Search for low mass dark photons in high energy p+A collisions at Fermilab

Theory efforts

FY 2016
Zhongbo Kang (co-PI, T-2) 15%
Vincenzo Cirigliano (T-2) 0%

FY 2017
Zhongbo Kang (co-PI, T-2) 15%
Vincenzo Cirigliano (T-2) 10%

Theory team with external collaborators

- Internal LANL theory members

Zhongbo Kang (T-2)
pQCD, resummation

Vincenzo Cirigliano (T-2)
fundamental symmetry, dark matter

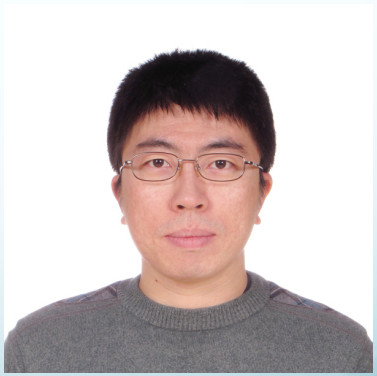
- Outstanding external theory collaborators

Stefania Gori
U of Cincinnati

Philip Schuster
SLAC

Dark photon

Natalia Toro
SLAC

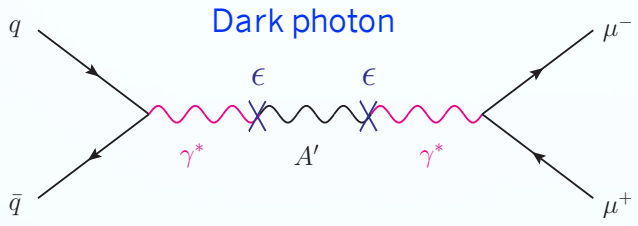


Yue Zhang
Caltech

Dark Higgs

Goals of theoretical efforts

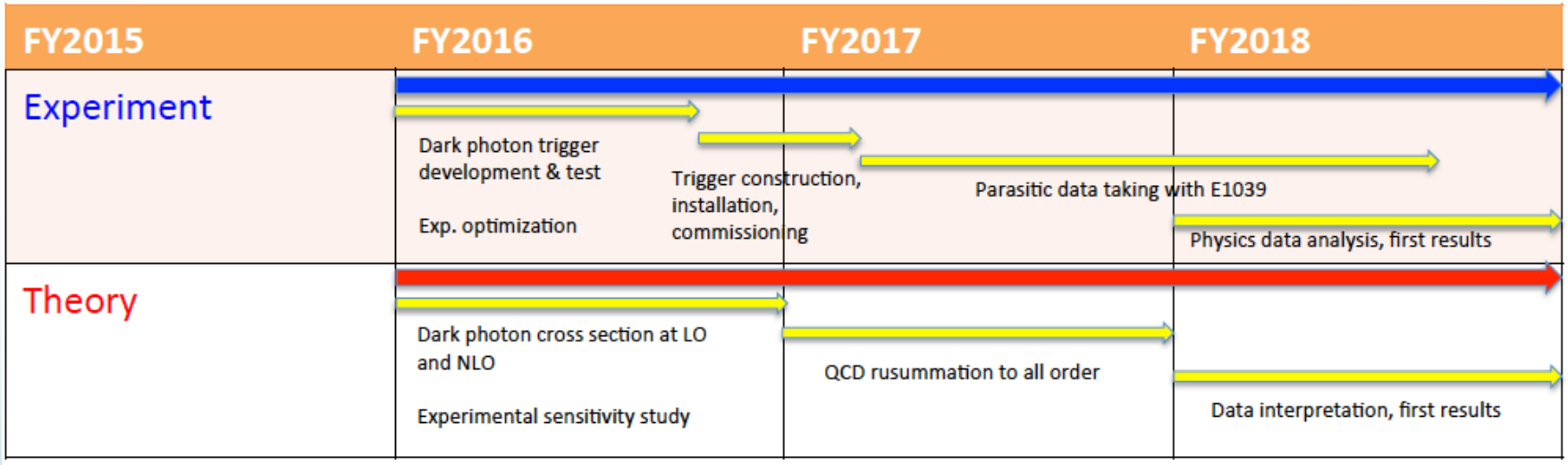
- To guide and optimize our experimental search
  - Signature: study in great detail the dark photon production cross section and decay width, branching ratio in p+A collisions
  - Background: Drell-Yan lepton pair production
  - Techniques: perturbative QCD calculations at both LO and NLO for x_F (or rapidity y) dependence, QCD resummation and effective field theory for p_T differential cross section



