 40 cm scintillating strips, SiPM readout

Straight line projection, 30cm Z-vertex resolution

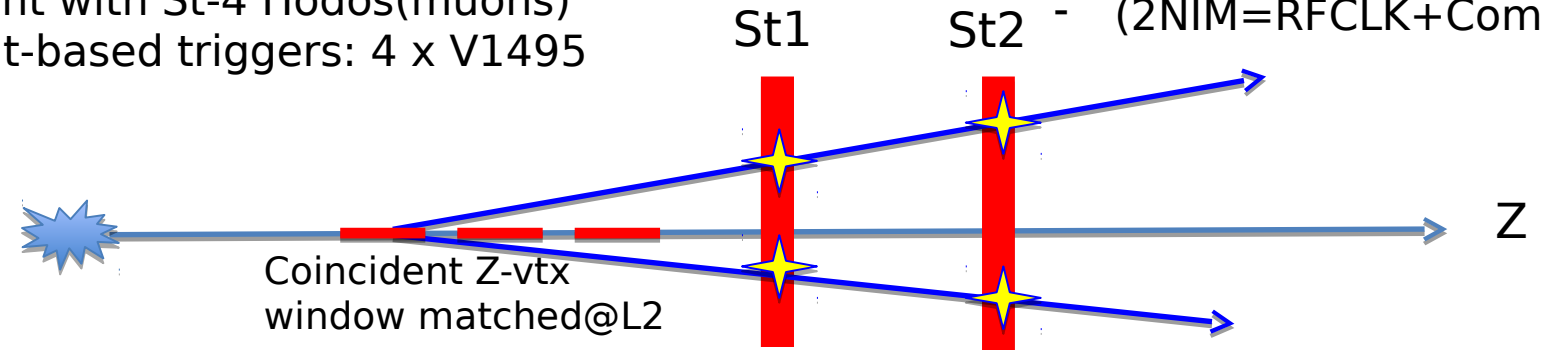
Displaced z-vertex, mostly low mass < 3GeV

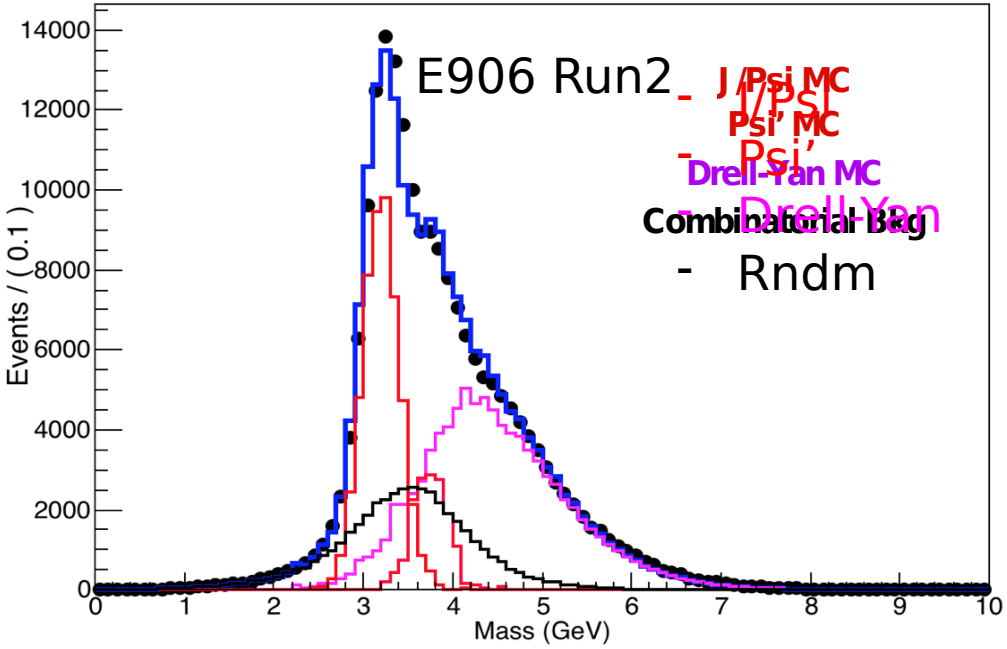
Coincident with St-4 Hodos(muons)

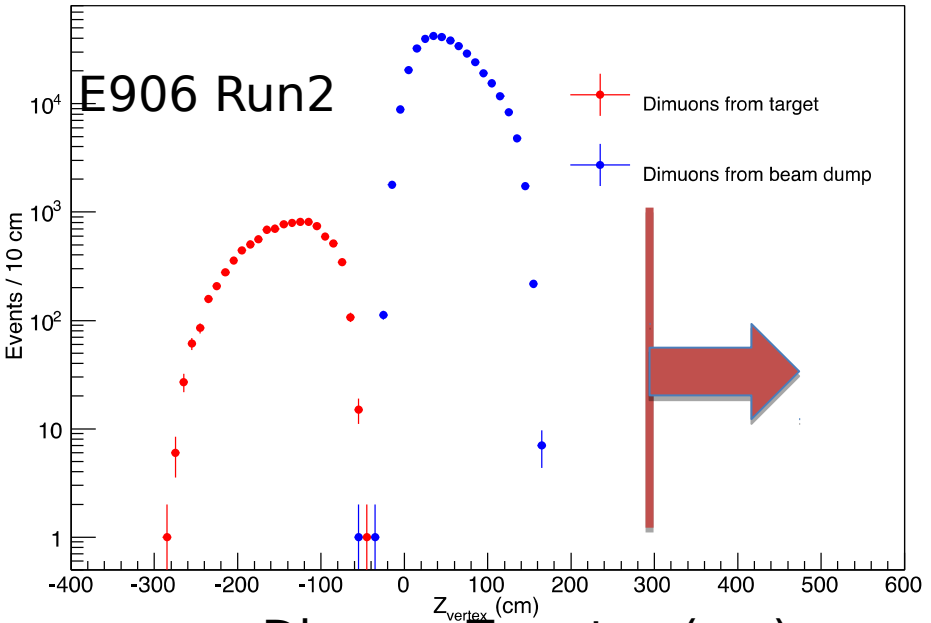
Quadrant-based triggers: 4 x V1495

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

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

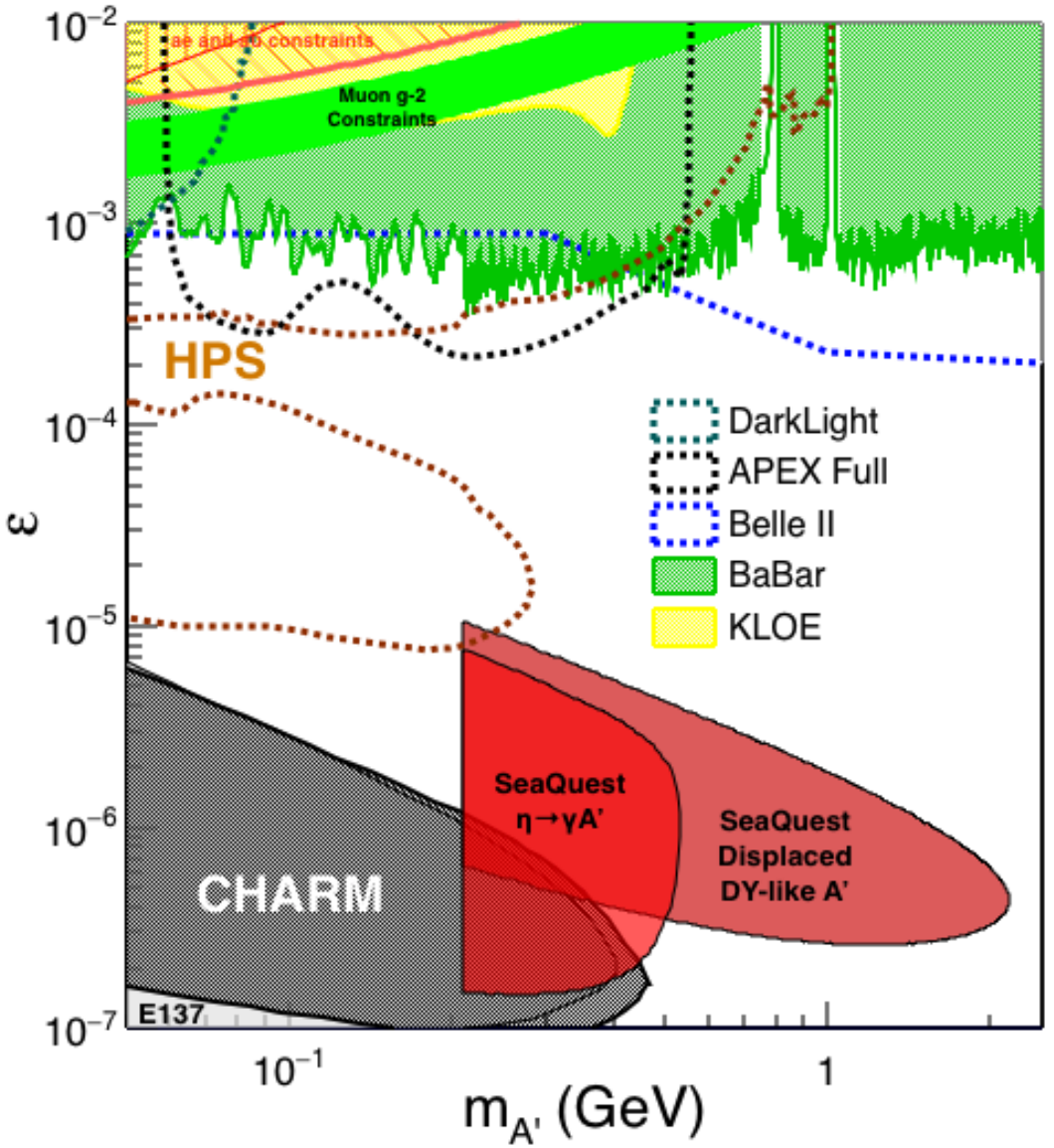
- $5x10^{12}$ ppp (current E906)
- 200 days

1.4×10^{18} POT (recorded)

- 4 events contours (2-sigma)

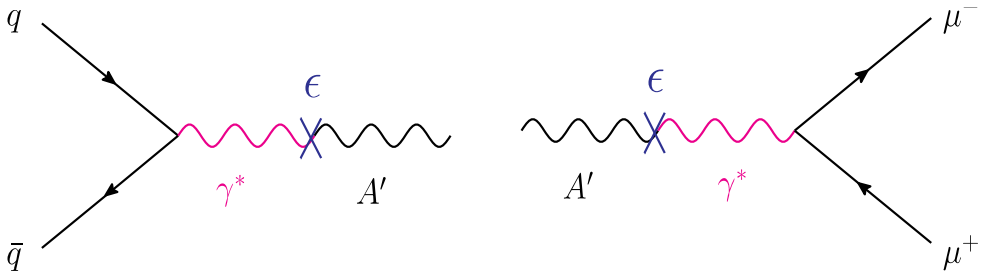
2-sigma (95%) exclusion plots

Excellent coverage of uncharted region!



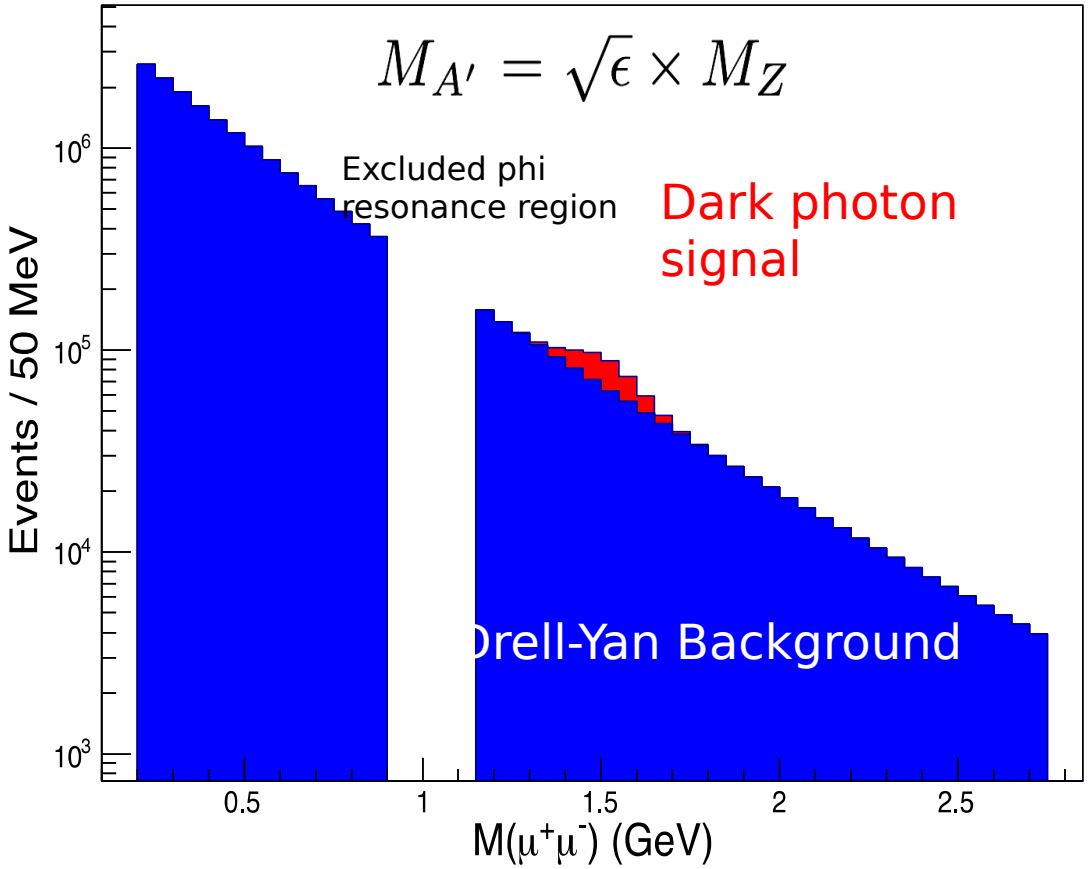
Search Mode (2): "Prompt" Dark Photons vs Drell-Yan

