Current and Future DY Spin and p-A Activities at Fermilab

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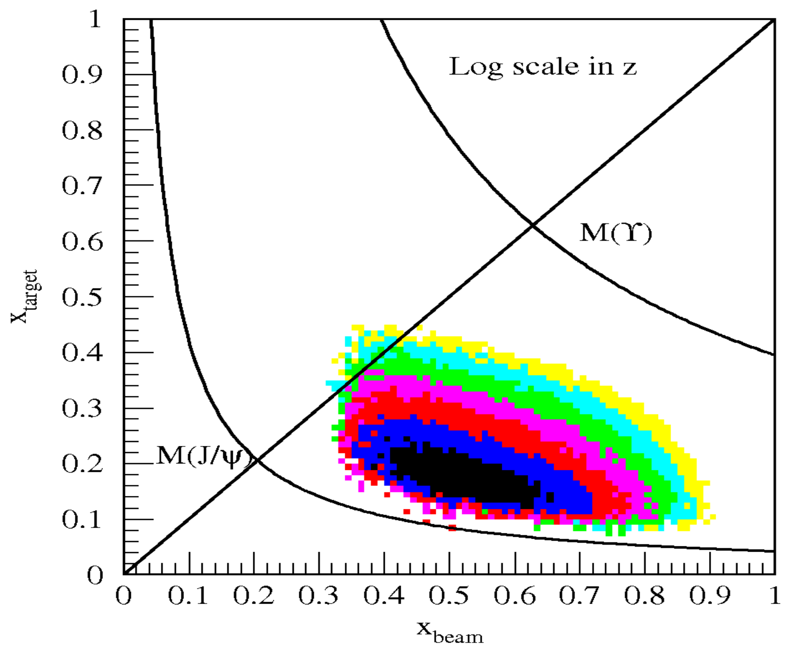
Los Alamos National Laboratory

Emerging Spin and Transverse Momentum Effects in p+p and p+A Collisions
Brookhaven National Laboratory, February 8-10, 2016

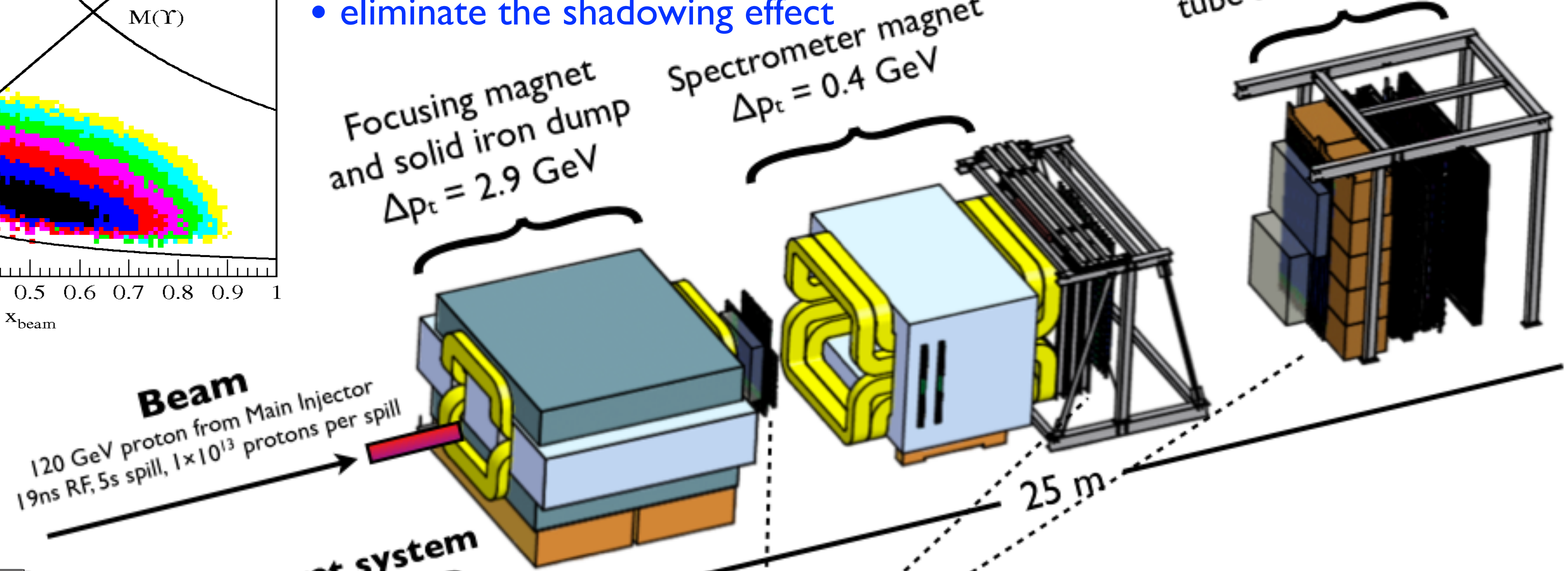
Spin Physics in Unpolarized and Polarized Drell-Yan Process

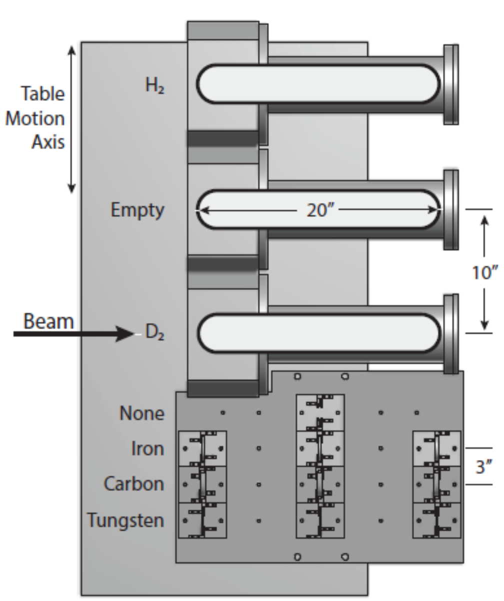
E906/SeaQuest experiment

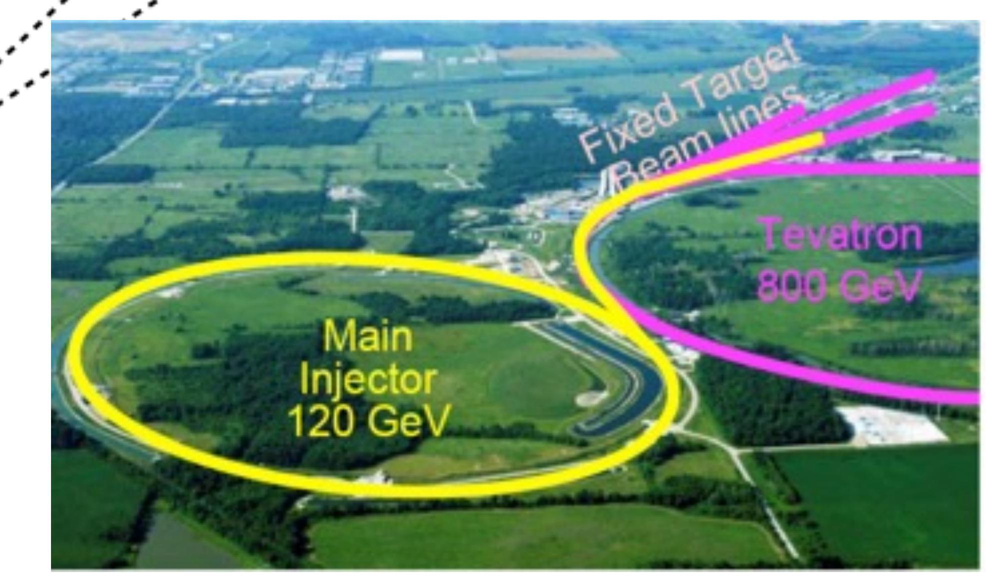


E906/SeaQuest spectrometer is optimized for covering higher x_2 than its predecessors:

- extend E866's measurement of $\bar{d}/\bar{u}$;
- eliminate the shadowing effect