- These theoretical results will be combined with the experimental simulations/measurements, to produce the realistic signature and background, and thus generate the sensitivity plot (money plot) for parameters
  - How our experiment will constrain the theory parameters
- Explore the opportunity for dark Higgs search

Milestones of the project

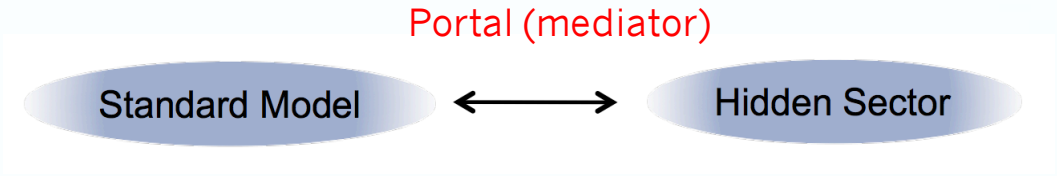
- FY2016 milestones
  - Dark photon cross section using perturbative QCD at LO and NLO
  - Study experimental sensitivity on the theory/model parameters
- Status: have completed FY2016 milestone, in good progress towards achieving FY2017 milestone for QCD resummation



- ✓ One paper in preparation, Kang, M. Liu, K. Liu, Gori, Schuster, Toro
- ✓ Some of our efforts are implemented in Dark Sectors 2016 Workshop: Community report, arXiv:1608.08632

Dark photon, Higgs portal

- We can explore two of three portals



Only three sizeable interactions allowed by Standard Model symmetries:

Vector Portal	$\frac{1}{2}\epsilon_Y F^Y_{\mu\nu} F'^{\mu\nu}$	Most visible
Higgs Portal	$\epsilon_h \lvert h\rvert^2 \lvert\phi\rvert^2$	exotic rare Higgs decays rare meson decays
Neutrino Portal	$\epsilon_\nu (hL)\psi$	not-so-sterile neutrinos

N. Toro, talk at BNL 2016 workshop on Dark Interactions

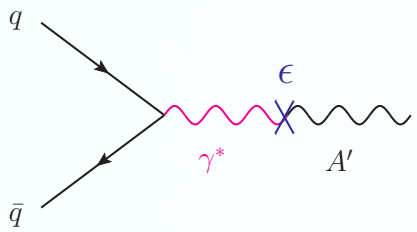
- Dark photon A'

$$\mathcal{L}_{A'} \sim \frac{\epsilon}{2} F'^{\mu\nu} F_{\mu\nu} - \frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} - \frac{1}{2} m^2_{A'} A'^{\mu} A'_{\mu}$$

Two key parameters: $(\epsilon,\ m_{A'})$

Dark photon production

- Dark photon cross section as a function of Feynman x_F at LO



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

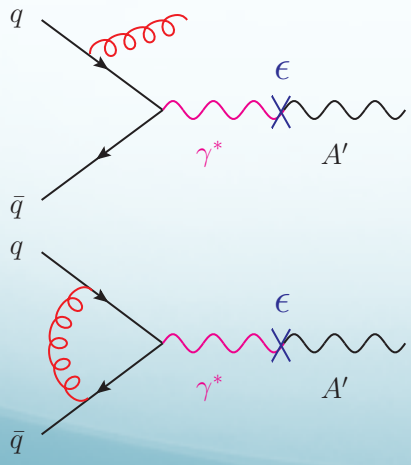
$$\sigma_0^{A'}=\frac{4\pi^2\alpha_{\rm em}\epsilon^2}{N_c m_{A'}^2},\qquad x_1=\frac{x_F+\sqrt{x_F^2+4m_{A'}^2/s}}{2},\qquad x_2=\frac{-x_F+\sqrt{x_F^2+4m_{A'}^2/s}}{2}$$