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

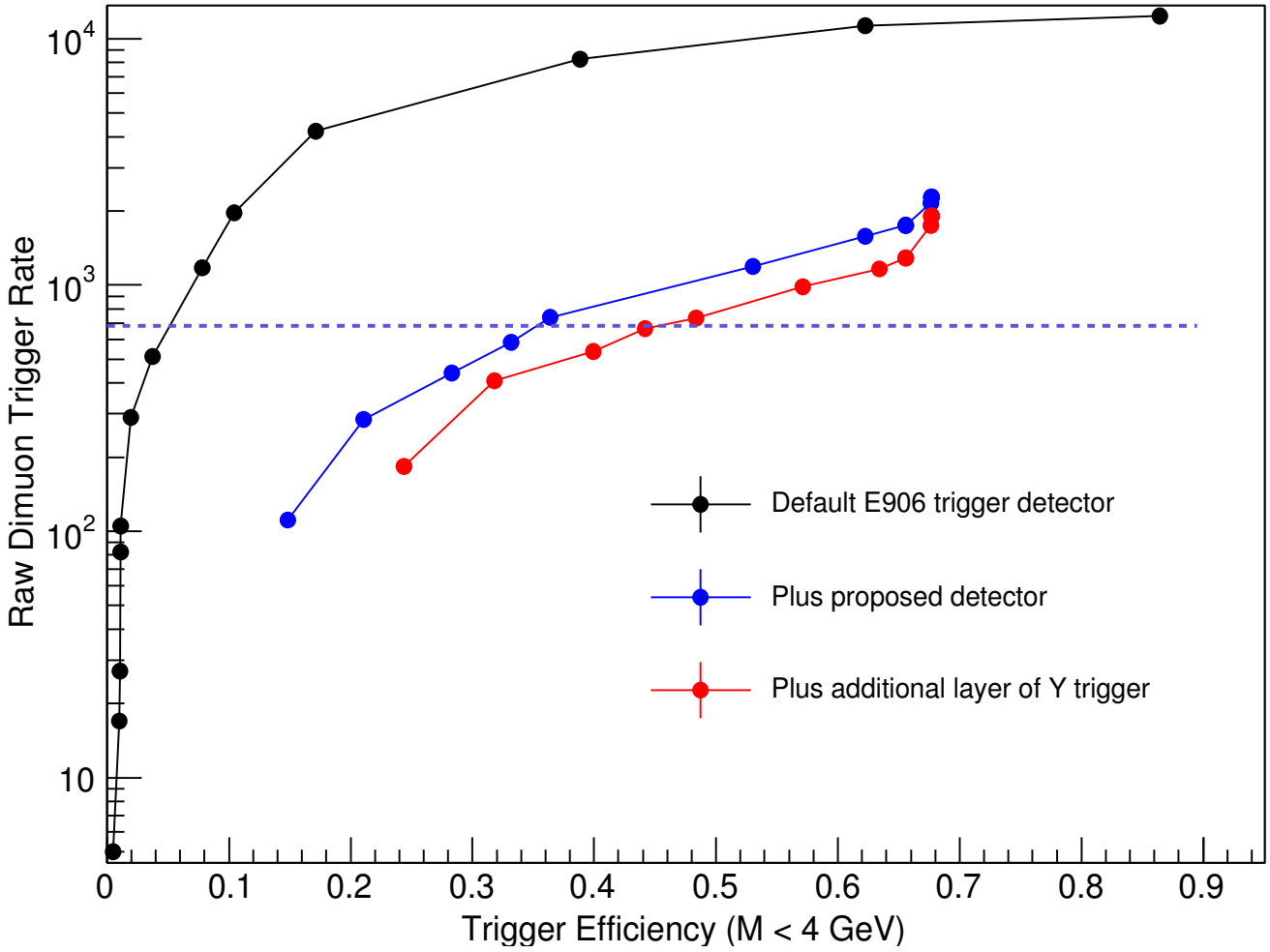
Low Mass Prompt Dimuon Trigger Rate Study

- Current E906 setup
- Proposed 2-layer trigger upgrade (10x improvement)
- Additional Y-trigger after ST-3 absorber, and also using existing E906 X-Plane trigger (additional ~2x improvement)

- Current E906 DAQ 1kHz, can be improved to 10kHz with small cost

- 200kHz possible in the future (reprograming trigger firmware etc.)

Parasitic mode: use up to ~10% DAQ bandwidth



(Prompt)Low mass dimuon trigger efficiency

Dark Photon Sensitivity: Summary

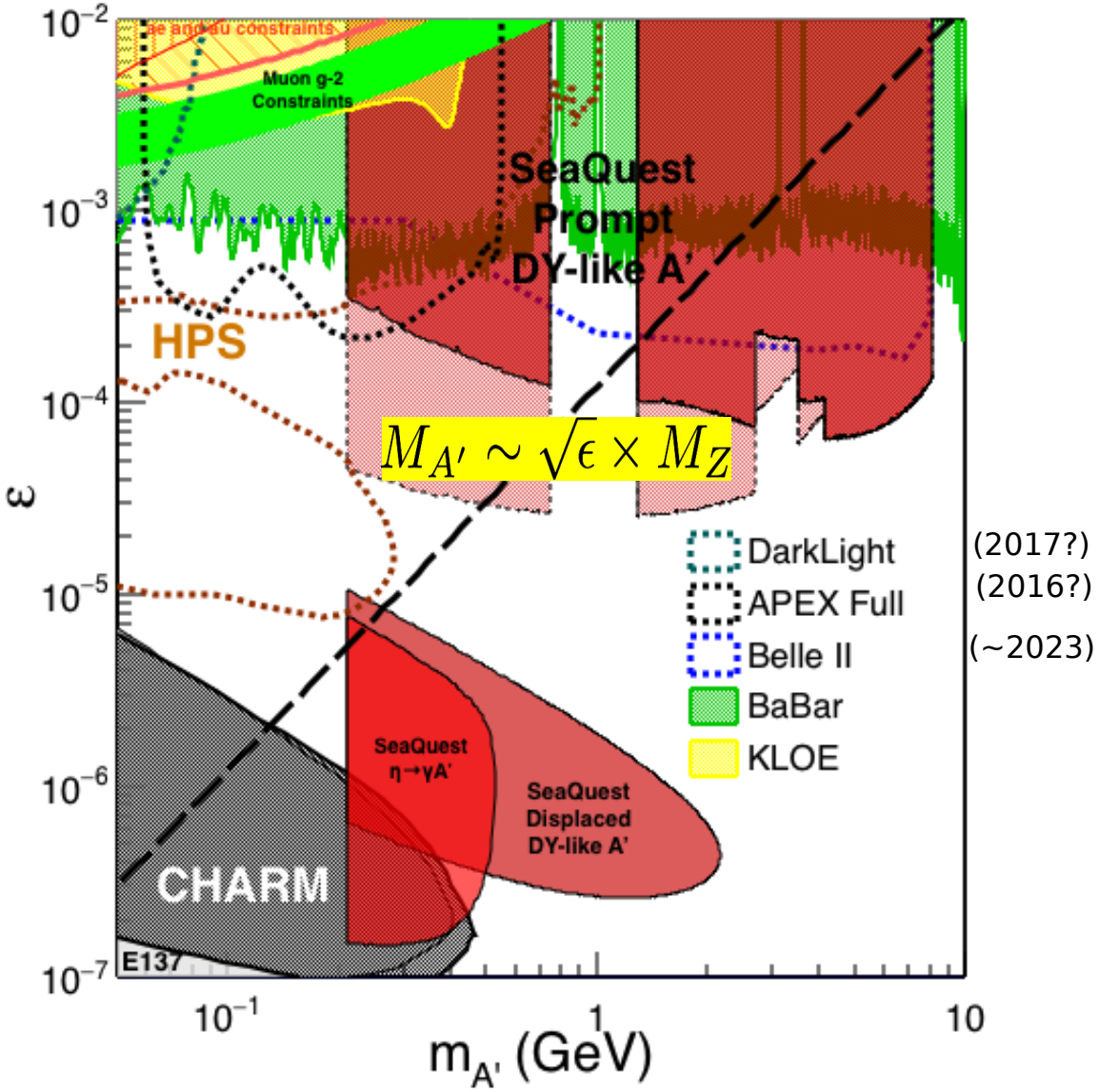
POT:1.4x10^{18} (parasitic w/ E1039)

Signals considered:

- Drell-Yan like
- Eta decays
- Bremsstralung

Covers a wide range of unexplored parameter phase space

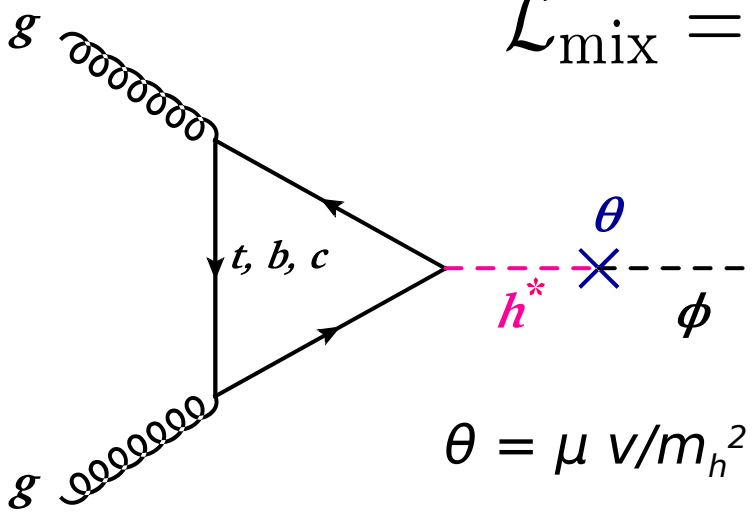
- Displaced dimuons
  - Minimal SM background
- Prompt dimuons
  - Excellent coverage over BELLE-II projection
  - Possible dedicated runs later to fully restore mass < 3GeV (Phase-II)
- ***Phase-II with upgrades***
  Access below 200MeV with di-electrons (add EMCal)



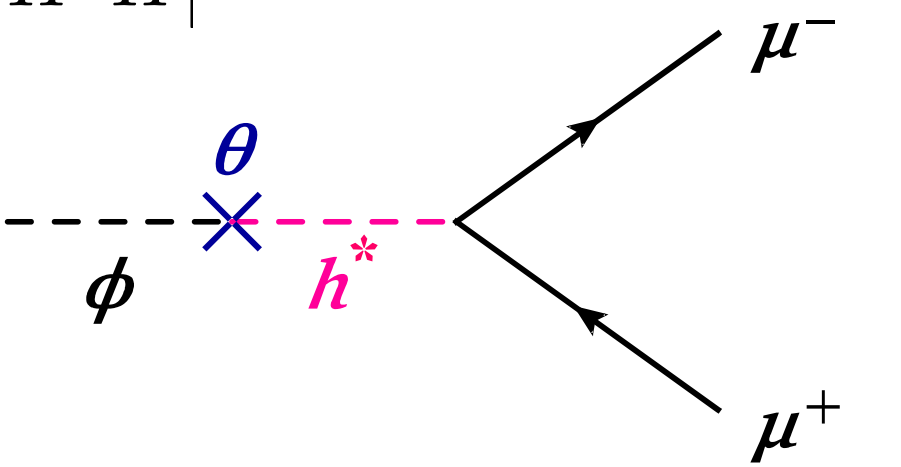
Dark Higgs Search at SeaQuest

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

Y. Zhang et al, arXiv:1502.06983



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



D. Curtin et al arXiv:1312.4992

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

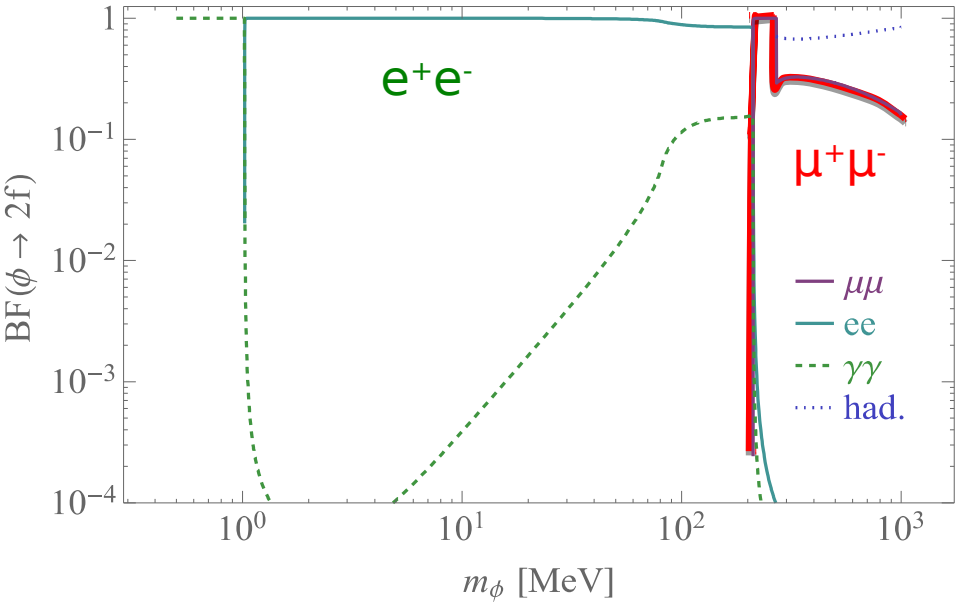
Phase-I:

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

Advantage of using hadron beams with muon probes over electrons

Phase-II:

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

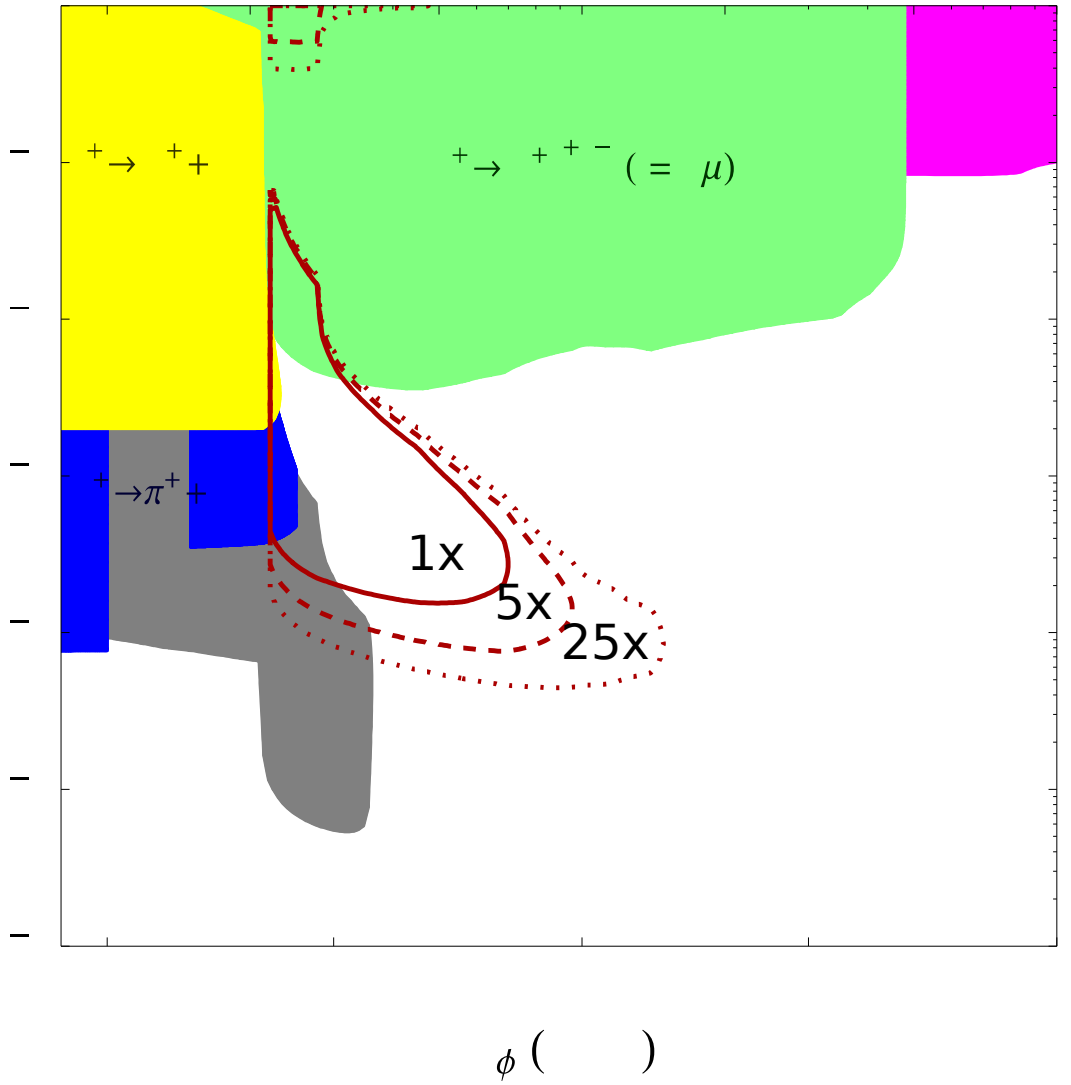


SeaQuest Dark Higgs Sensitivity

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

Y. Zhang (2015)

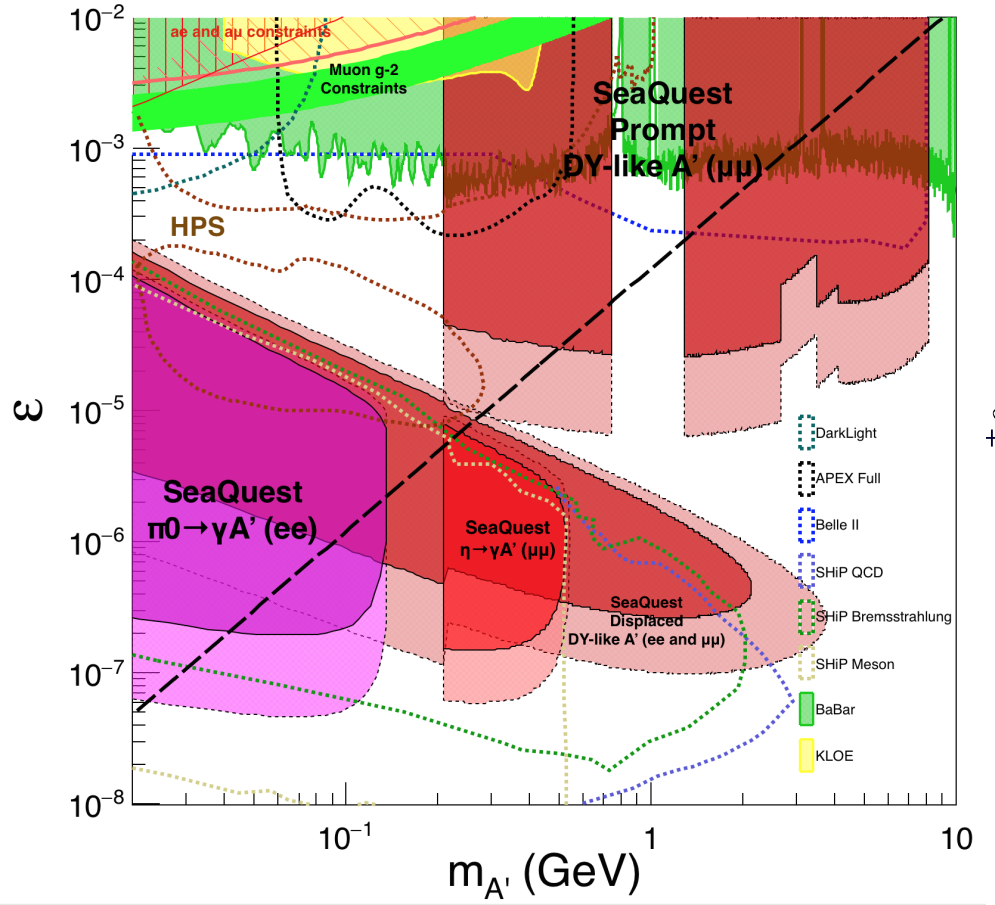
- Dimuons with downstream displaced decay vertices
- Limited sensitivity to "prompt" large mixing case due to small cross-section
- Dark Higgs or dark photons?
  - Dimuon kinematic and angular distributions
- Phase-II
  - Dedicated high luminosity runs optimized for low mass acceptance, mass<3GeV