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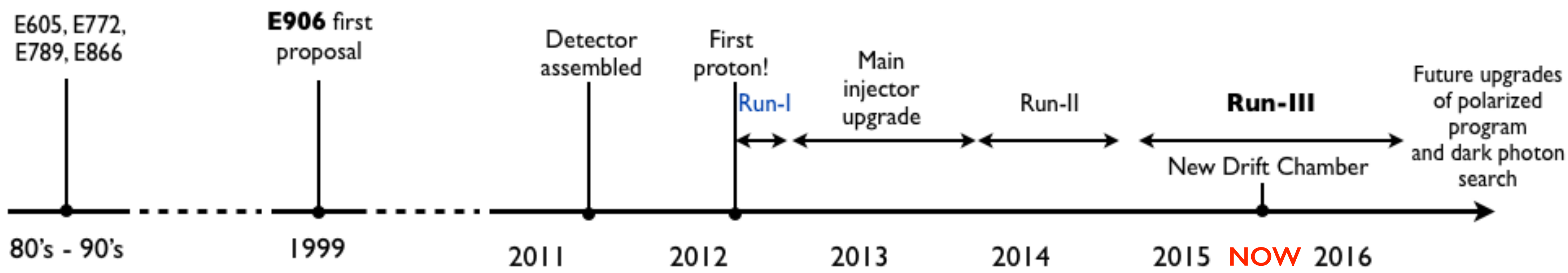
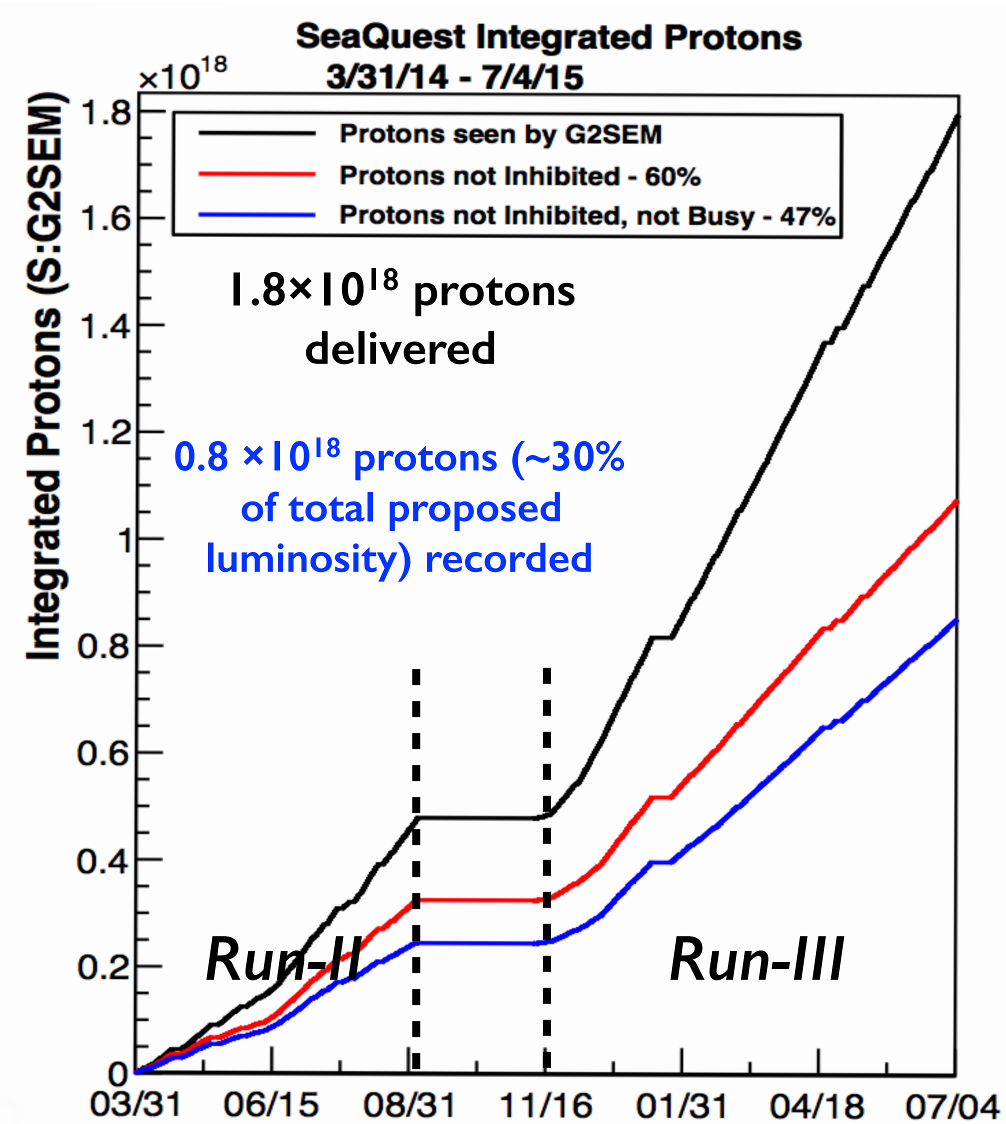
E906/SeaQuest experiment at Fermilab

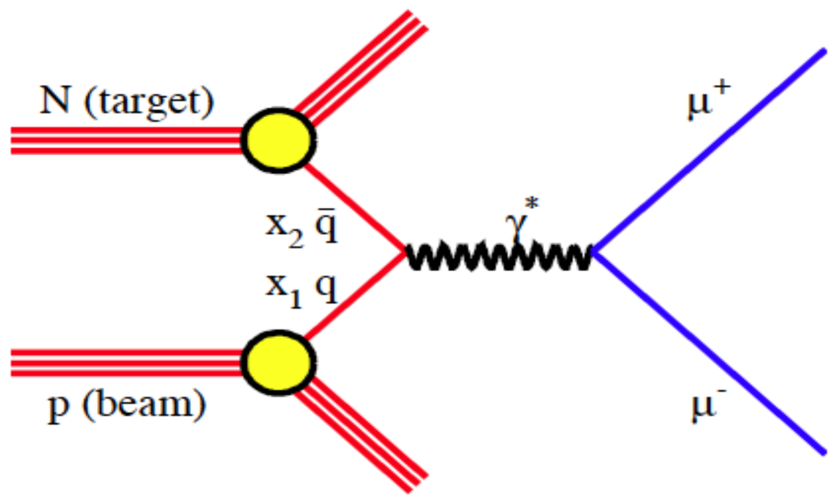




- **Run-I**: 2-month commissioning, first convincing J/ψ signal
- **Run-II**: solved almost all the technical problems and substantial improvement in beam quality, *first physics results!*
- **Run-III**:
  - high quality beam
  - accumulated 30% of the expected statistics
  - new station-1 DC to increase the x_2 coverage
- *Polarized target experiment (E1039) will take over in summer 2016*
- *Parasitic dark photon/higgs search*

E906 kinematic coverage

The Drell-Yan process:

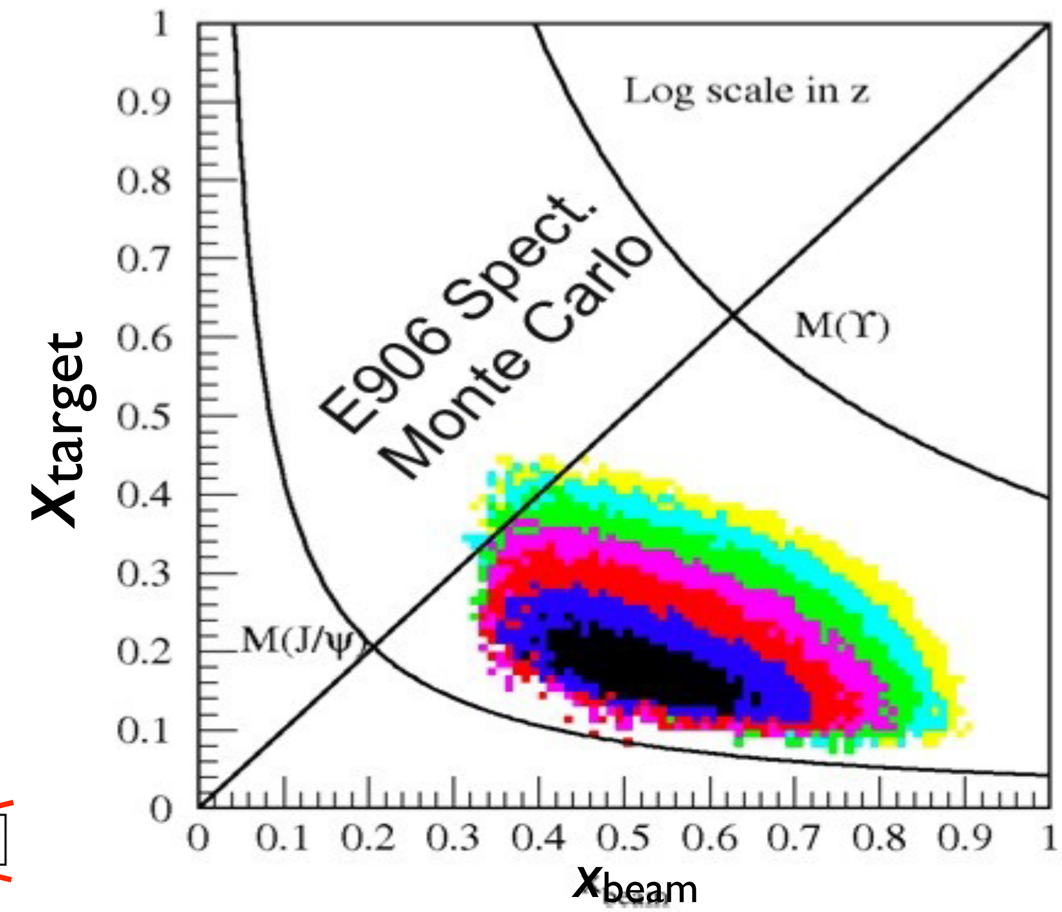


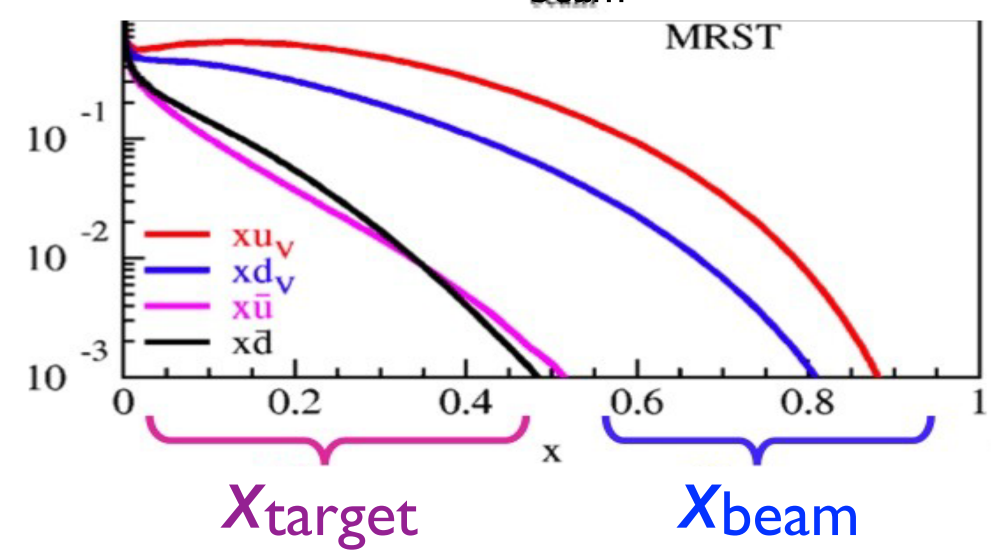
$$\frac{d^2\sigma}{dx_b\, dx_t} = \frac{4\pi\alpha^2}{9 x_b\, x_t} \frac{1}{s} \sum_q e_q^2 \left[\bar{q}_t(x_t) q_b(x_b) + \cancel{q_t(x_t)\bar{q}_b(x_b)}\right]$$

small

Unique sensitivity to sea quarks!