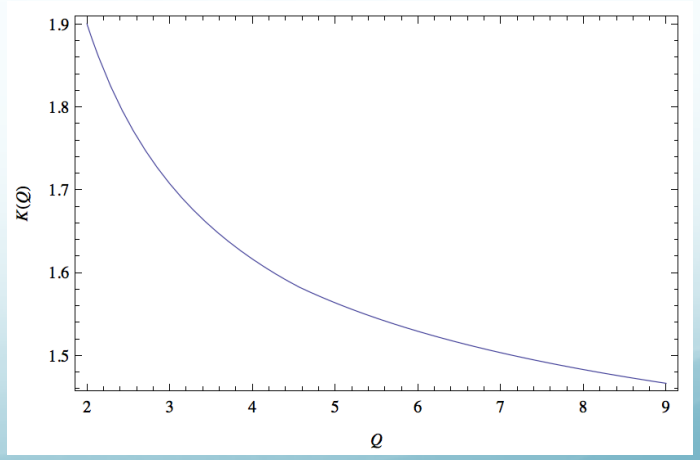
- NLO computation is also available, which can be modeled by the so-called K-factor = NLO/LO

$$K(Q)=\exp\left[\frac{\alpha_s(Q)}{2\pi}C_F\pi^2\right]\qquad Q=m_{A'}$$

real

virtual



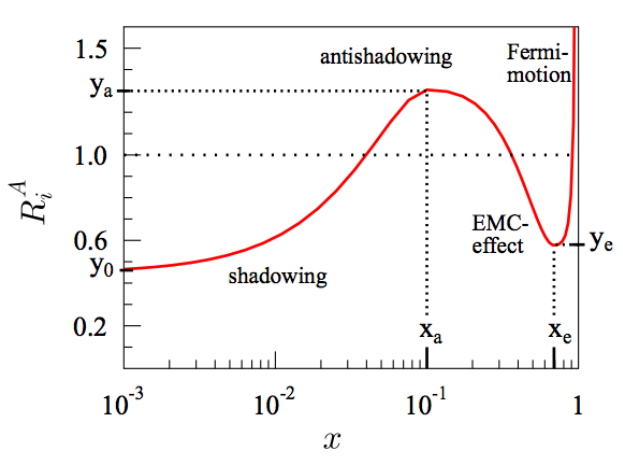


Nuclear PDFs

- Our experiment is performed for proton-nucleus (p+Fe) collisions
  - Isospin effect (26 proton + 30 neutron)

$$u^p(x) = d^n(x)$$
$$d^p(x) = u^n(x)$$
$$\bar{u}^p(x) = \bar{d}^n(x)$$
$$\bar{d}^p(x) = \bar{u}^n(x)$$

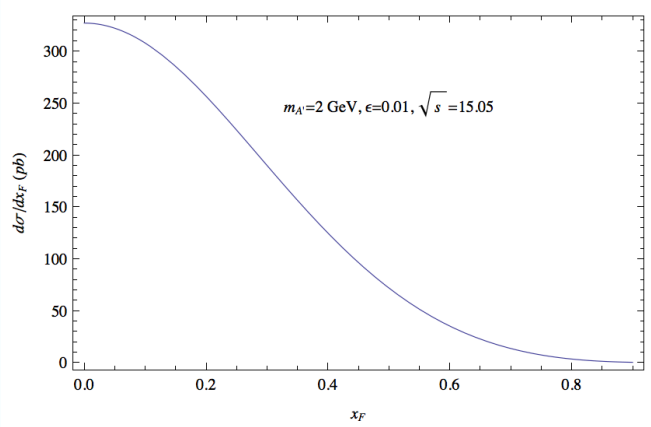
  - Parton distribution functions in a *bound* proton of a large nucleus are different from that in a *free* proton



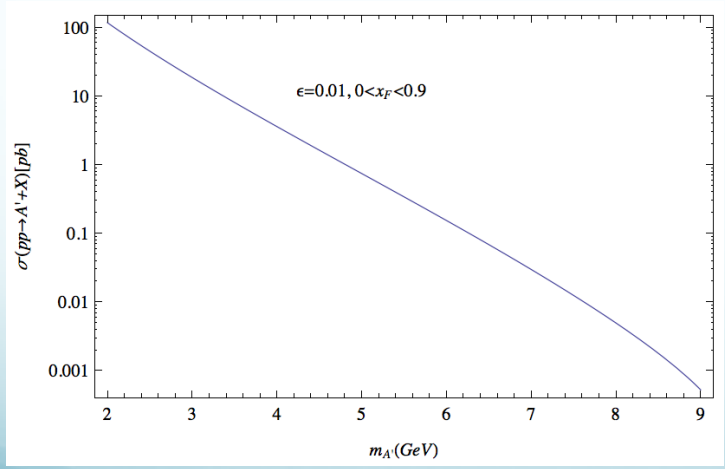
EPS09 nuclear PDFs, arXiv:0902.4154, JHEP