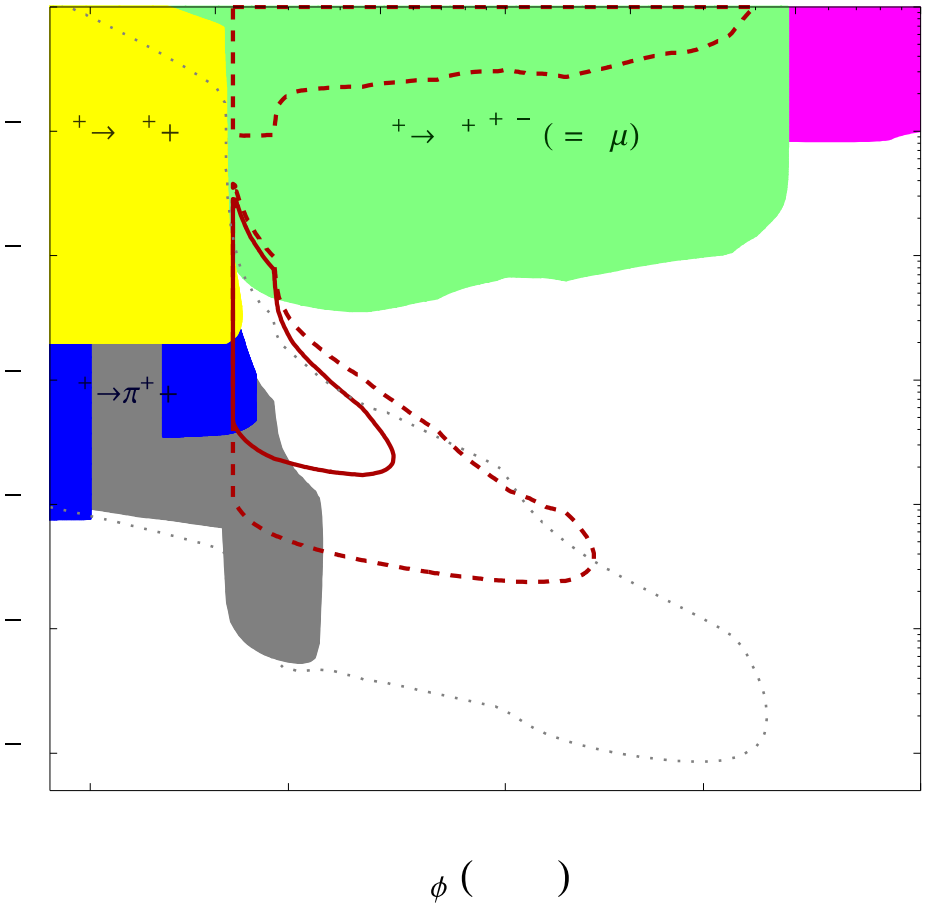


Comparison with SHiP Proposal

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

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



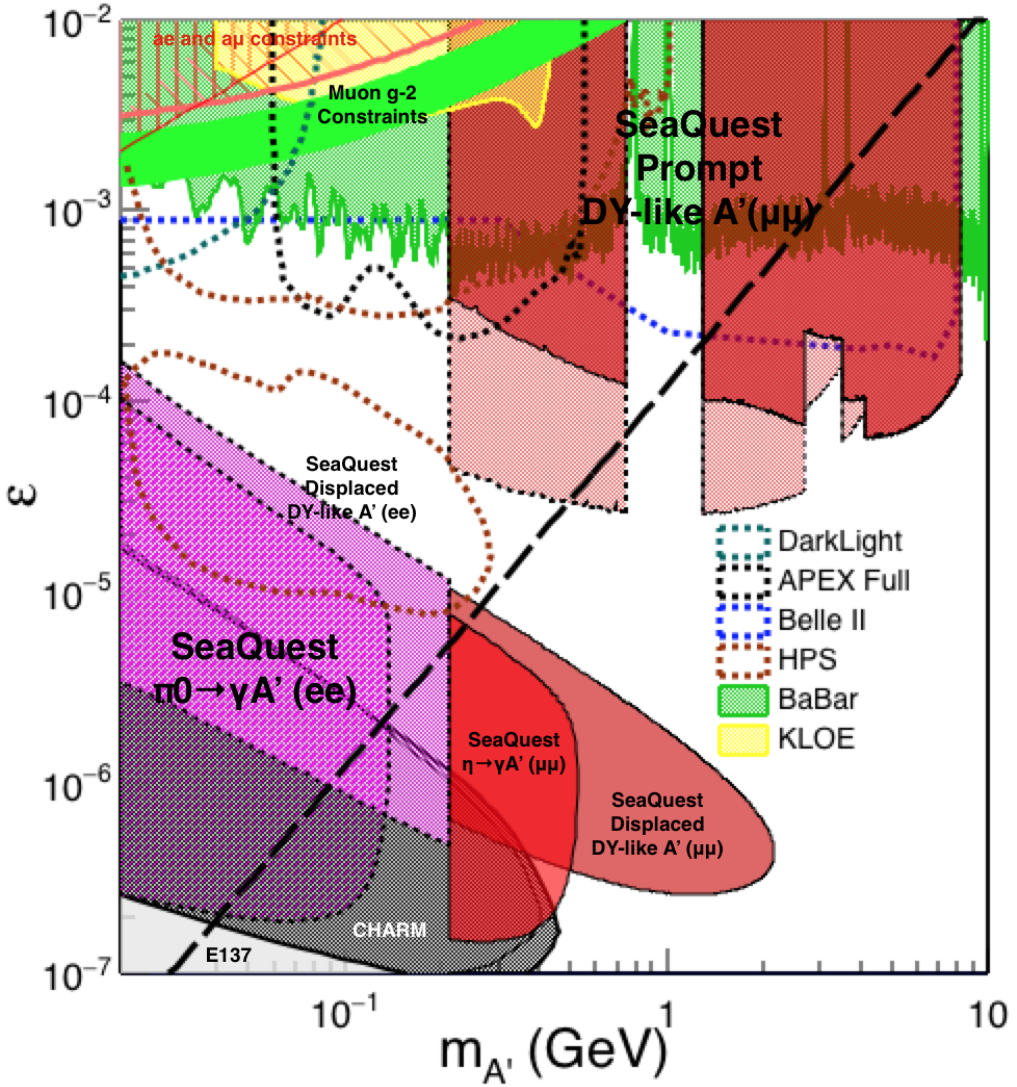


Phase-II: Full Coverage

with future detector "EMCal/HCal" upgrades

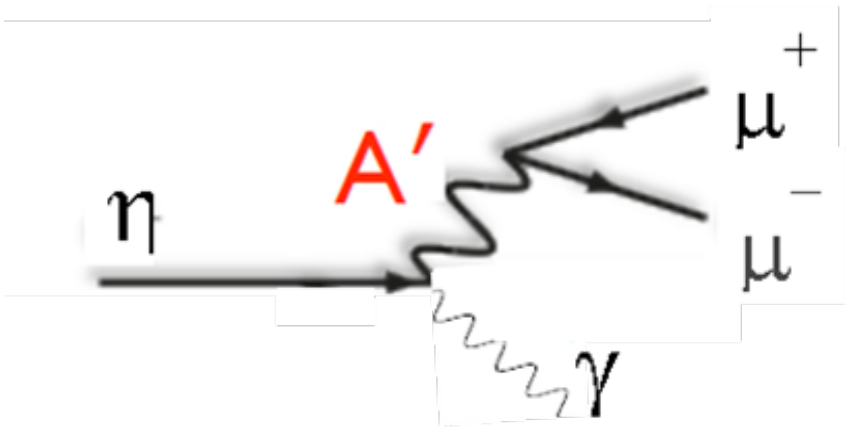
Projection: POT 1.4 x 10^{18}

- 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

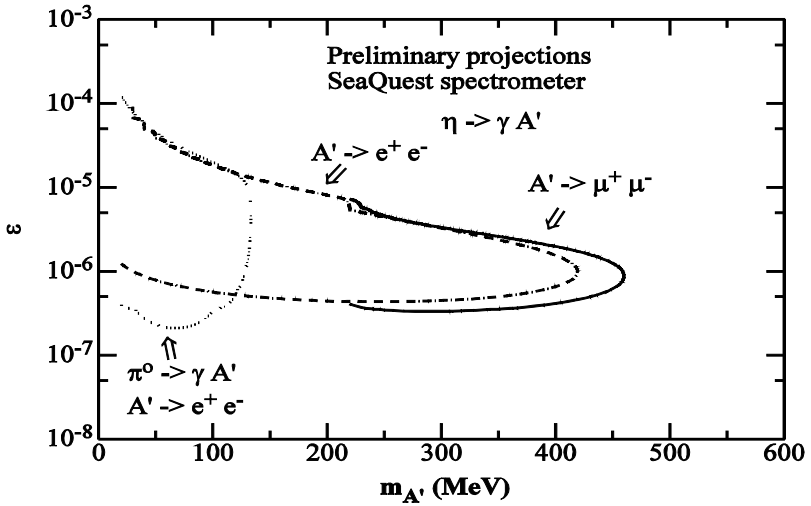


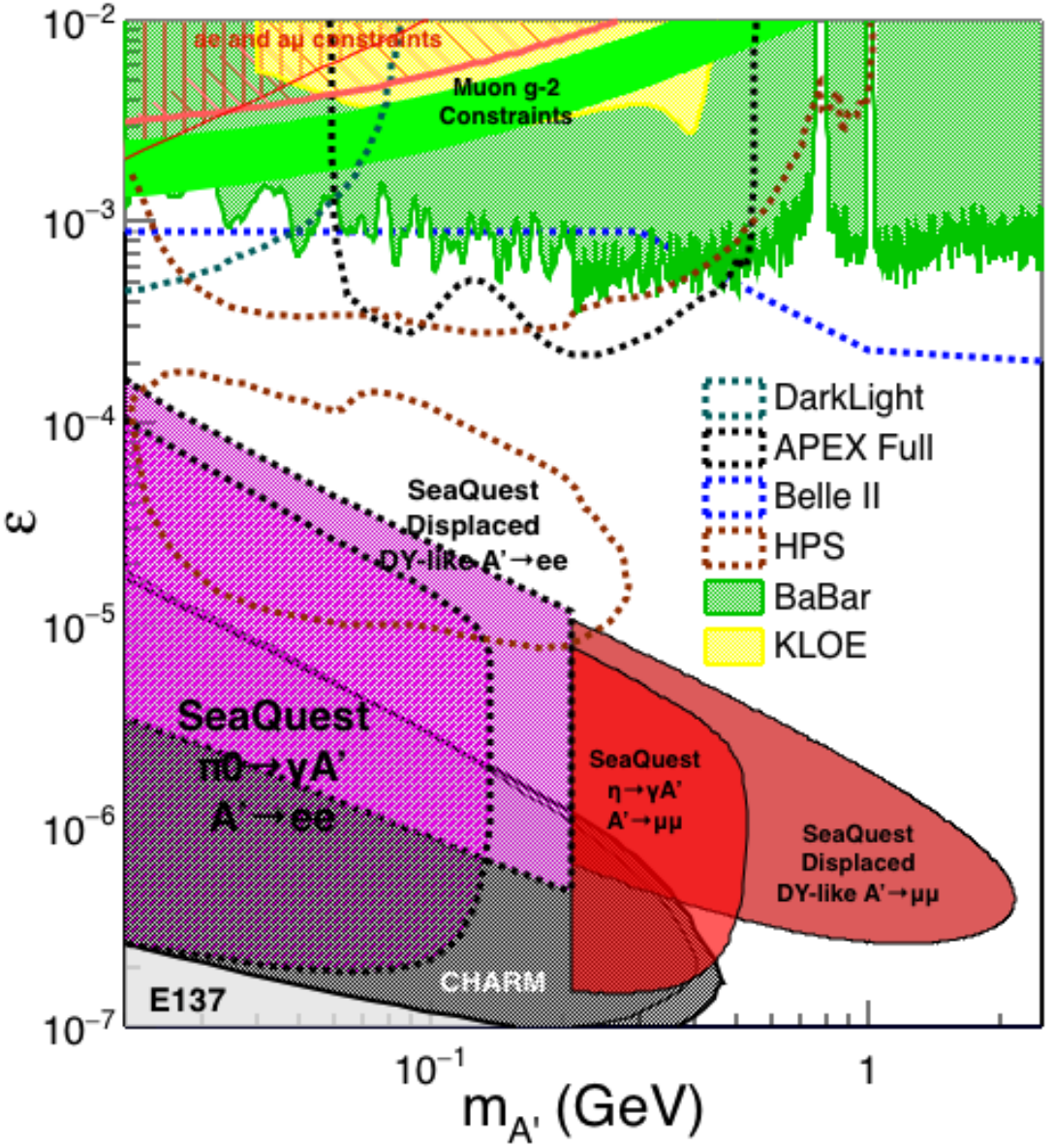
Phase-II: Access Low Mass Region with e^+e^-

with future detector "EMCal" upgrades



S. Gardner, R. Holt et al

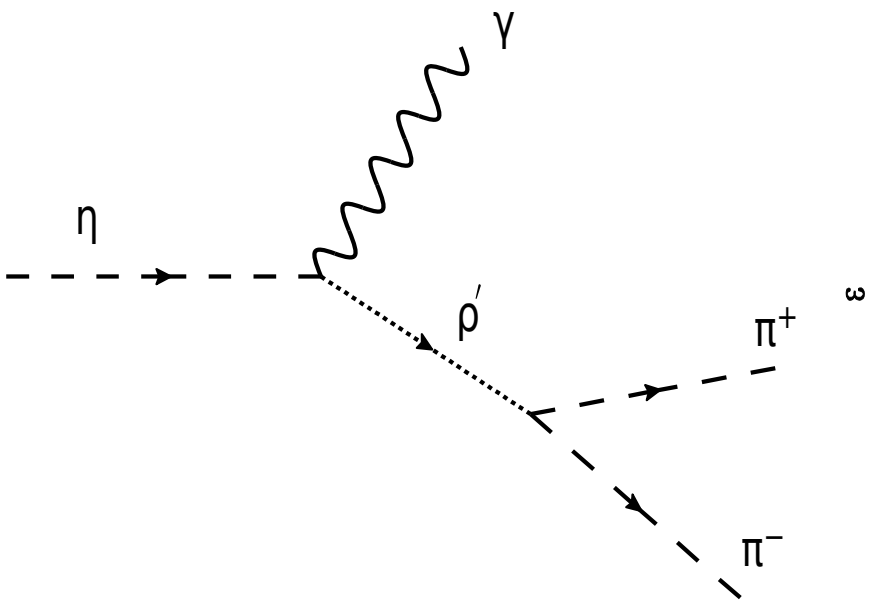




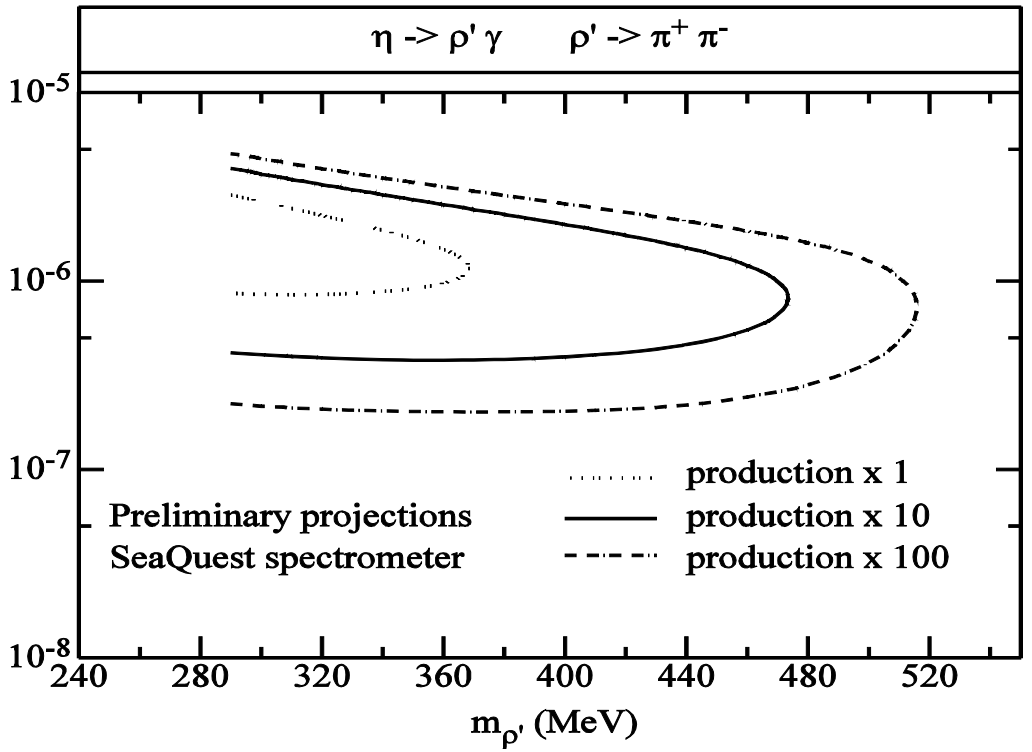
Non Abelian Dark Sector

with future detector "HCal" upgrades

non-Abelian dark sector process



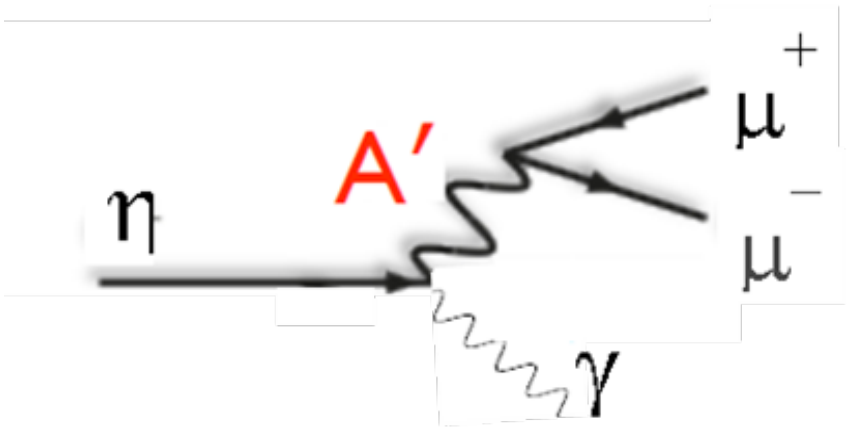
S. Gardner and R. Holt

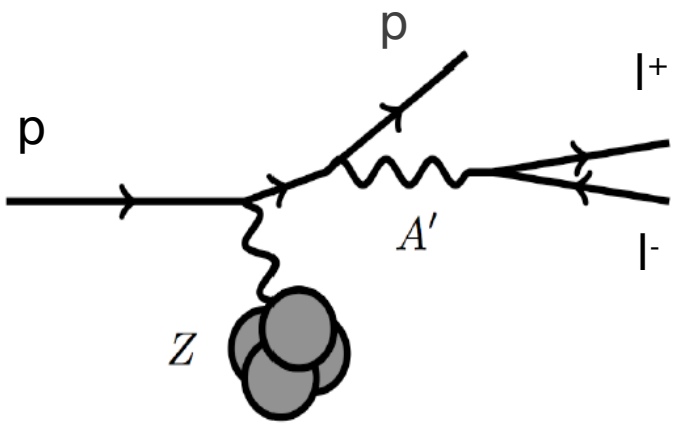


[Note: Batell, Pospelov, and Ritz, PRD 80 (2009) 095024 for a review re fixed target expts.]
Here we consider a non-Abelian (gluon) portal
[Baumgart et al., JHEP 0904, 014 (2009); Gardner and He, PRD 87 (2013) 116012]
The "shining through walls" design – unique to Seaquest – makes this possible ,
to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

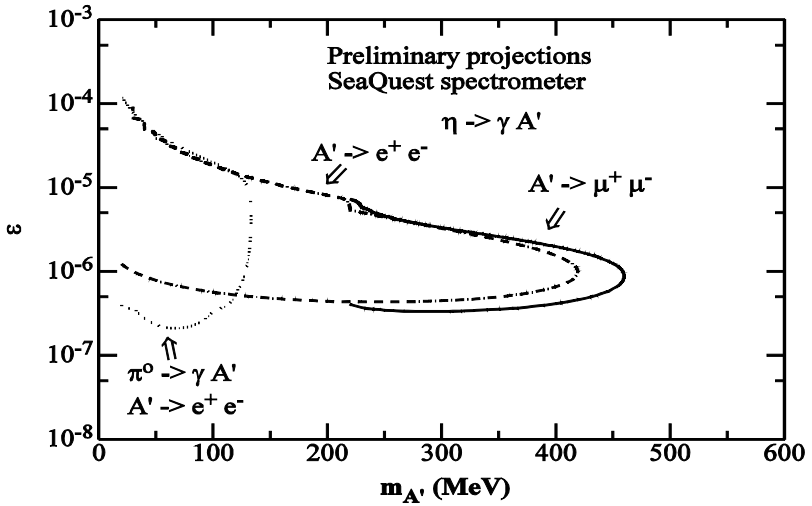
Phase-II: Access Low Mass Region with e^+e^-