$\bar{q}_t(x_t)$: target sea quark at low/intermediate x
$q_b(x_b)$: beam valence quark at high x





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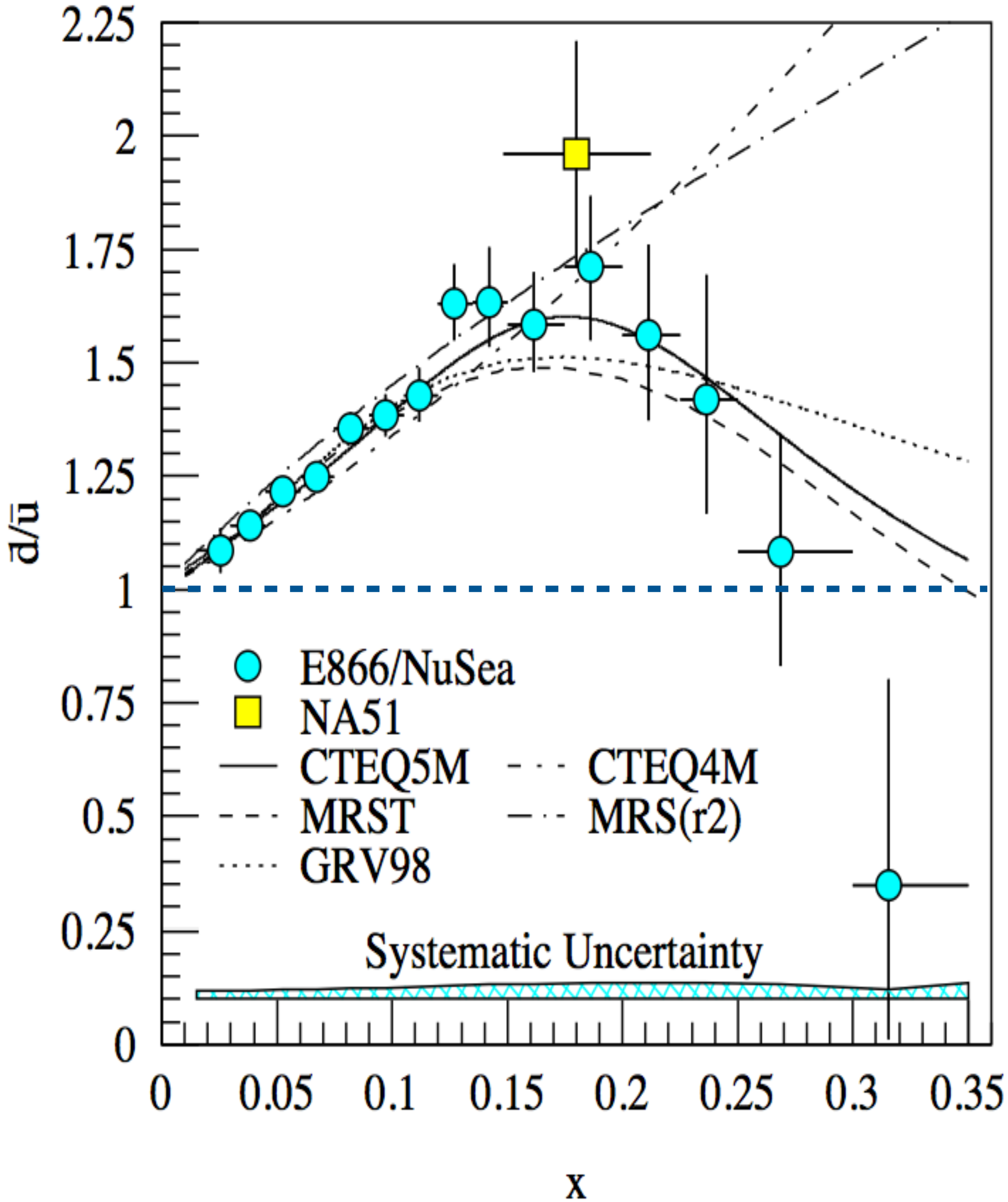
Flavor asymmetry in light quark sea

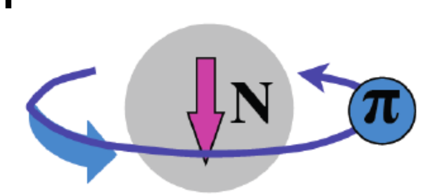


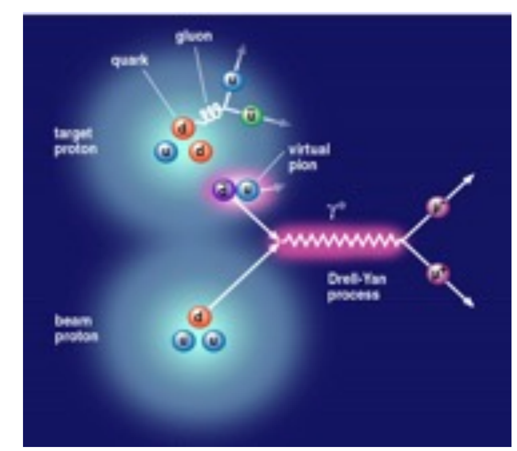
E906's *x* coverage: 0.1 - 0.45

- Assuming charge symmetry, ignoring nuclear effects of deuterium and heavy quark contributions:

$$\left.\frac{\sigma^{pd}}{2\sigma^{pp}}\right|_{x_1 \gg x_2} \approx \frac{1}{2}\left[1 + \frac{\bar{d}(x_2)}{\bar{u}(x_2)}\right].$$

- Naively we would expect flavor symmetry between $\bar{u}$ and $\bar{d}$
- E866/NuSea experiment reveals a striking asymmetry in the sea distributions at moderate x
- Caused by virtual pions?





- Important constraints on light sea polarization
- No models until 2014 (Peng *et al*, PLB 736 2014, 411) could incorporate the behavior beyond $x > 0.25$

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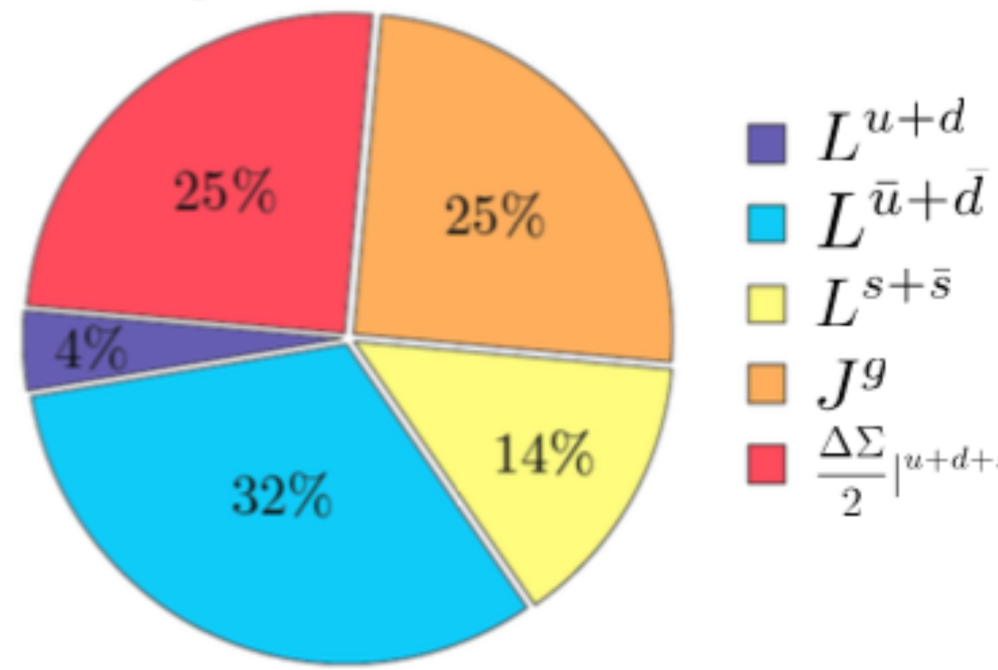
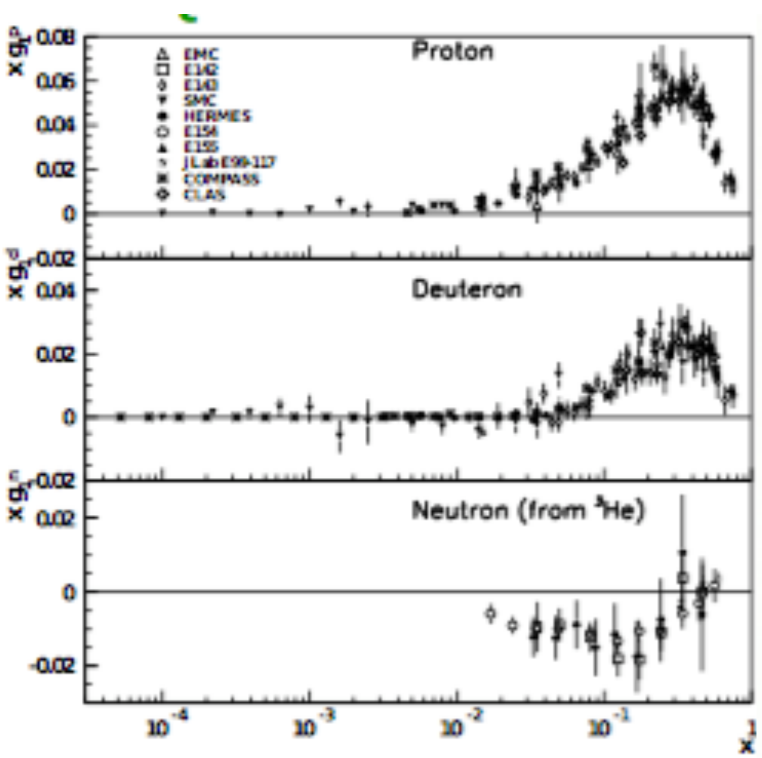
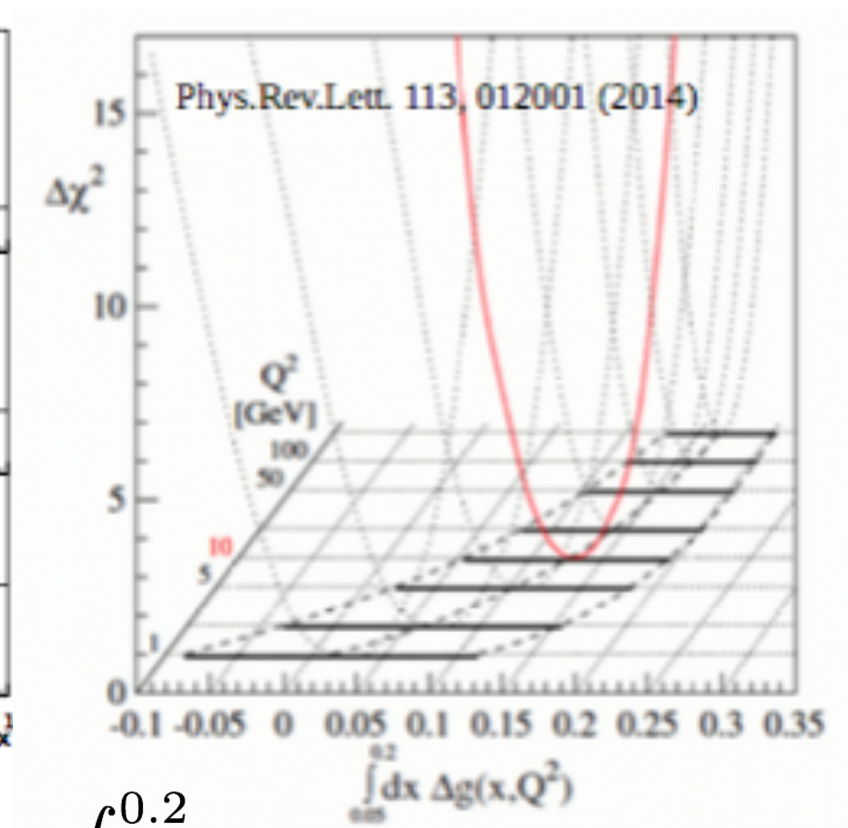
Nucleon spin puzzle