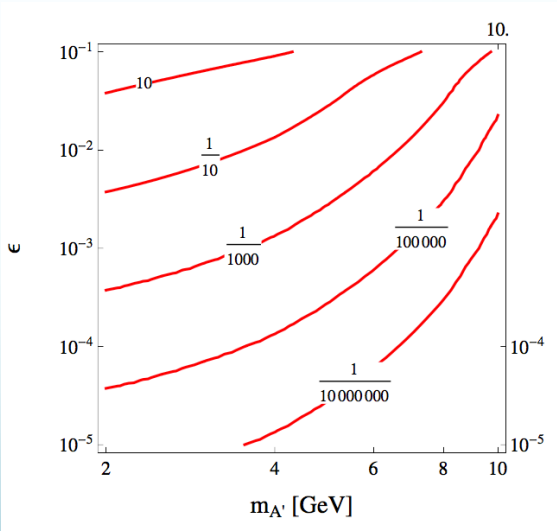
Dark photon cross section

- x_F dependence



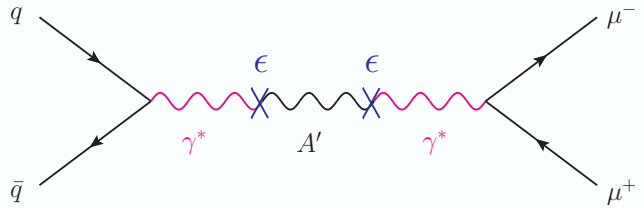
- Dependence on dark photon mass and mixing parameter





Muon pair cross section from dark photon decay

- Dimuon cross sections from dark photon decay



$$\frac{d\sigma_{A'\to\ell^+\ell^-}}{dM^2 dx_F} = \sum_q e_q^2 q(x_1)\bar{q}(x_2)\frac{x_1 x_2}{x_1+x_2}\frac{4\pi\alpha_{\rm em}^2\epsilon^4}{3N_c}\frac{1}{\left(M^2-m_{A'}^2\right)^2+m_{A'}^2\Gamma^2}\left(1+\frac{2m_\mu^2}{M^2}\right)\sqrt{1-\frac{4m_\mu^2}{M^2}}$$

- Under narrow-width approximation

$$\frac{1}{\left(M^2-m_{A'}^2\right)^2+m_{A'}^2\Gamma^2} \approx \frac{\pi}{m_{A'}\Gamma}\delta(M^2-m_{A'}^2)$$

- We have

$$\left.\frac{d\sigma_{A'}}{dx_F}\right|_{\mu^+\mu^-} = \sum_q e_q^2 q(x_1)\bar{q}(x_2)\frac{x_1 x_2}{x_1+x_2}\frac{4\pi^2\alpha_{\rm em}\epsilon^2}{N_c m_{A'}^2}\frac{\Gamma_{\mu^+\mu^-}}{\Gamma}$$

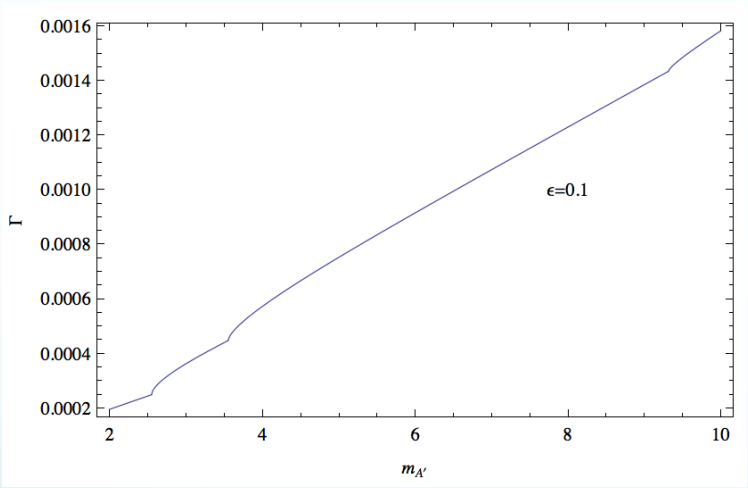
$$= {\rm Br}(\mu^+\mu^-)\frac{d\sigma_{A'}}{dx_F}$$