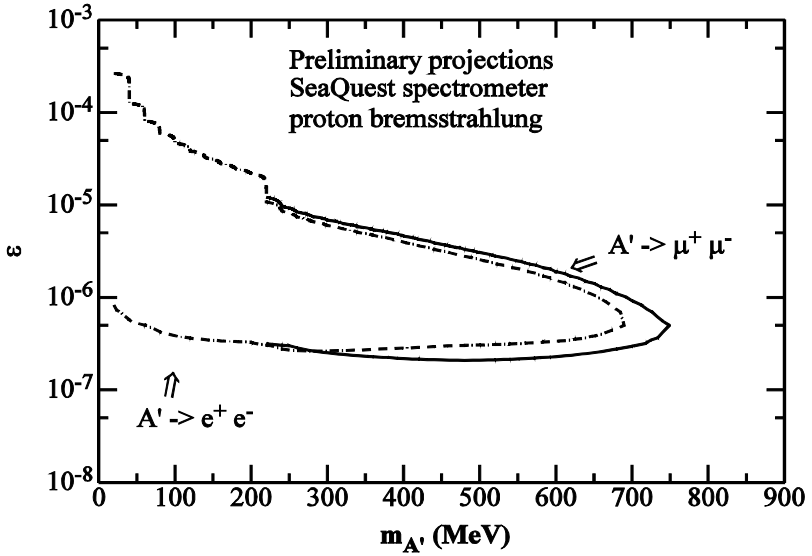
with future detector upgrades



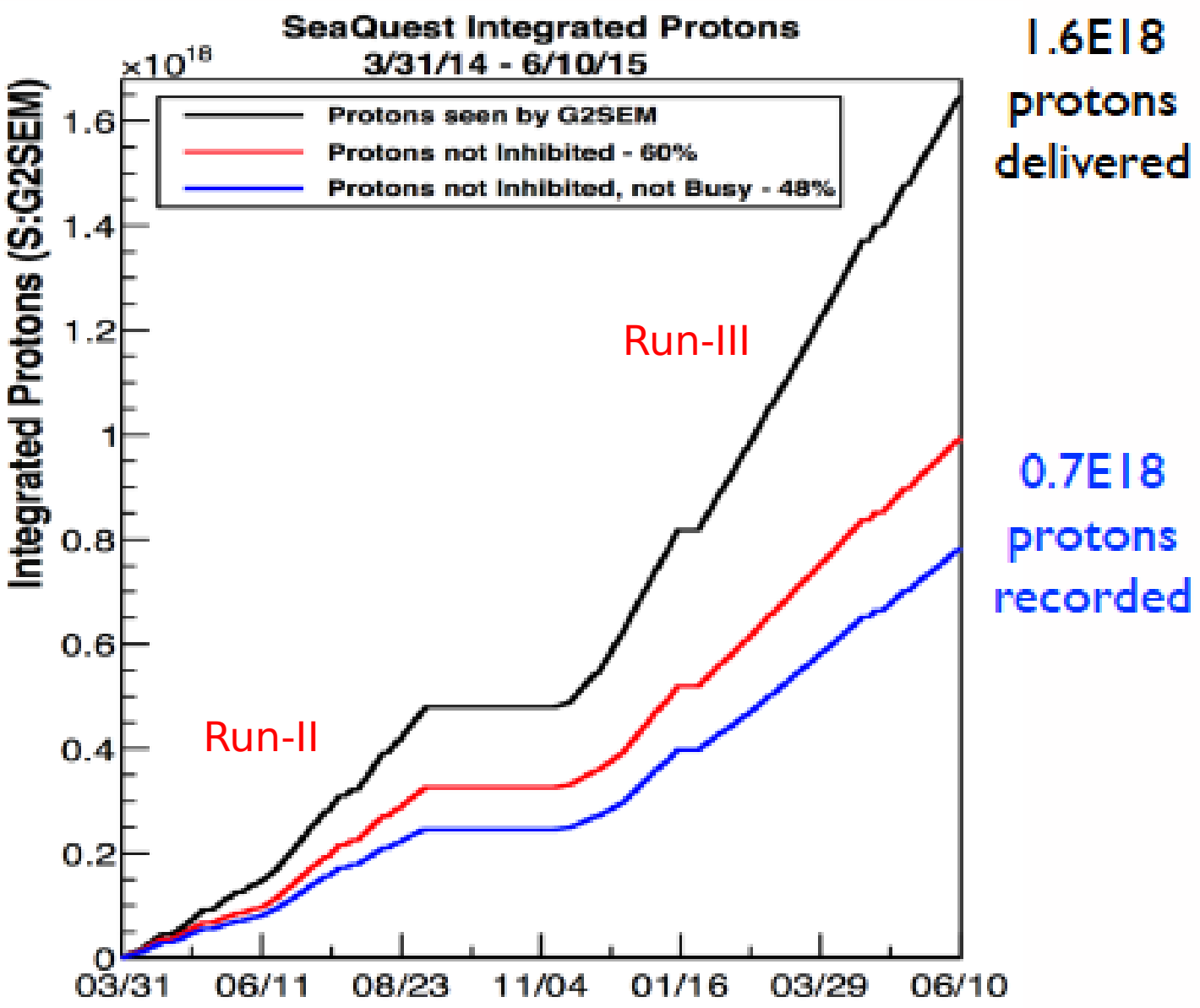


S. Gardner, R. Holt et al





E906 Run-II and III Performance

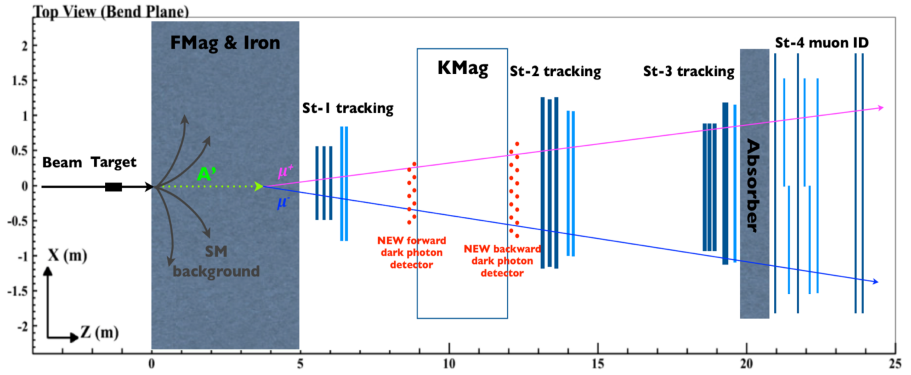


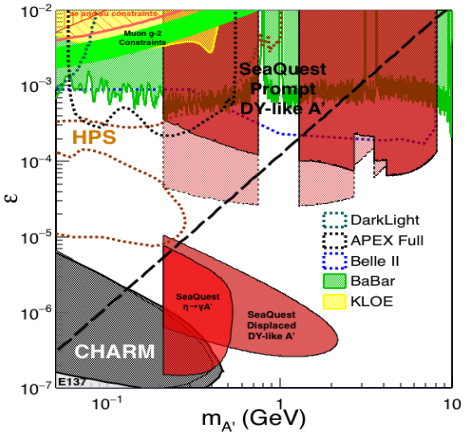
J-PARC Possibility

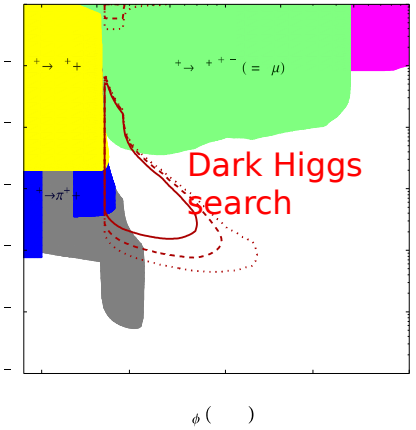
- 30GeV primary beam
  - High luminosity in a beam-dump mode
- Similar setup to E-1067
  - Di-electrons
  - Di-hadrons
  - Using/Recycling existing detectors?
- Access different phase space
  - MC study needed

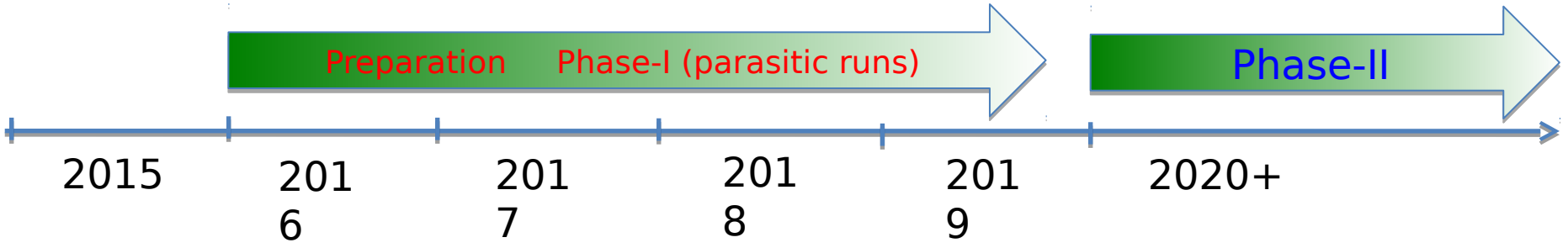
Summary and Outlook

- ***Phase-I (this LOI)***
  - ***Great discovery potential!***
  - ***Add a new displayed vertex trigger***
  - ***Early parasitic data taking 2017-2019+***
    - ***A short dedicated run up to ~1 month if needed***
  - ***POT 1.4 x10¹⁸***
- ***Phase-II (future request)***
  - ***Possible detector upgrade later, add electrons and hadrons***
  - ***A new dedicated dark matter program at Intensity Frontier!***







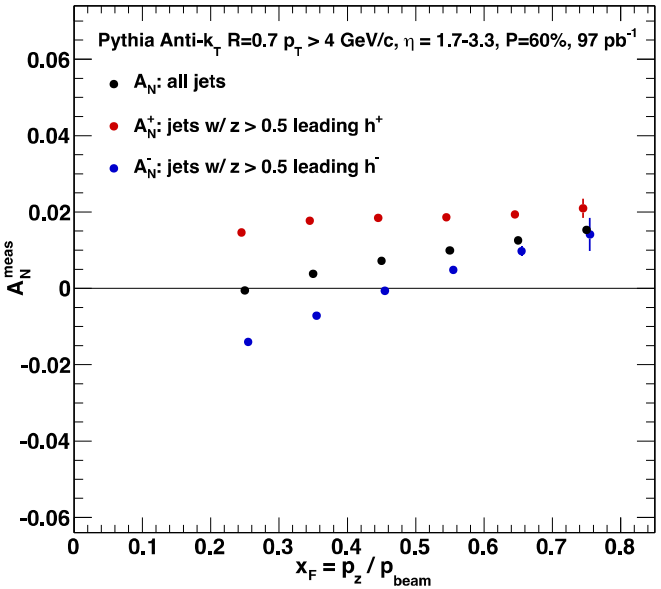


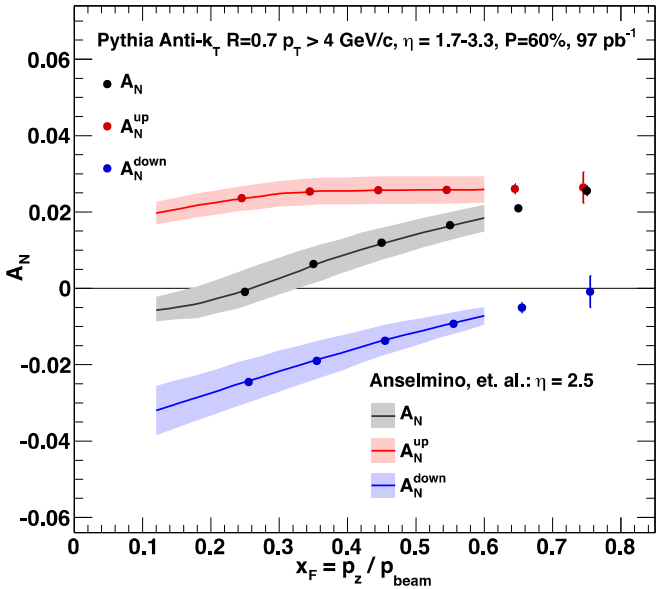
Backup slides

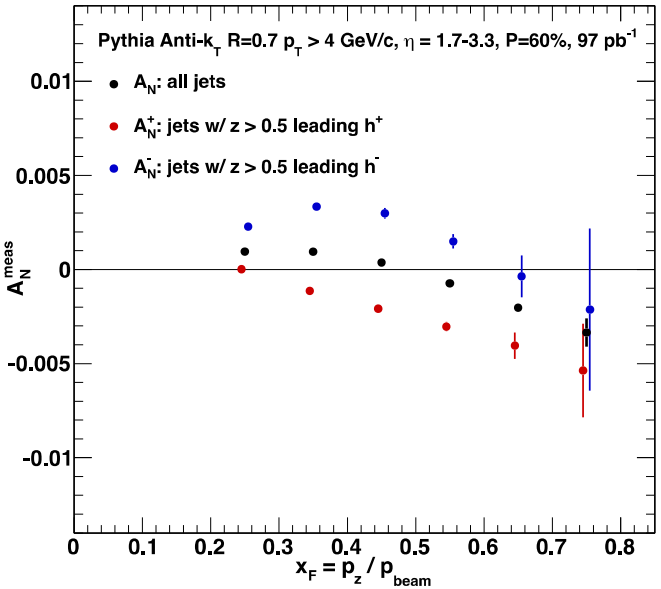
Spin backup

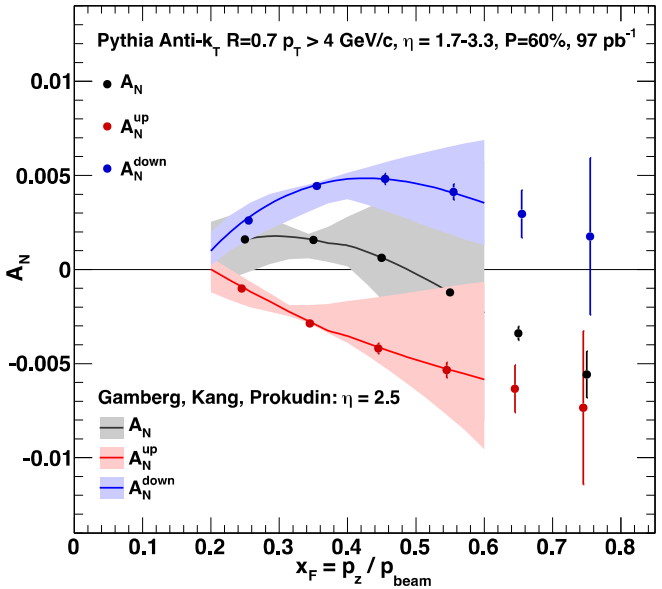
fsPHENIX Projected Jet Sivers Asymmetries

Test the universality of QCD description of TSSA: pp vs SIDIS



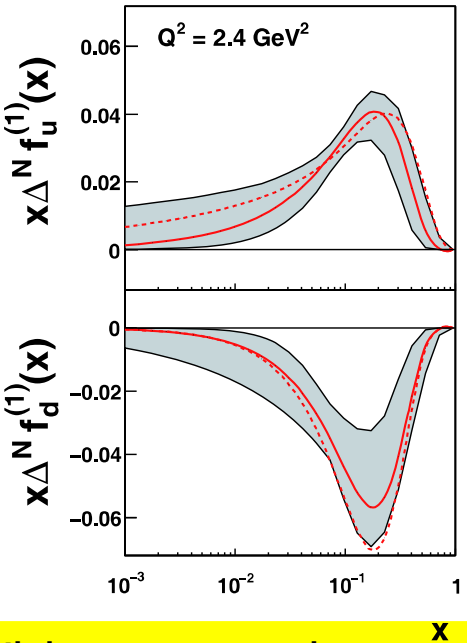






Naïve direct mapping from SIDIS Sivers (GPM)
- "u-quark jet" $A_N > 0$

Sivers, SIDIS fit



With process-dep from SIDIS Sivers (Twist-3)
- "u-quark jet" $A_N < 0$

Future Running at RHIC

Years	Beam Species and Energies	Science Goals	New Systems Commissioned
2014	Au+Au at 15 GeV Au+Au at 200 GeV ^{3}He+Au at 200 GeV	Heavy flavor flow, energy loss, thermalization, etc. Quarkonium studies QCD critical point search	Electron lenses 56 MHz SRF STAR HFT STAR MTD
2015-16	p↑+p↑ at 200 GeV p↑+Au, p↑+Al at 200 G High statistics Au+Au Au+Au at 62 GeV ?		
NEW! 2017	p↑+p↑ at 510 GeV		
2018	No Run		
2019-20	Au+Au at 5-20 GeV (BI		
2021-22	Au+Au at 200 GeV p↑+p↑, p↑+Au at 200 GeV	Jet, di-jet, γ-jet probes of parton transport and energy loss mechanism Color screening for different quarkonia Forward spin & initial state physics	sPHENIX Forward upgrades ?
≥ 2023 ?	No Runs		Transition to eRHIC