$$S_{\text{proton}} = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

Lattice QCD: K.-F. Liu *et al* arXiv:1203.6388







$$\Delta\Sigma \sim 25\%,$$
$$2L_q \sim 46\%[0\%(L_{\text{valence}}) + 46\%(L_{\text{sea}})],$$
$$2J_g \sim 25\%$$

$$\Delta\Sigma \sim 0.25 \pm \ldots \qquad \int_{0.05}^{0.2} dx \Delta g(x) = 0.2 \pm 0.06$$

Lattice QCD calculations indicate the missing 50% come from sea quark OAM
Could be quantified through the measurement of TMD Sivers function

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Leading twist TMDs

Nucleon \ Parton	U	L	T
U	Unpolarized $f_1(x)$		Boer-Mulders $h_1^{\perp}(x, k_T)$
L		Helicity $g_{1L}(x)$	Worm-Gear $h_{1L}^{\perp}(x, k_T)$
T	**Sivers** $f_{1T}^{\perp}(x, k_T)$	Worm-Gear $g_{1T}^{\perp}(x, k_T)$	Transversity $h_{1T}(x)$ Pretzelosity $h_{1T}^{\perp}(x, k_T)$

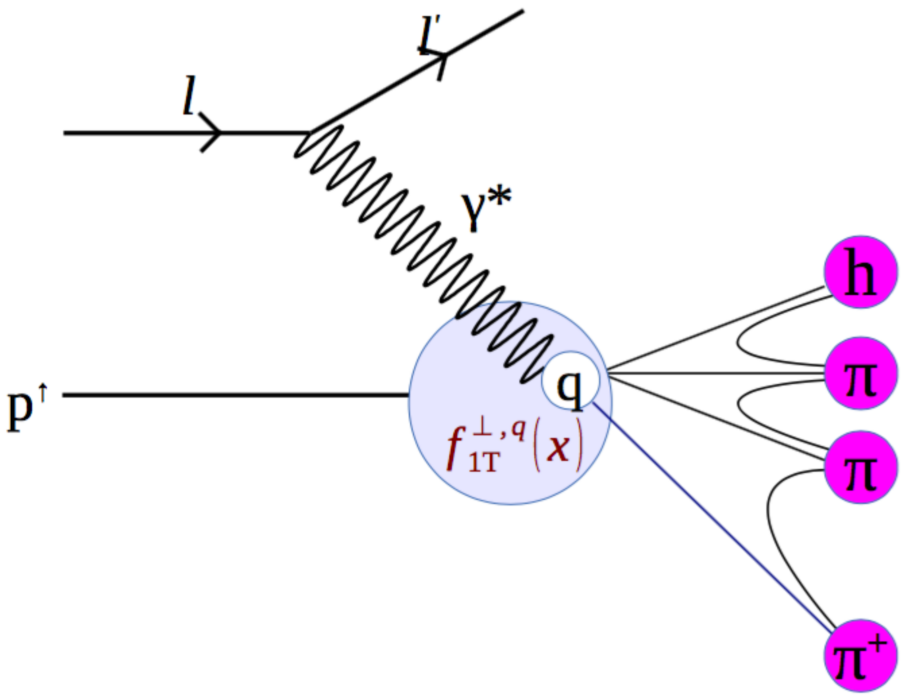
Access through the angular distribution of unpolarized DY at E906

Access through L-R asymmetry in polarized DY at E1039

- Both TMDs lack experimental measurement in DY
- Compared with SIDIS, DY provides unique probe to sea quarks
- Both TMDs are naive T-odd, leading to a sign change between DY and SIDIS

Accessing Quark Sivers function

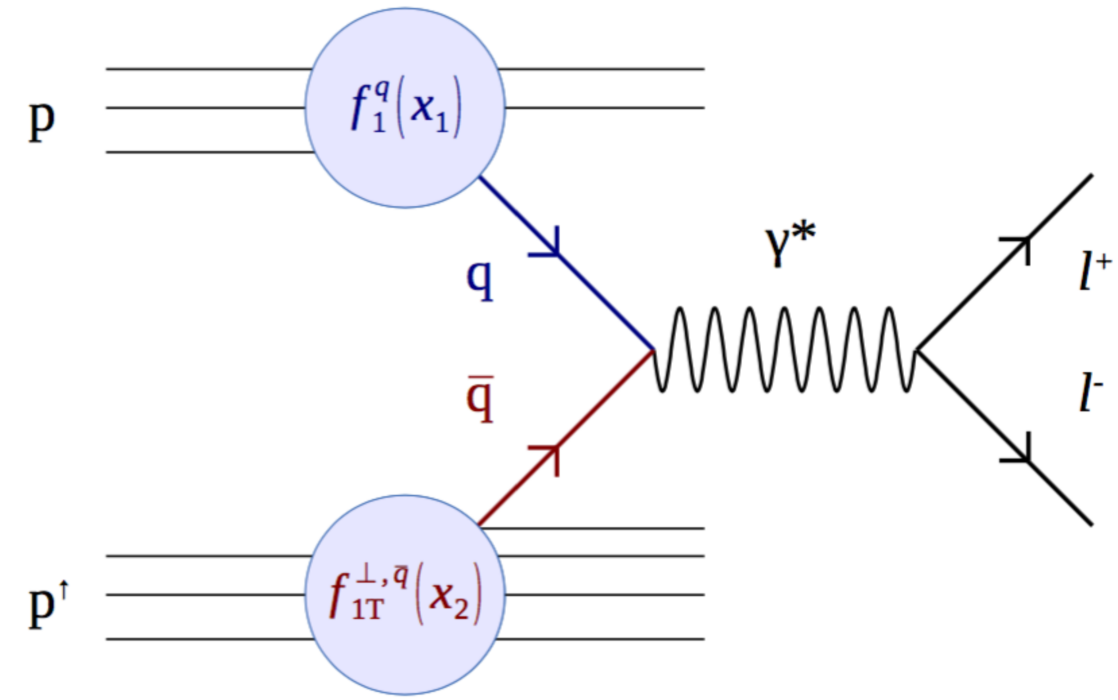
Polarized Semi-Inclusive DIS



$$A_{UT}^{SIDIS} \propto \frac{\sum_q e_q^2 f_{1T}^{\perp,q}(x) \otimes D_1^q(z)}{\sum_q e_q^2 f_1^q(x) \otimes D_1^q(z)}$$

- L-R asymmetry in hadron production
- Quark to hadron fragmentation function
- Valence-sea quark: mixed