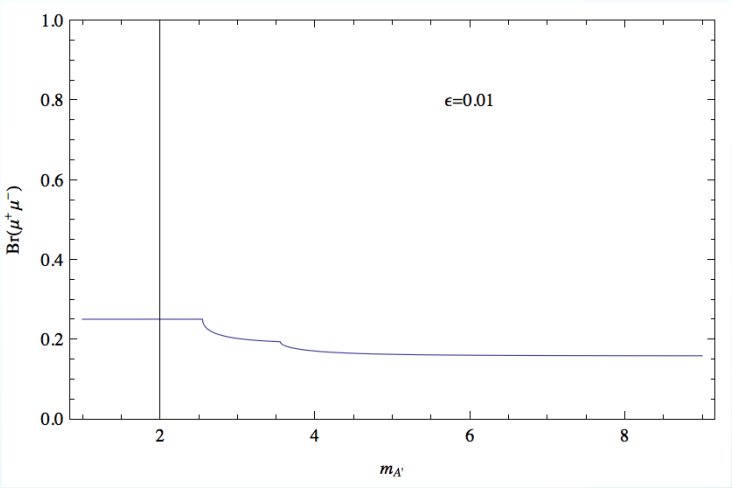
Dark photon width

- Dark photon width and branching ratio

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

$$\mathrm{Br}(\mu^+\mu^-) = \frac{\Gamma_{\mu^+\mu^-}}{\Gamma}$$



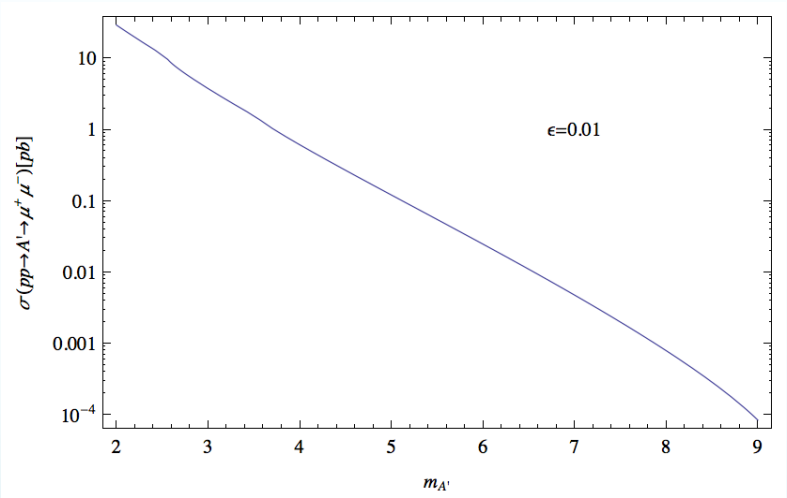


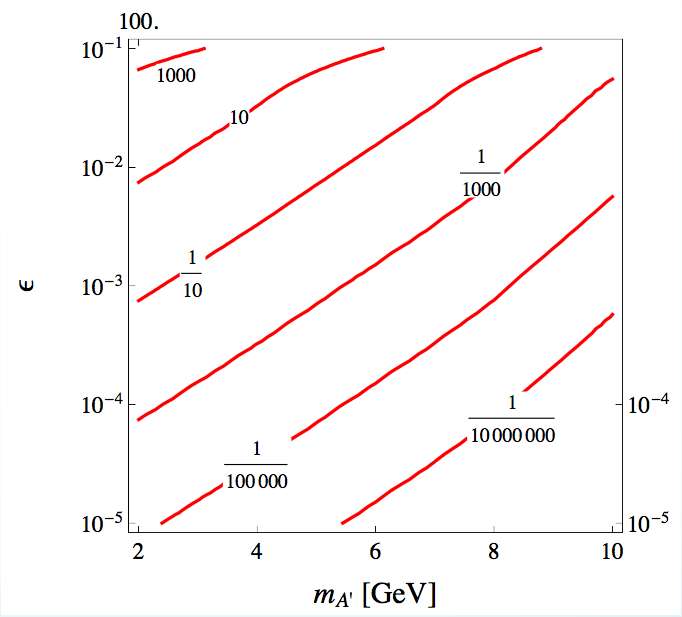
Assuming all decay particles are standard model particles