For Run 16 the PAC recommends the following (*in order of priority*):

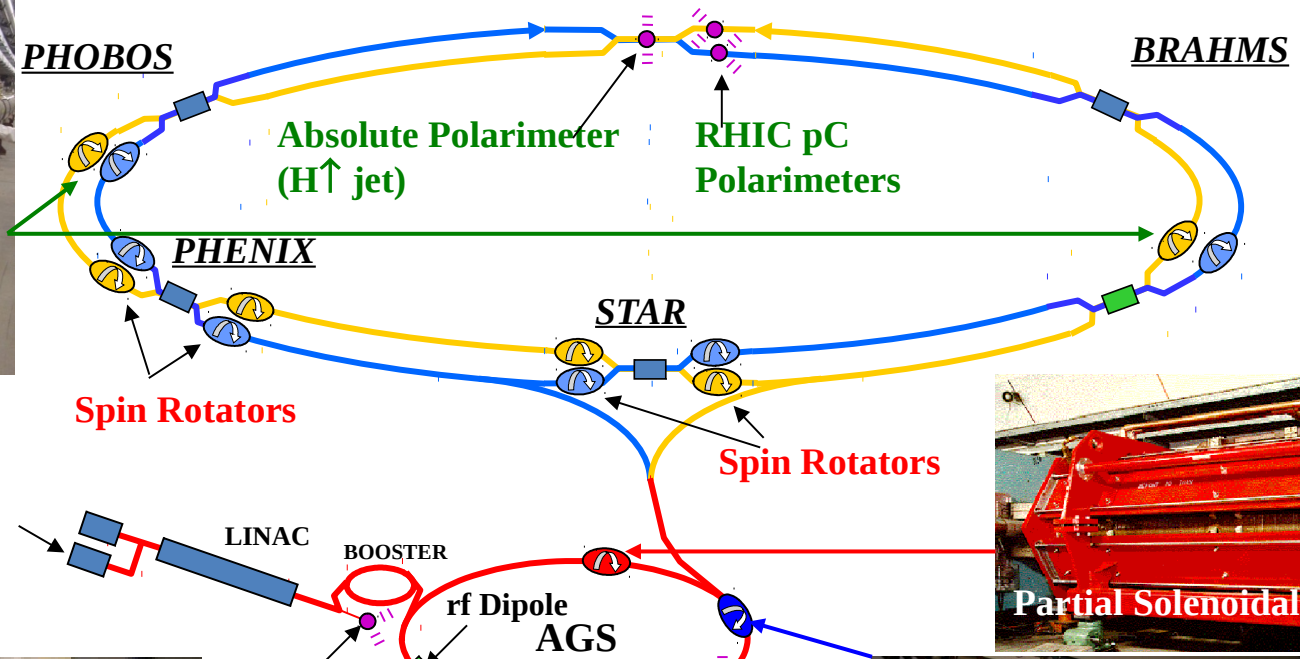
1. 10 weeks Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV
2. 5 weeks for a small system beam energy scan. This program can be realized with
   a. Au+polarized proton collisions for a set of energies chosen among 200, 62, 39 and 20 GeV to optimize the physics output, or
   b. d+Au collisions at 200, 62, 39, and 20 GeV
3. 2 weeks of polarized p+p collisions at $\sqrt{s} = 62$ GeV
4. Up to 4 weeks of Au+Au collisions at $\sqrt{s_{NN}} = 62$ GeV

Transverse Spin Physics

- Origins of large TSSA remain a major challenge to QCD description of hadron interactions
  - Very active filed of study, with great progress in the last 10 years
- New experimental data are needed to better understand the physics
- Drell-Yan TSSA
  - SIDIS vs DY in TMD
  - COMPASS
  - PHENIX and STAR at RHIC, Luminosity limited
- Jet TSSA in p+p
  - SIDIS TMD vs pp Twist-3
  - Forward sPHENIX

Polarized Proton Collider at RHIC

Full Helical
Siberian Snakes



Partial Solenoidal Snake

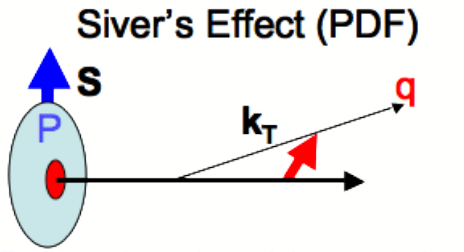

Cold Partial
Helical Siberian Snake


Warm Partial
Helical Siberian Snake

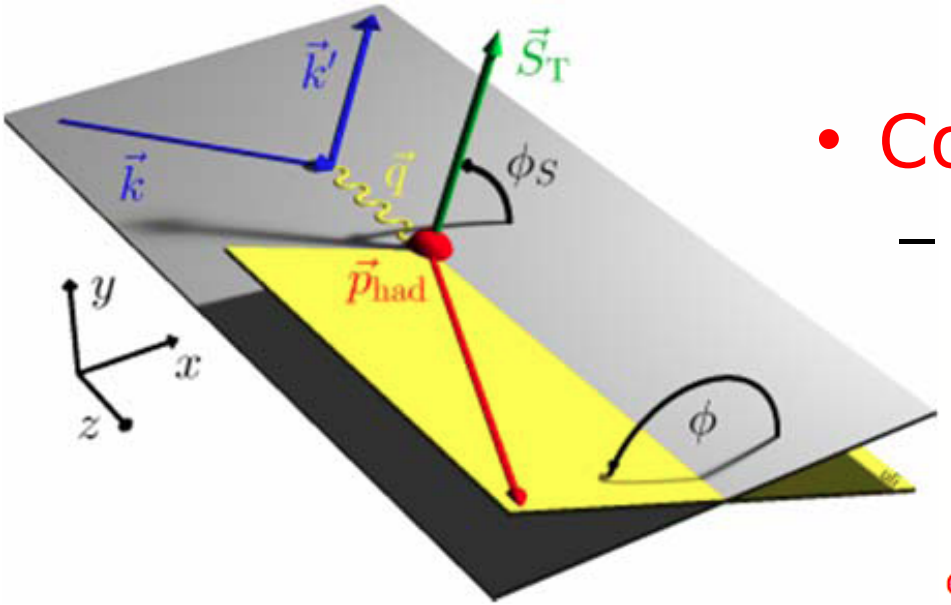
TSSA: Sivers and Collins Mechanisms

Significant Asymmetries Observed in Polarized Target SIDIS

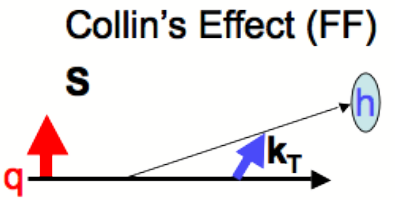
- Sivers
  - $<\sin(\Phi-\Phi_s)>$



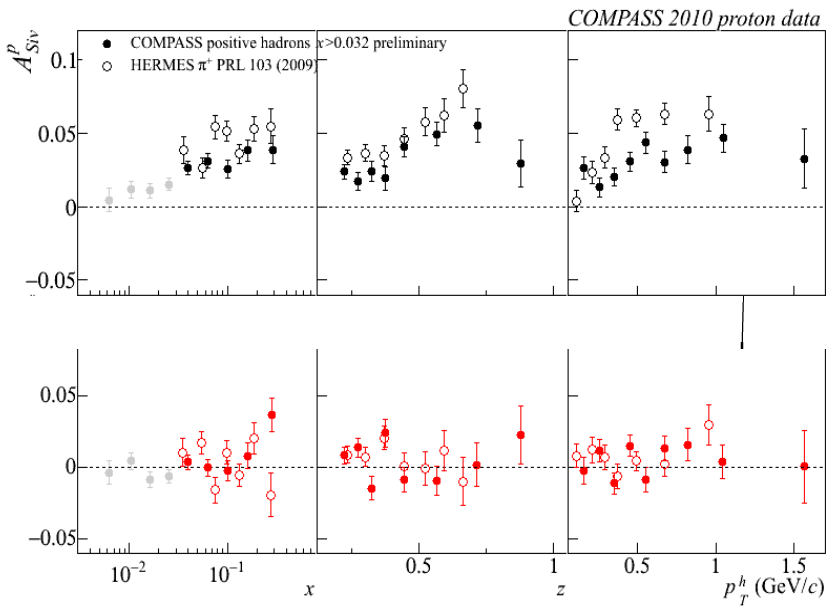
Proton spin and quark k_T correlation

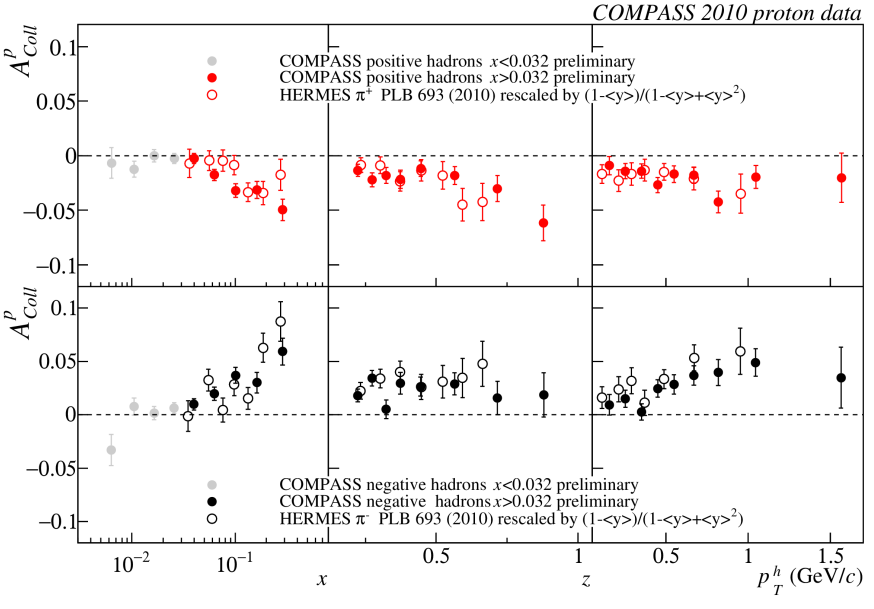


- Collins
  - $<\sin(\Phi+\Phi_s)>$



Quark spin and hadron k_T correlation



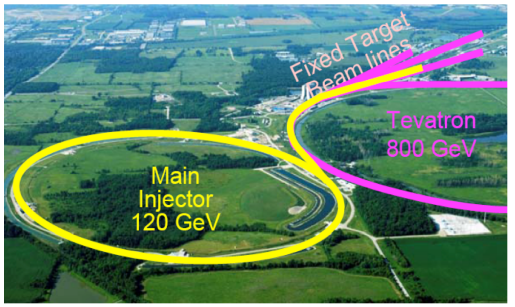


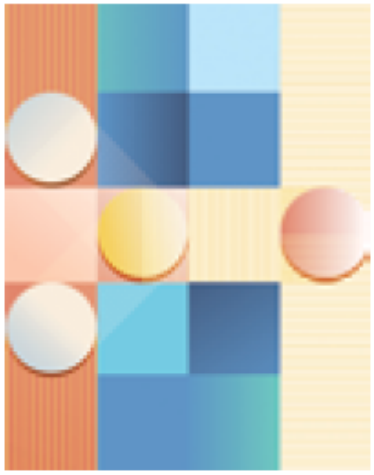
Dark particle backup

2014 US P-5 Report

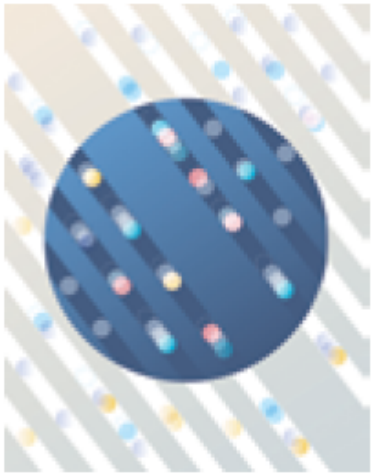
Five intertwined scientific Drivers were distilled from the results of a yearlong community-wide study:

- Use the Higgs boson as a new tool for discovery
- Pursue the physics associated with neutrino mass
- Identify the new physics of dark matter
- Understand cosmic acceleration: dark energy and inflation
- Explore the unknown: new particles, interactions, and physical principles