Polarized Drell-Yan

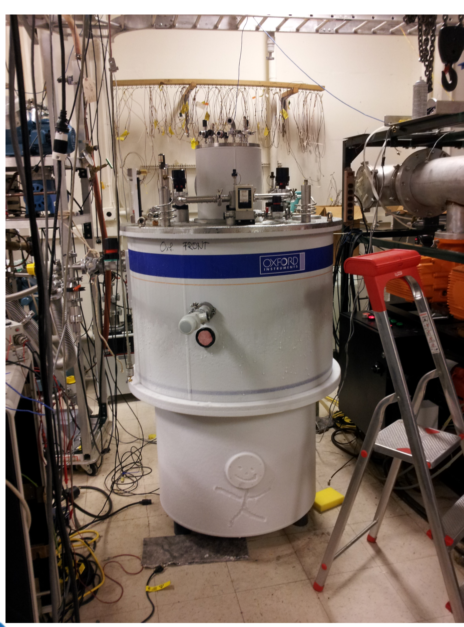


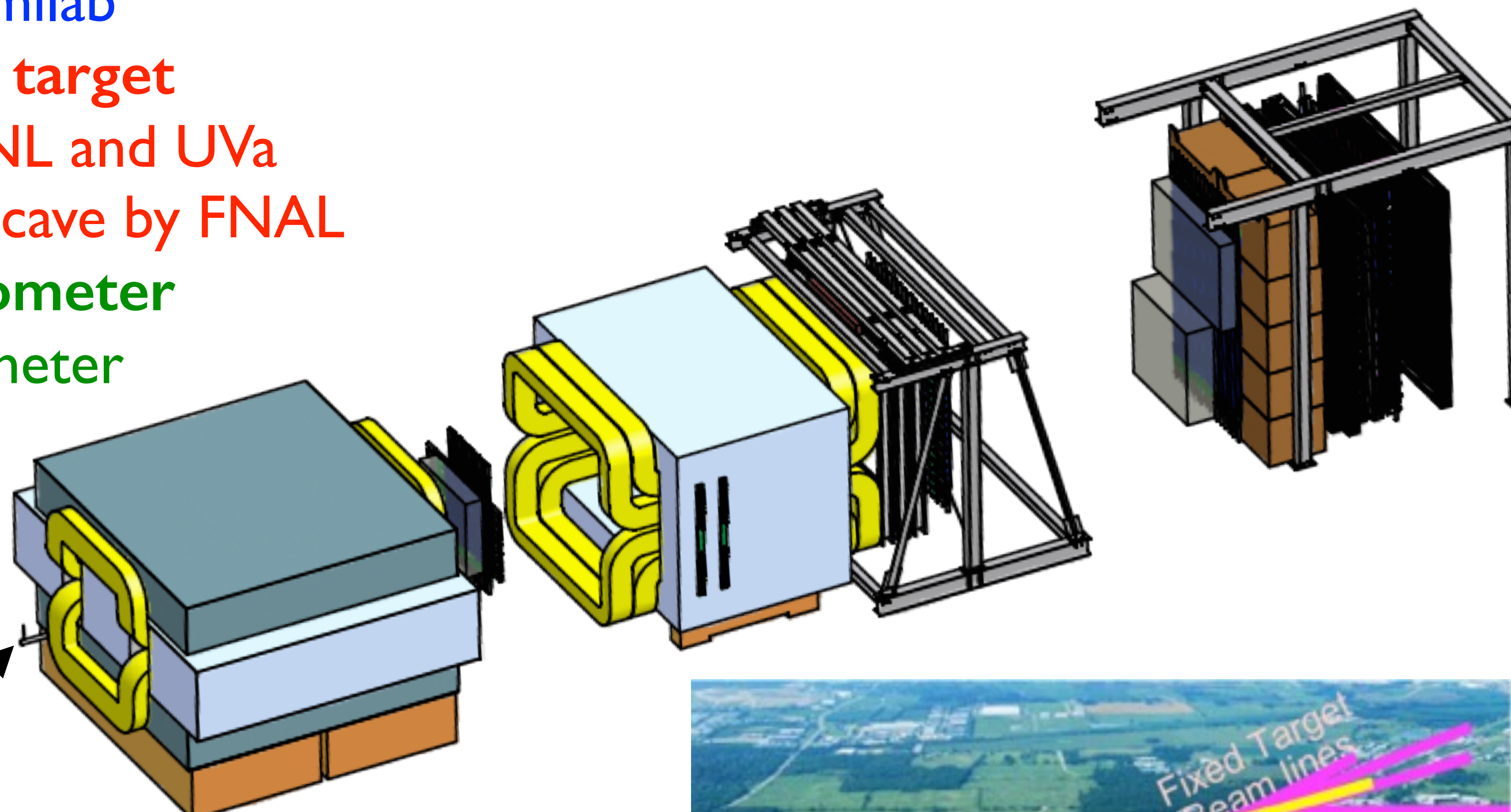
$$A_N^{DY} \propto \frac{\sum_q e_q^2 \left[f_1^q(x_1) \cdot f_{1T}^{\perp,\bar{q}}(x_2) + 1 \leftrightarrow 2 \right]}{\sum_q e_q^2 \left[f_1^q(x_1) \cdot f_1^{\bar{q}}(x_2) + 1 \leftrightarrow 2 \right]}$$

- L-R asymmetry in Drell-Yan production
- **No fragmentation function involved**
- Valence-sea quark: **isolated**

E1039 experiment with polarized proton (NH_3) target

- **120 GeV proton beam from Main Injector**
  - ➢ Improved focusing
  - ➢ In development at Fermilab
- **Polarized proton (NH_3) target**
  - ➢ In development at LANL and UVa
  - ➢ Modification to target cave by FNAL
- **Existing dimuon spectrometer**
  - ➢ Existing E906 spectrometer
- **Collaboration**



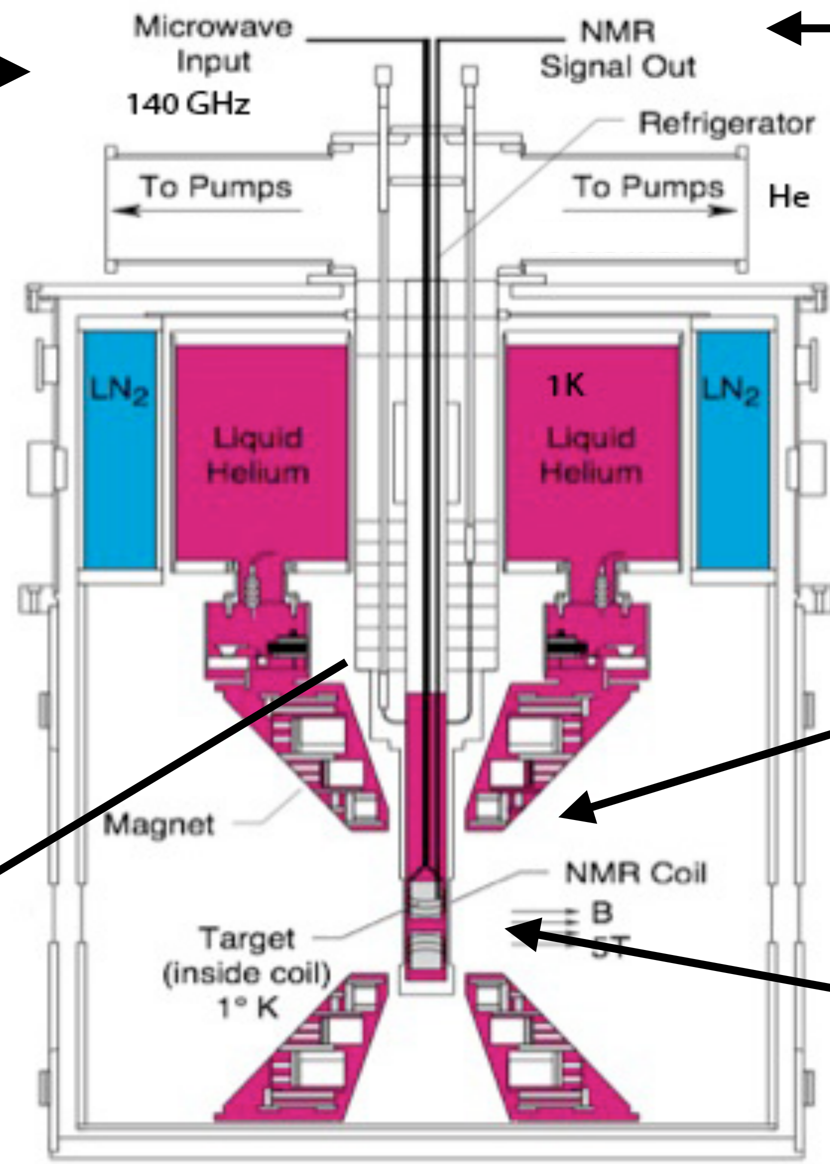


Status of polarized target system

Dynamic Nuclear Polarization (DNP) Microwave signal
ν = 140 ± 0.256 GHz

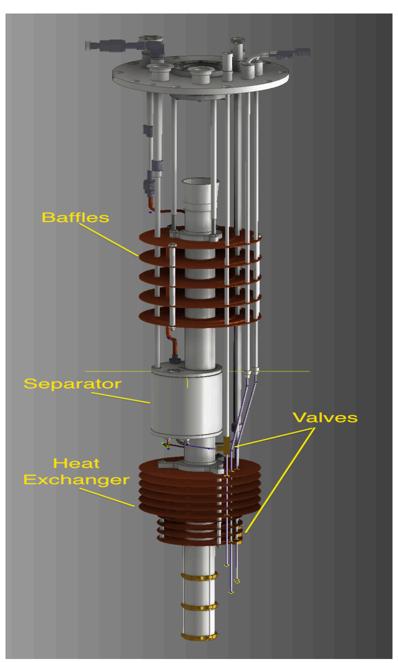
NMR Polarization Measurement

Roots pump system to pump on liquid ^{4}He evaporation to reach 1K, power15,000 m^3/hr

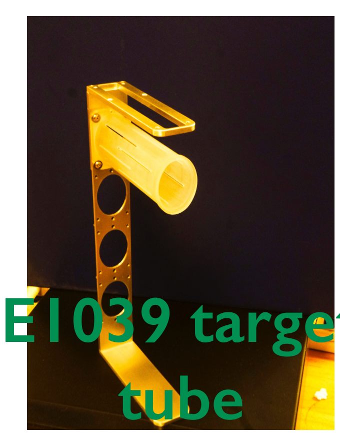


Superconductor Coils 5T magnetic field

Cryostat



Irradiated NH_3 at NIST (P ~ 92%)