$$e, \mu, \tau, u, d, s, c, b$$

Dimuon cross section from dark photon decay

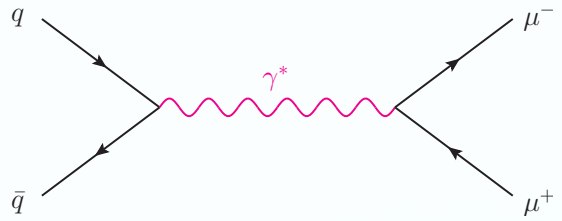
- As a function of dark photon mass and mixing parameter



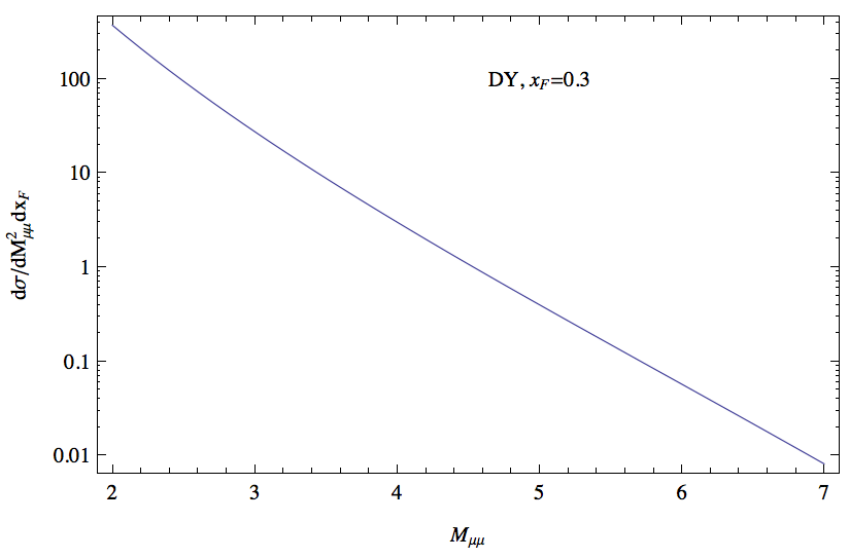


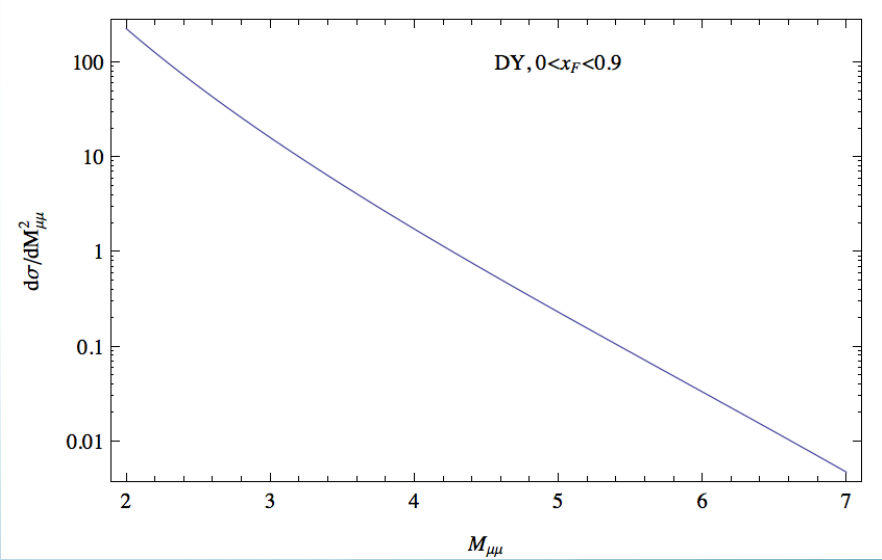
Background: Drell-Yan cross section

- Drell-Yan process at both LO and NLO



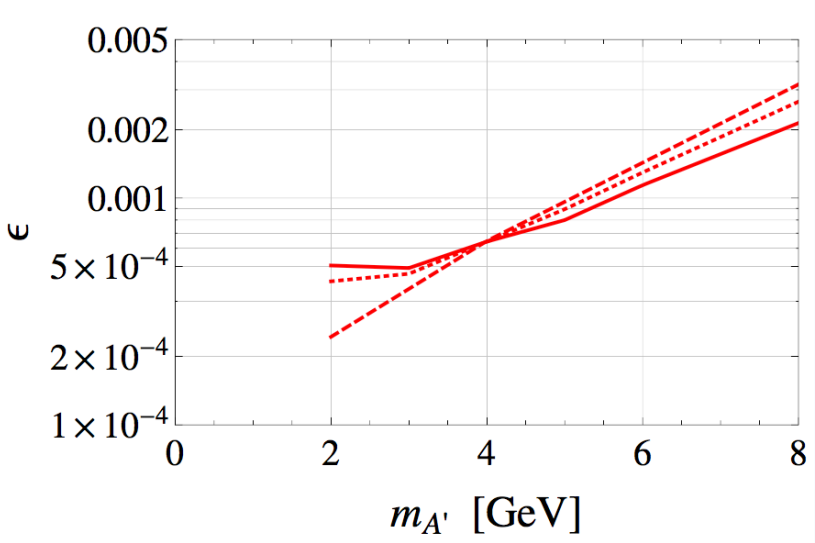
$$\frac{d\sigma_{\gamma^* \to \ell^+\ell^-}}{dM^2 dx_F} = \sum_q e_q^2 q(x_1)\bar{q}(x_2)\frac{x_1 x_2}{x_1 + x_2}\frac{4\pi\alpha_{\rm em}^2}{3N_c M^4}\left(1 + \frac{2m_\mu^2}{M^2}\right)\sqrt{1 - \frac{4m_\mu^2}{M^2}}$$





Experimental sensitivity

- Using the current calculations for dark photon dimuon cross sections, we provide first preliminary experimental sensitivity for the theory parameters