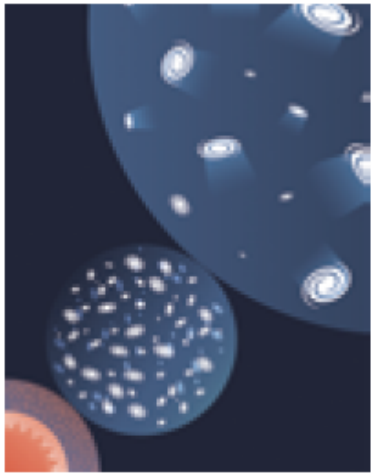


Higgs boson



Neutrino mass

Dark matter



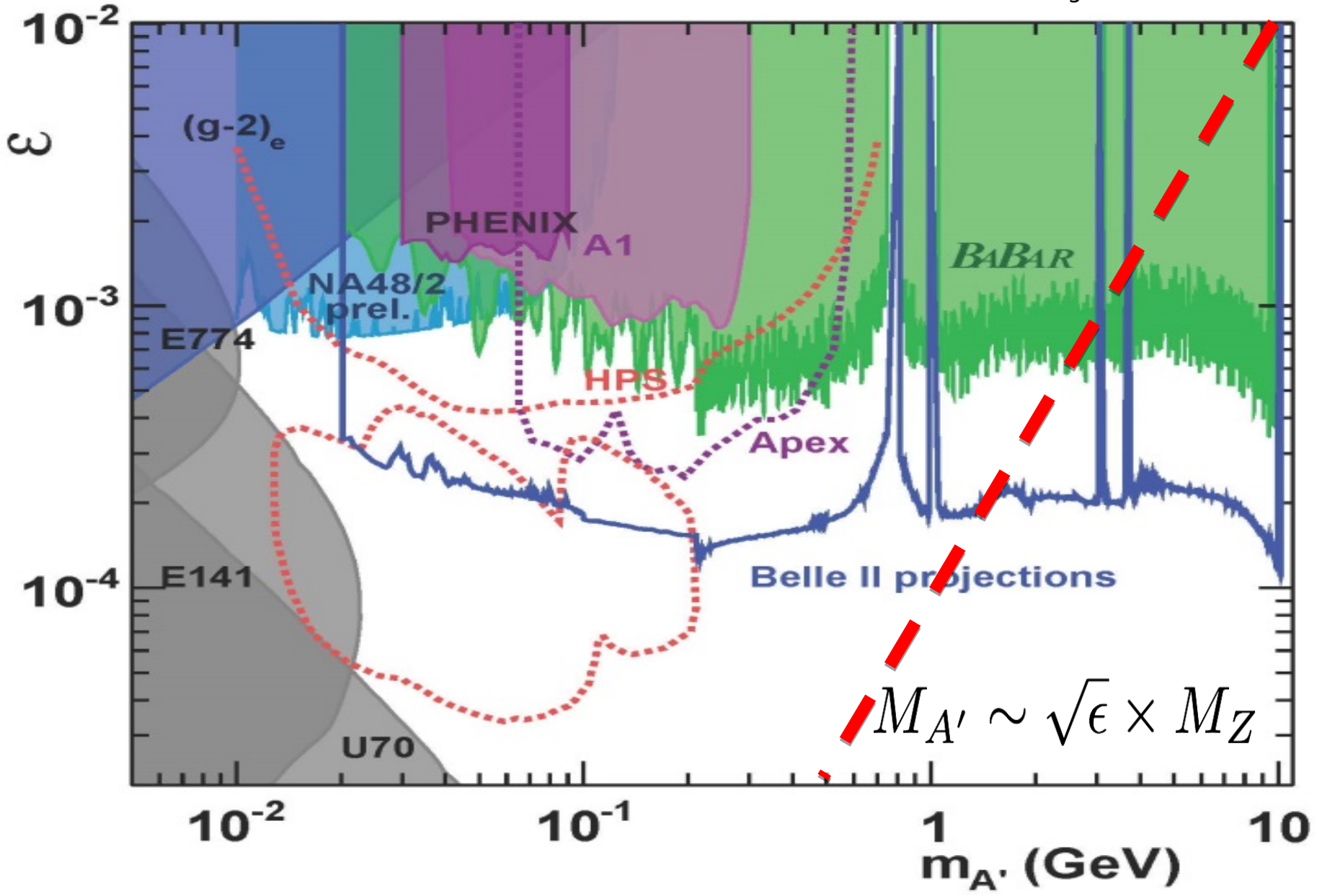
Cosmic acceleration

Explore the unknown

Great Opportunities at the Fermilab Intensity Frontier!!!

Current Limits on Dark Photon Search

R. Essig et al arXiv:1309.5084



Work in Progress Sensitivity Study

2-year parasitic run and more

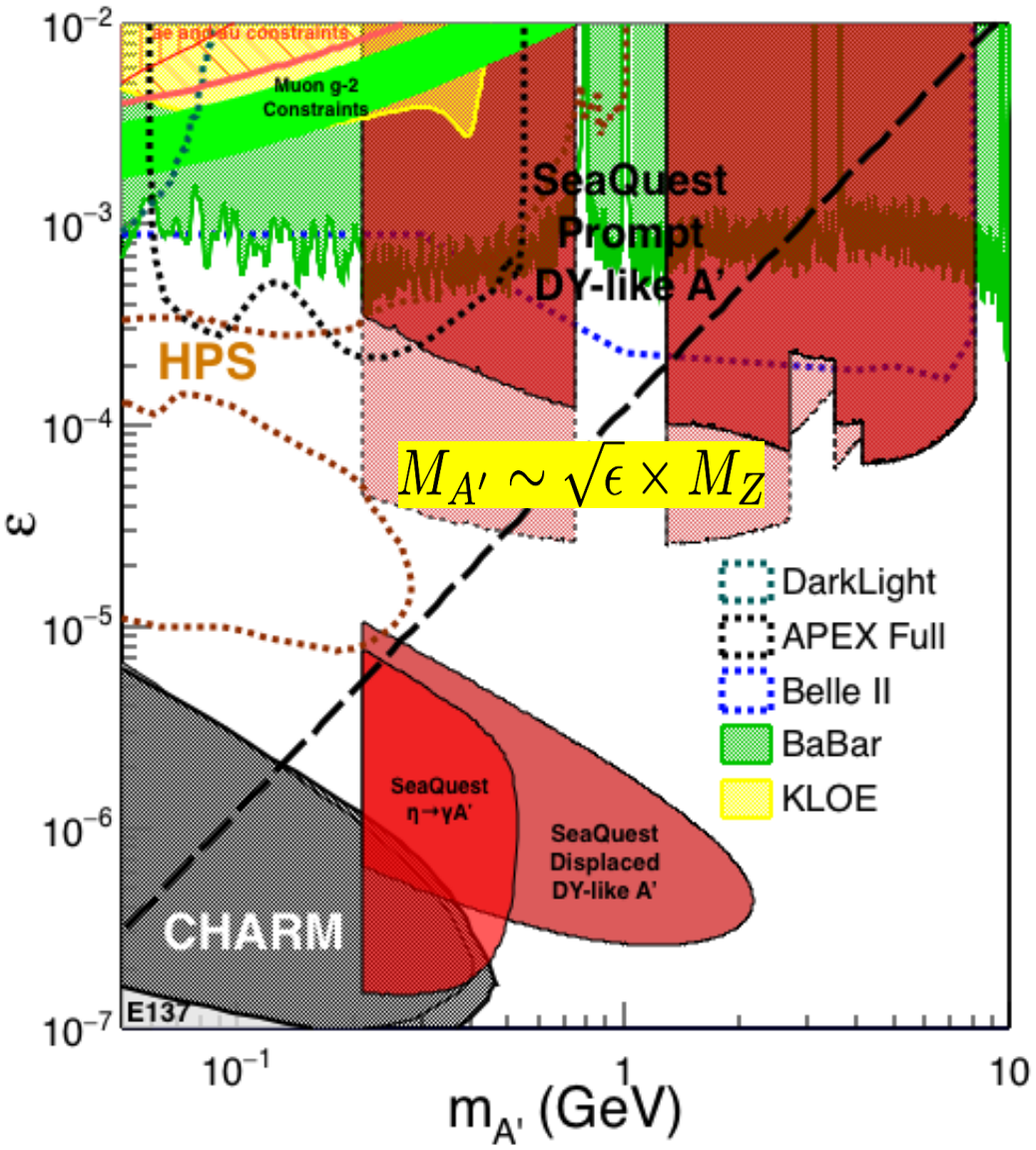
With 10kHz DAQ bandwidth, the accepted low mass “prompt” dimuons, M<3GeV, are statistically limited by DAQ throughput and detector acceptance (assuming only uses 10% DAQ).

100kHz DAQ bandwidth is needed to fully cover the phase space (assuming 10% usage of DAQ bandwidth) and dedicated dark photon run.

In the first two-year parasitic runs with E1039, our focus is on 1)the displaced dimuons for low mass; 2)prompt high mass dimuons M> 3GeV.

We can still cover more phase space than what BELLE-II can achieve in ~2023.

Full coverage of low mass (M<3GeV) can be achieved later through dedicated runs with much improved DAQ bandwidth after E1039.



Scope and Compatibility

- Preparation work: 2016 – 2017
  - Displaced vertex dimuon trigger upgrade (LANL LDRD? $100K)
    - Add a new trigger bit
    - No change to existing trigger matrix
  - Possible upgrade of DAQ bandwidth under consideration (external $$)
    - 1kHz (E906) -> 10+ kHz
  - Commissioning with cosmic rays

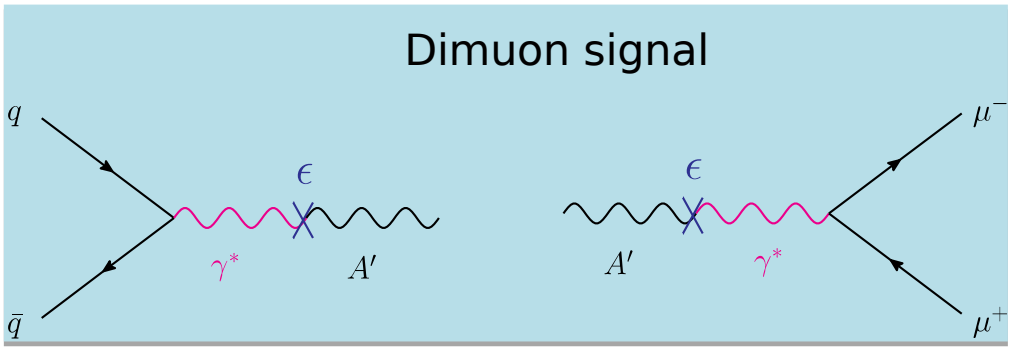
- Parasitic runs w/ E1039: 2017 – 2019
  - Displaced vertex dimuon trigger upgrade
  - Use up to ~10% DAQ bandwidth
  - Achieve 1.44 x10^{18} POT

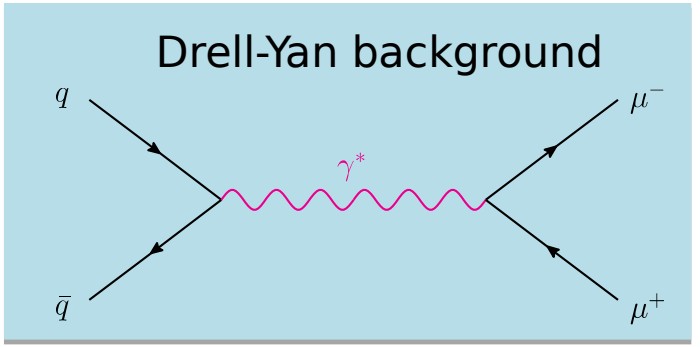
- Possible parasitic runs w/ E1027 and/or dedicated runs later with upgrades: 2019+
  - High luminosity goals:
    - POT >> 1.4x10^{18}
  - DAQ
    - 10 – 100 kHz capability
  - EMCAL/HCAL/PID
    - Electrons
    - charged hadrons
  - Fully cover the accessible phase space
    - Low mass “prompt photon” region, M < 3 GeV
  - Possible parasitic runs with other proposals

Integrated theory efforts

Signal: detailed calculation for dark photon (dark Higgs) cross section

- To provide expected dimuon signal from dark photon decay as function of decay length L and model parameters (ε, $m_{A'}$), theory team will
  - Compute Dark photon production cross section at both LO and NLO
  - Derive the branching ratio of dark photon to dimuon
  - Theory team: expertise in perturbative QCD and effective field theory for resummation





Background: detailed calculation for Drell-Yan cross section

- Main background is DY dimon production: reliable computation of the cross section is essential to calculate our experimental sensitivity to (ε, $m_{A'}$), and understand implication of dark photon search
  - We have a NLO DY code that works well in the required energy range
  - Calculations will be performed in the necessary energy and kinematic regions

How important are dark photons in current models of new physics ?

- 2014 US High-Energy Physics Report (P5)
  - Top 5 science drivers:

    "Identify the New Physics of Dark Matter"

  - Dark photons

    "one of the key search area for physics beyond the SM"

    One of the two most important portals to "dark sector":
    - *Vector coupling, kinetic mixing*
    - (scalar coupling, dark Higgs)

- On-going and/or proposed experimental programs in all major accelerator facilities in the world!
  - World wide competitions!

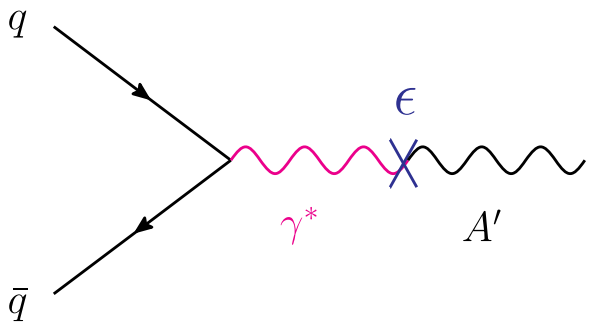
Ongoing A' Searches

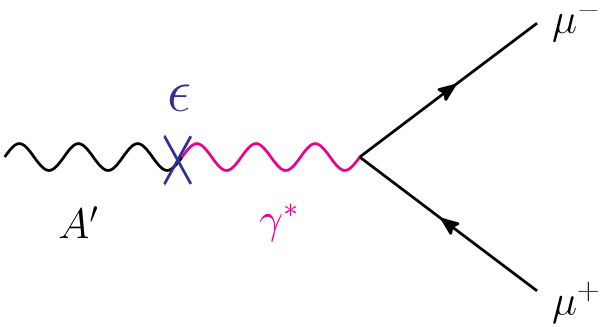
- KLOE-2@DAϕNE(ϕ➔ϕA' followed by A'➔e+e-)
- HADES@GSI (p+p, p+^{93}Nb, p+^{40}Ar, ^{84}K+^{35}Cl production: π^0,η, Δ decay followed by A'➔e+e-)
- BaBar@SLAC (e+e-➔ϒ➔γA' with A'➔μμ)
- WASA@COSY (π^0 decay)
- PHENIX@RHIC (π^0 decay)
- A1@MAMI (e on ^{181}Ta)
- ATLAS and CMS @LHC
- SeaQuest @ FNAL
- milliQ@SLAC: 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(MIT) at the Fundamental Interactions Town Meeting, Chicago, Sept. 28-29, 2014