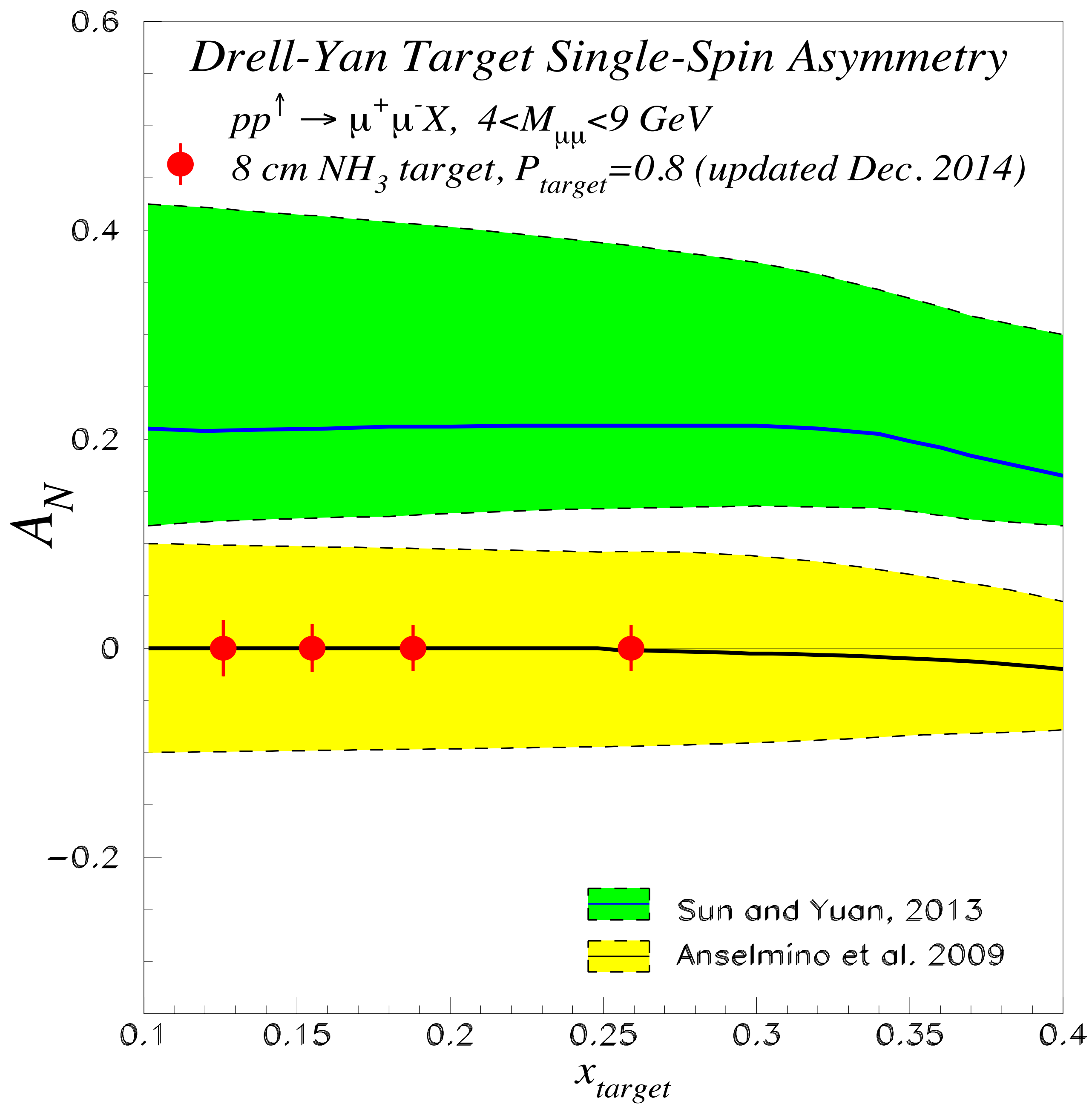


E1039 target tube

JLab NH_3 target

- Full system tested at UVa
- Expect installation at Fermilab in Summar 2016
- Data taking expected to start in Fall 2017

Projected precision with a polarized target at E1039



Statistics shown for one calendar year of running:
L = 5.2×10^{42} cm^{-2} ⟺ POT = 9.7×10^{17}

$$A_N^{DY} \propto \frac{u(x_b) \cdot f_{1T}^{\perp,\bar{u}}(x_t)}{u(x_b) \cdot \bar{u}(x_t)}$$

Existing data do not put enough constraints on the sea quark Sivers distribution, neither sign nor value.

If $A_N \neq 0$, major discovery:

- "Smoking gun" evidence for $L_{ubar} \neq 0$
- Determine sign and value for ubar Sivers distribution
- Confirm Lattice QCD and Meson Cloud Model expectations

If $A_N = 0$:

- $L_{ubar} = 0$, spin puzzle more dramatic ?
- Sea flavor asymmetry hard to explain
- In contradiction to Lattice QCD and Meson Cloud Model expectations

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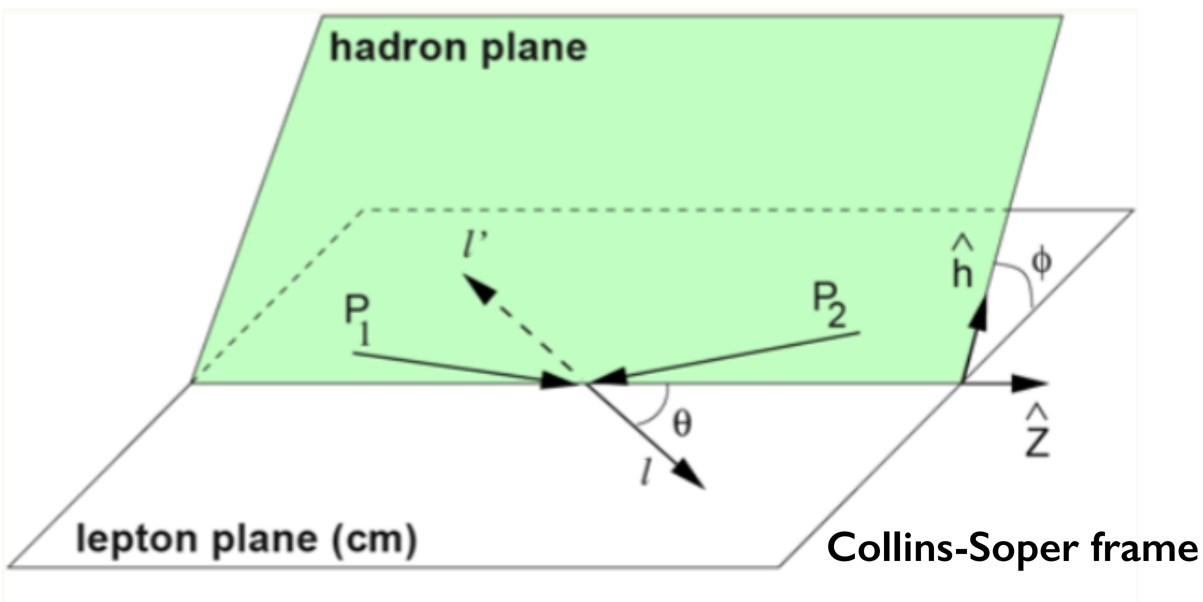
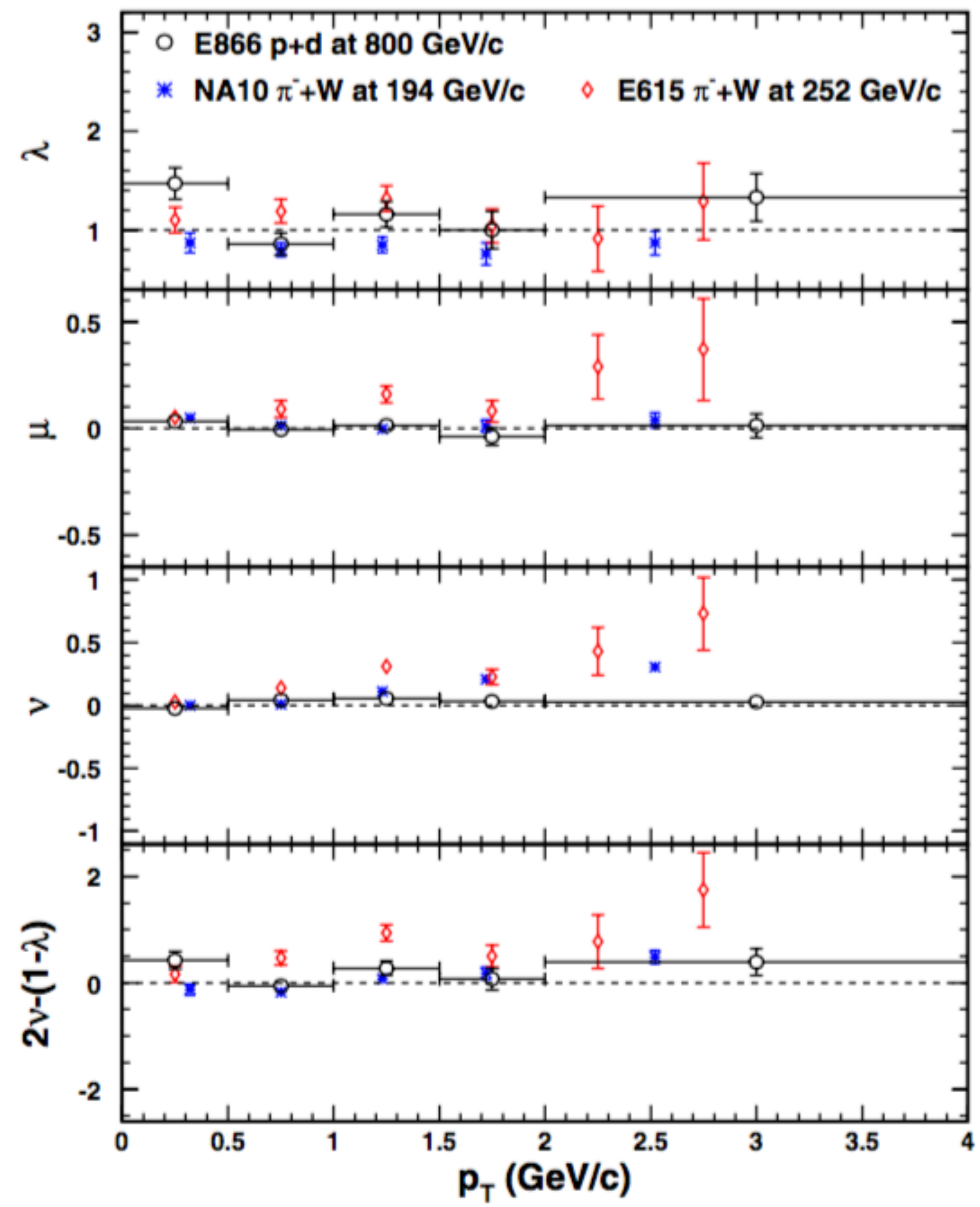
Data taking expected to start in 2017 fall!