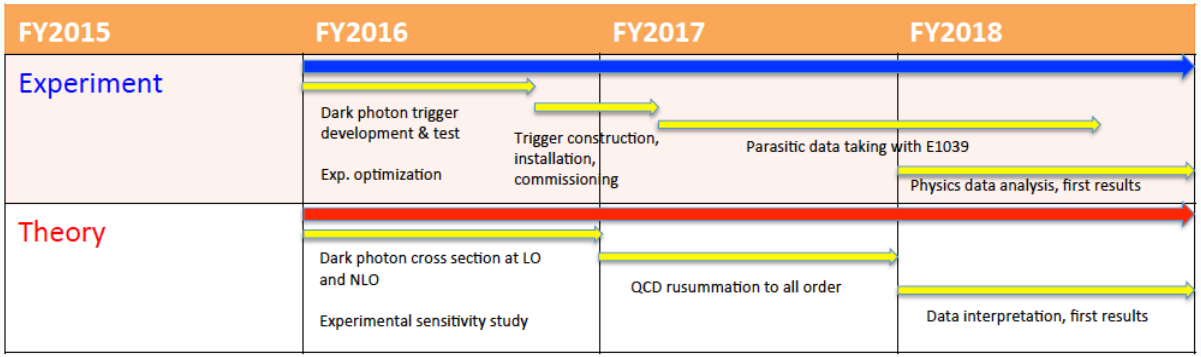
from S. Gori

Figure 5: Exclusion bound using 35 ab^{-1} data (solid line). Dashed curve: our results with the requirements: two muons with total momentum larger than 1.5 GeV and with $\frac{p_T}{p_z} < 0.1$. Dotted curve: our results with the mass window $m_{A'} \pm 6\% \cdot m_{A'}$.

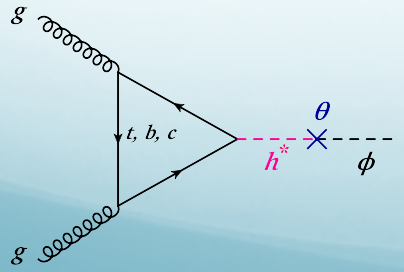
- To do list
  - Cross check this result
  - Implement realistic experimental cuts and simulations

FY17 plan

- QCD resummation for transverse momentum distribution of dark photon
  - To have realistic simulation for dimuon signature, one also need the full kinematic information for dark photons
  - Our FY16 pQCD computations provide longitudinal momentum distribution (x_F-dependence), FY17 we will study in addition p_T-distribution