Probe-1: Drell-Yan Like

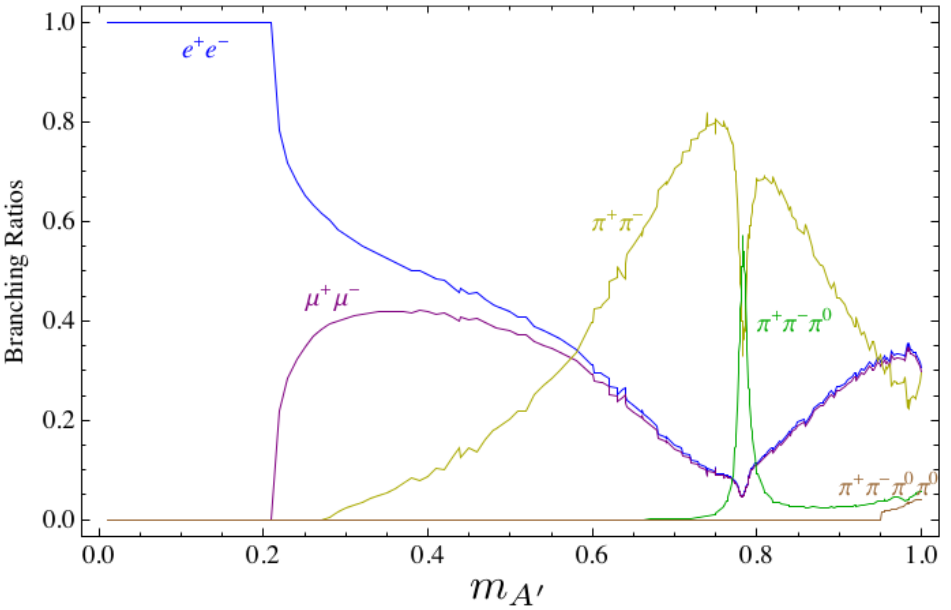
sensitive to both prompt and long-lived decay





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

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

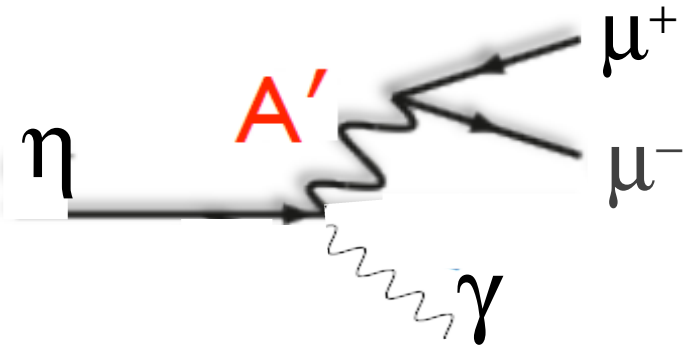


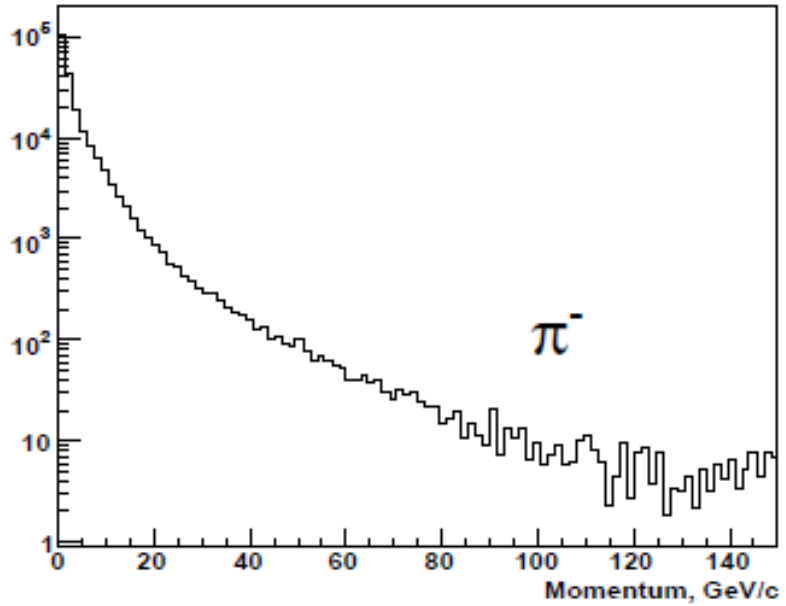
Probe-2: η Meson Production at 120 GeV

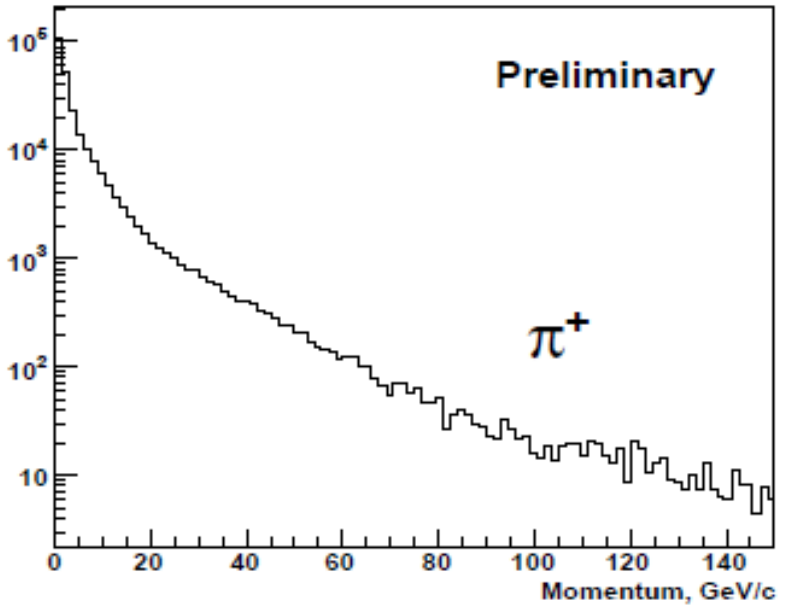
2.2 b for all charged particle production
ume that π's represent 90% of charged particles,

$$\sigma_{\pi^\circ} = \frac{1}{2}(\sigma_{\pi^+} + \sigma_{\pi^-})$$

η production is ~1/10 of this value.





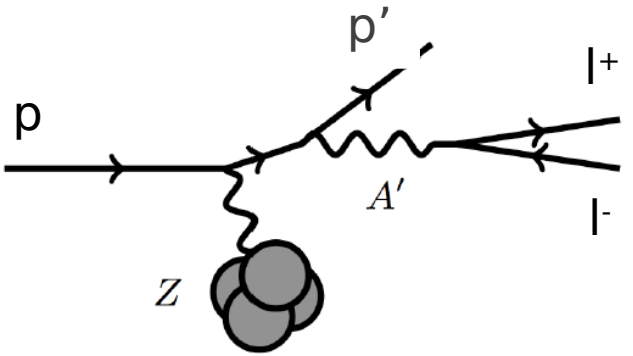


S. Mahajan, R. Raja, arXiv:1311.2258; FNAL E907, MIPP

Probe-3: Proton Bremsstrahlung

Generalized Fermi-Williams-Weizsacker approximation

J. Blumlein, J.Brunner, PLB **731** (2014) 320



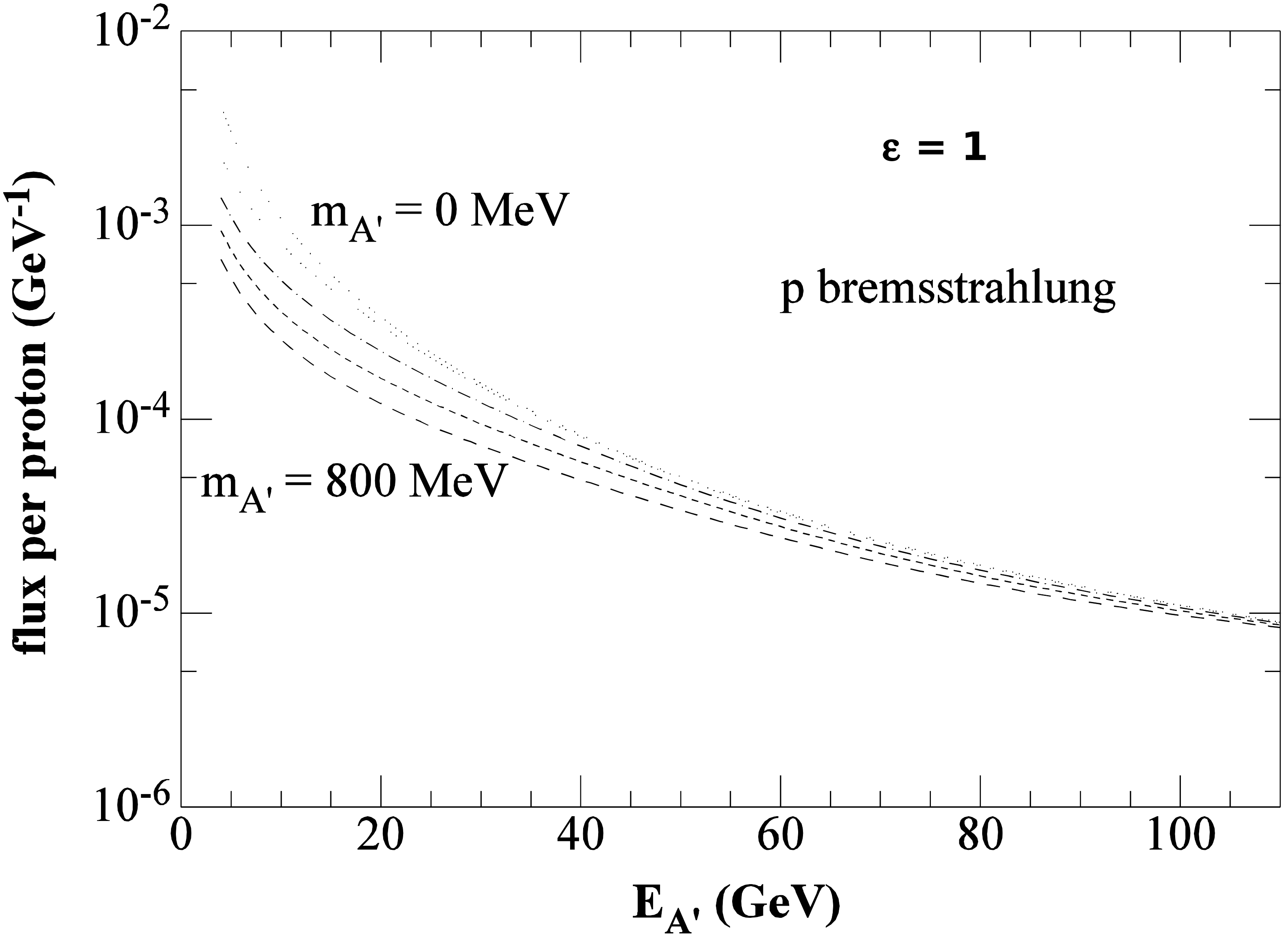
$\gamma + p \rightarrow A' + p'$

$$w_{ba}(z,p_\perp^2)dzdp_\perp^2 = \frac{\alpha'}{2\pi}\left\{\frac{1+(1-z)^2}{z} - 2z(1-z)\left[\frac{2M^2+m_{\gamma'}^2}{H} - z^2\frac{2M^4}{H^2}\right]\right.$$
$$\left. +2z(1-z)[1+(1-z)^2]\frac{M^2m_{\gamma'}^2}{H^2} + 2z(1-z)^2\frac{m_{\gamma'}^4}{H^2}\right\}\frac{dzdp_\perp^2}{H}$$

$$\frac{dN}{dE_{\gamma'}} = \frac{1}{E_p}\frac{\sigma_{pA}(s')}{\sigma_{pA}(s)}\int_0^{p_{\perp,\max}^2} w_{ba}(z,p_\perp^2)dp_\perp^2,$$

$z = (E_p - E_p')/E_p$; $s = 2ME_p$; $s' = 2M(E_p - E_{A'})$

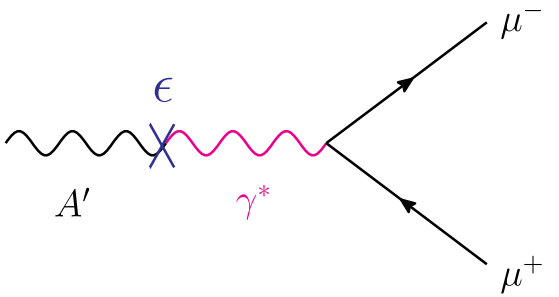
Proton Bremsstralung Flux



Dark Photon Decay Modes

"Minimal" Decay:

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

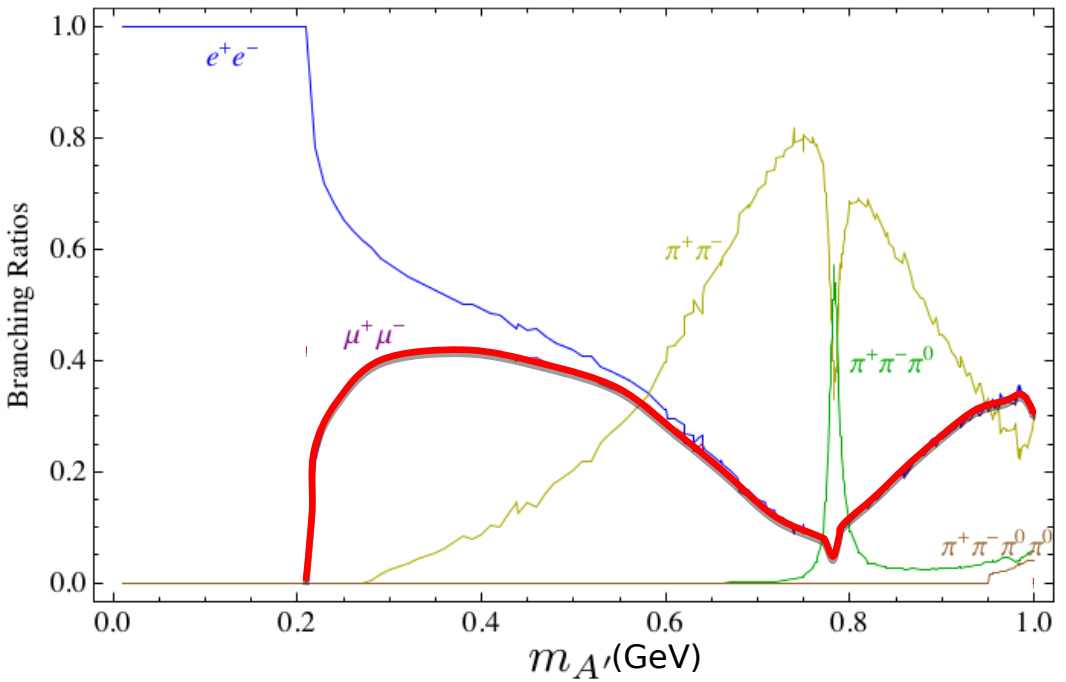


$$\Gamma(A' \to f + \bar{f}) = C\frac{\epsilon^2 m_{A'}}{3} e_f^2 \alpha_{\rm em} \left(1 + \frac{2m_f^2}{m_{A'}^2}\right) \sqrt{1 - \frac{4m_f^2}{m_{A'}^2}},$$

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