Accessing Boer-Mulders (BM) function in unpolarized DY

$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda\cos^2\theta + \mu \sin 2\theta \cos\phi + \frac{\nu}{2}\sin^2\theta \cos 2\phi$$





- Lam-Tung violation: $1 - \lambda \neq 2\nu$
- ν can be decomposed to the convolution of two BM functions: $\nu \propto [h_1^\perp \text{ of } \bar{q}] \times [h_1^\perp \text{ of } q]$
- Measurement of BM in proton-induced DY using pp and pd data:
  - ➢ identify the source of Lam-Tung violation
  - ➢ test the flavor dependence prediction

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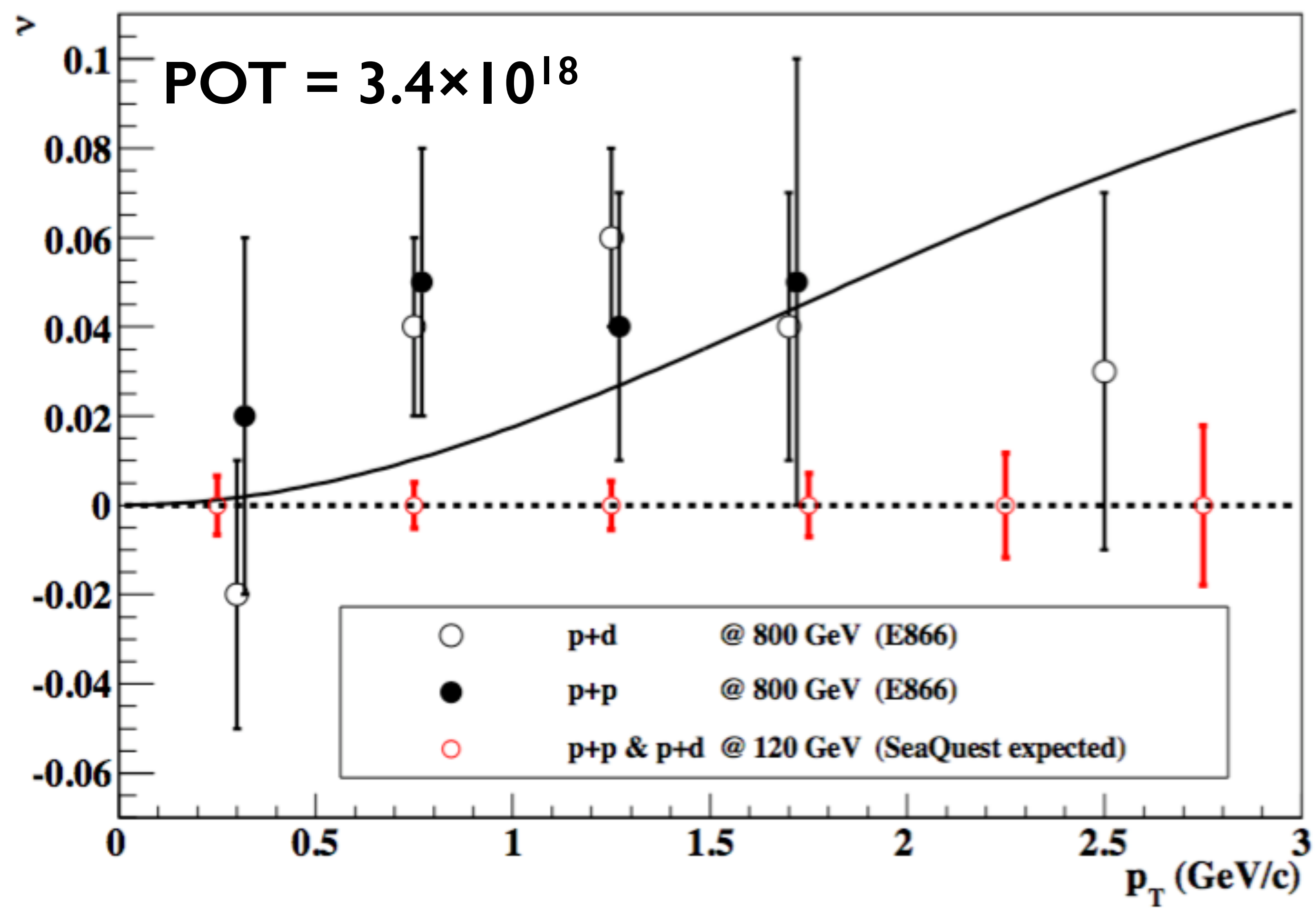
Expected precision of E906

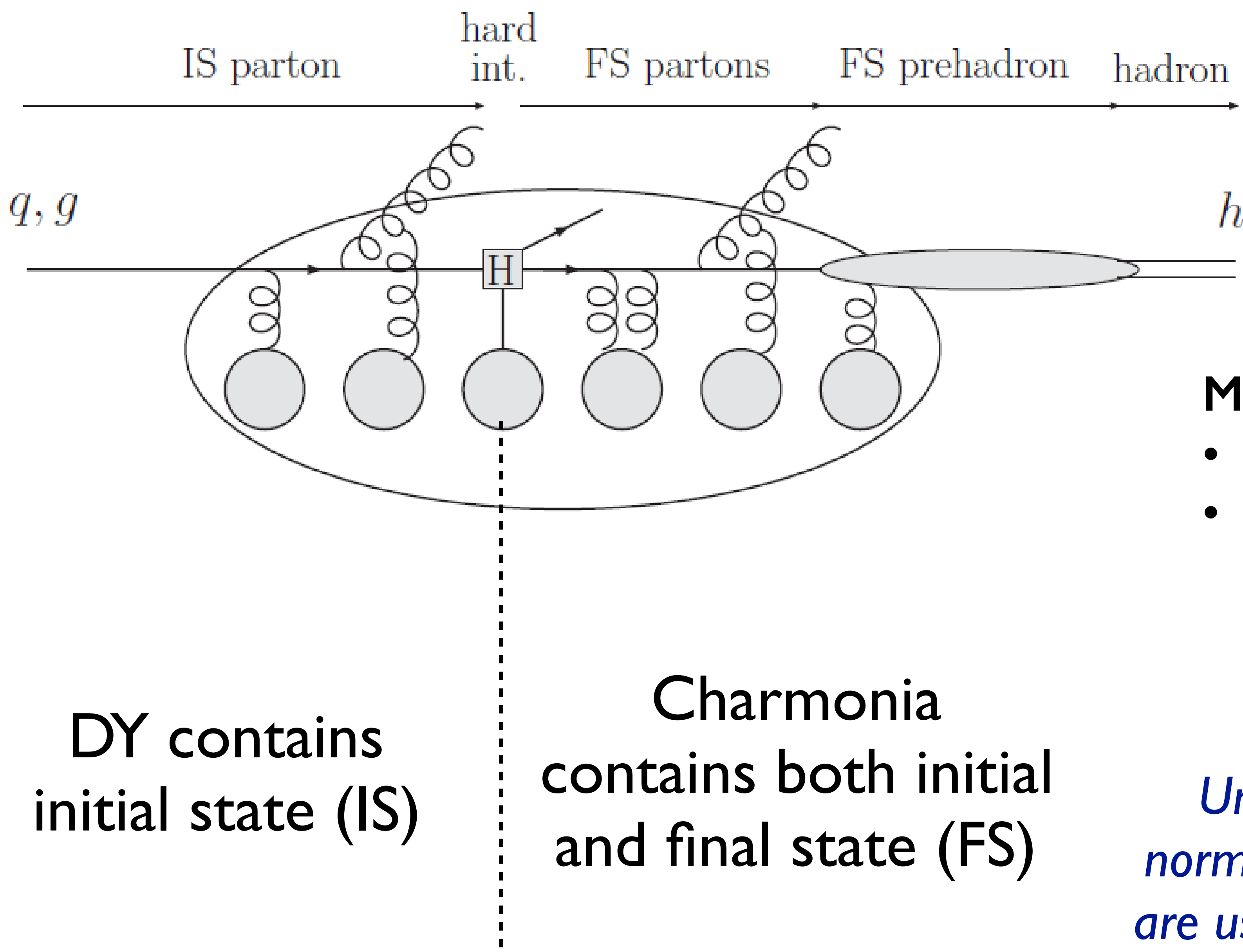
- Significant improvement in precision compared with previous experiments
- Very challenging analysis
- Both p+p and p+d data available



Nuclear Dependence of Transverse Momentum Distribution in DY and Charmonia Production

Understanding the p_T spectrum of DY and charmonia

Accord, PRC 76, 034902 (2007)



Origin of p_T spectrum

- intrinsic p_T of IS parton
- elastic scattering of IS parton
- gluon emission of IS parton
- can be isolated in DY process

Modification to p_T spectrum

- absorption of FS prehadron
- interaction of FS prehadron with nuclear medium

DY contains initial state (IS)

Charmonia contains both initial and final state (FS)

Understanding the suppression in normal nuclear matter is critical if they are used as a probe for hot high density matter (QGP) in heavy-ion collisions