- We will further explore the dark Higgs opportunity



$$\mathcal{L} = \mu\phi H^\dagger H$$

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

See also G. Krnjaic, arXiv: 1512.04119

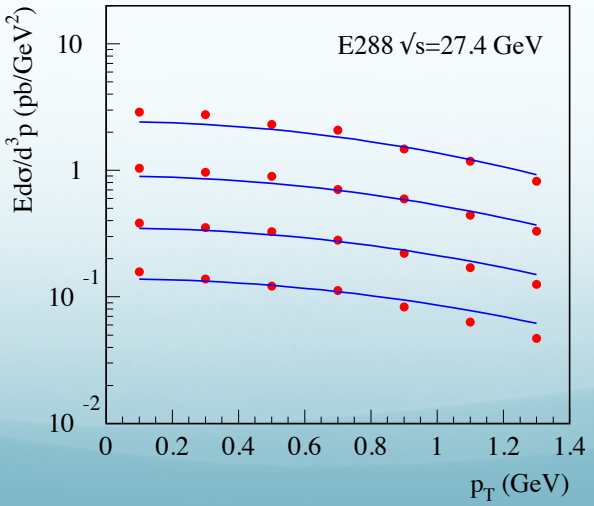
Preliminary study for pt distribution

- Need of QCD resummation for p_T distribution
  - Problem when $p_T << m_{A'}$: naïve perturbative QCD computation will generate large logarithms, which blow up

$$\left[\alpha_s \ln^2\left(\frac{m_{A'}^2}{p_T^2}\right)\right]^n$$

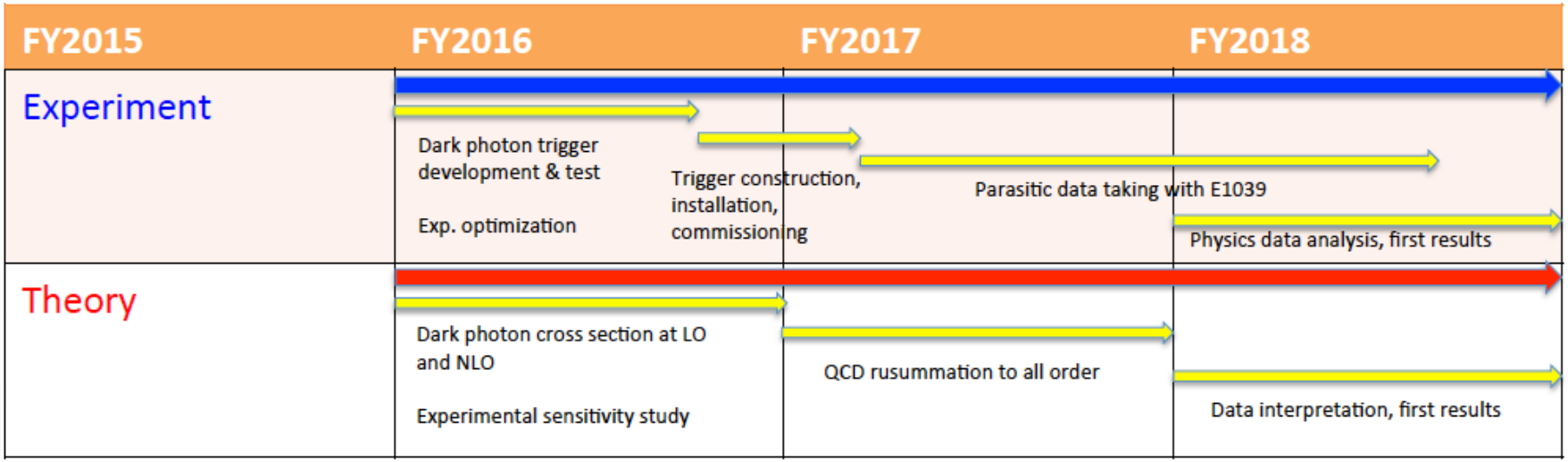
  - Needs an all-order resummation

- We have some preliminary study along this direction, and have compared with earlier Fermilab data
  - Will complete our calculations and apply to our experimental kinematic region, provide realistic computations for dark photon cross section for the full momentum distribution



Summary: FY16 performance on theory efforts

- Theory performance for FY16
  - Completed FY16 milestone: cross section at LO and NLO & experimental sensitivity study



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