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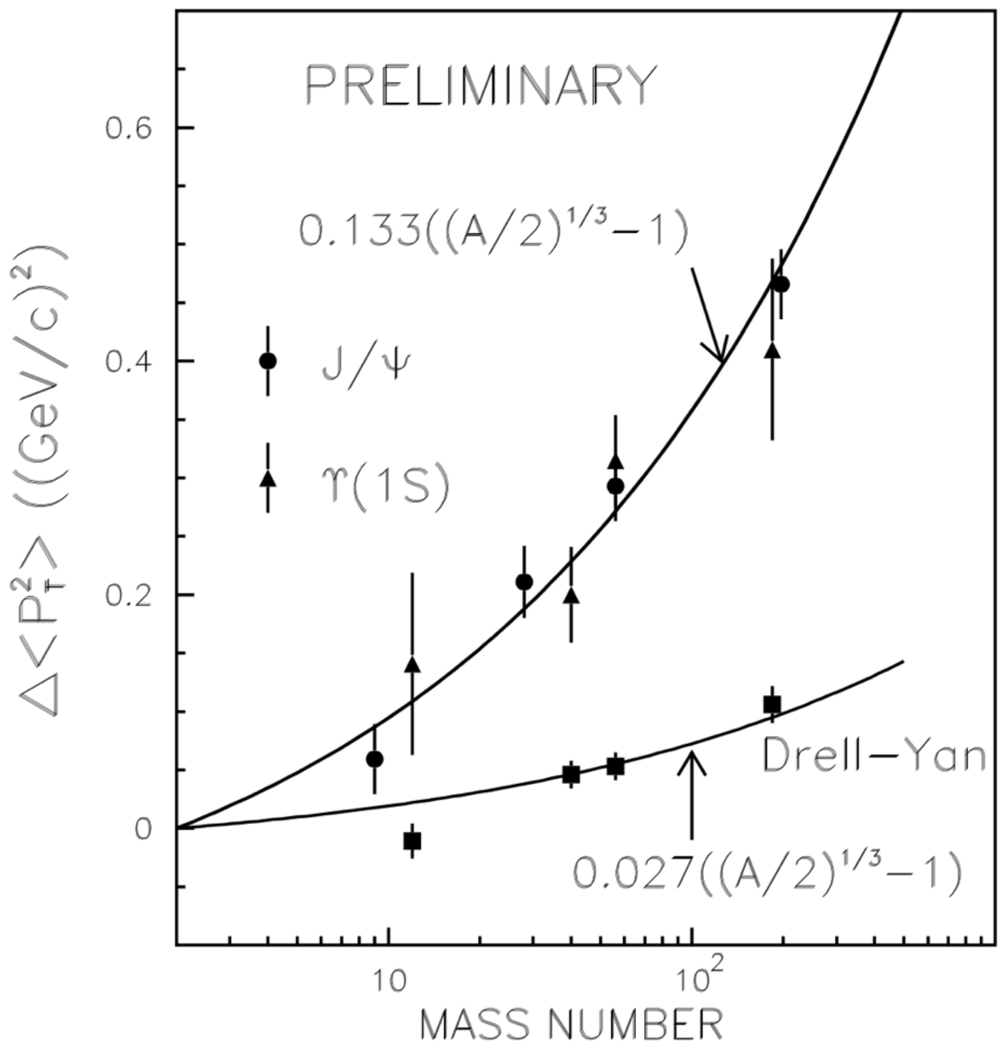
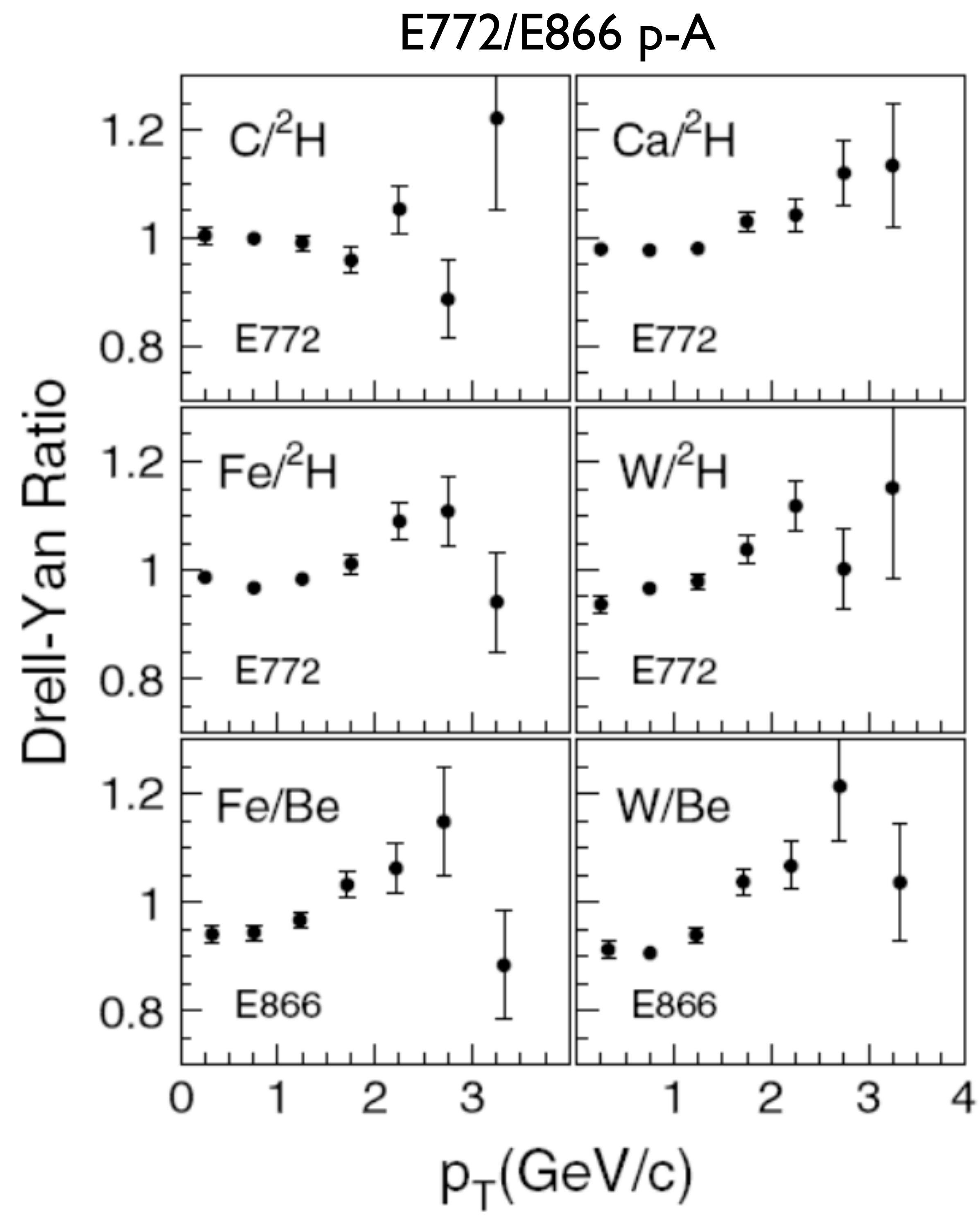
Transverse momentum broadening (Cronin effect)

P. L. McGaughey, J. M. Moss and J. C. Peng, Annu. Rev. Nucl. Part. Sci. 49, 217 (1999); J. C. Peng, arXiv:hep-ph/9912371.



E772/E866 p-A



A combined analysis of p_T-broadening and x_F degradation is needed to extract the initial-state interaction

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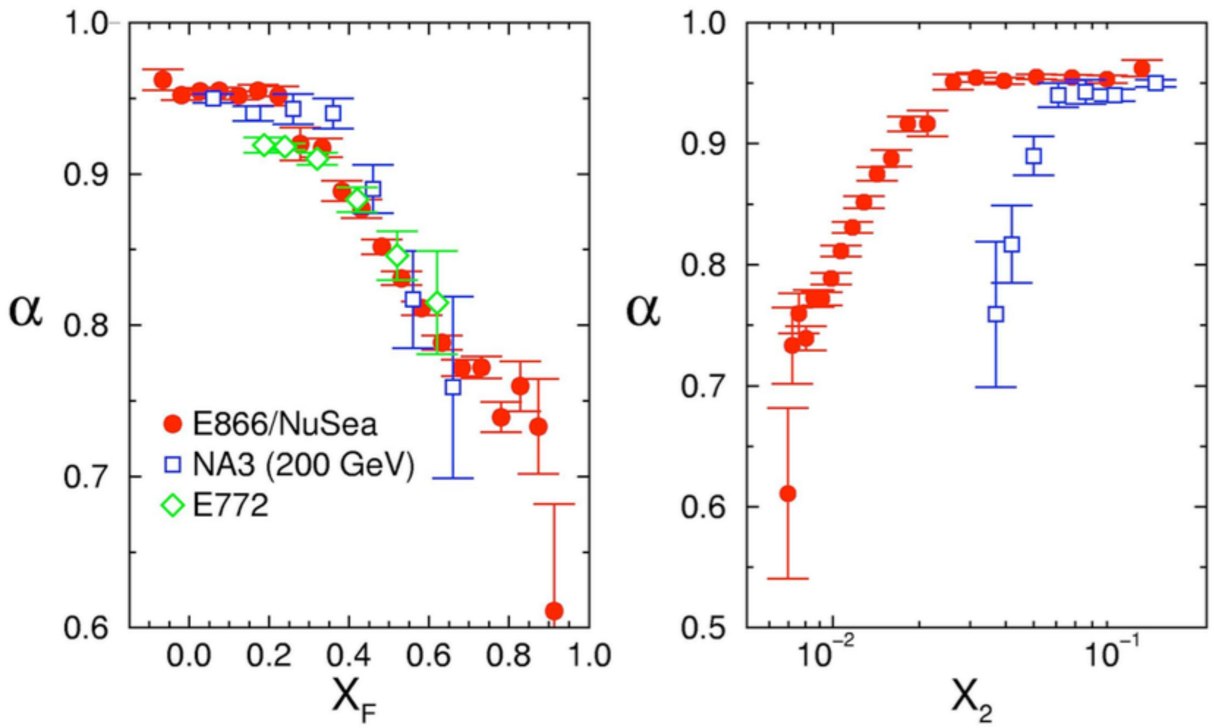
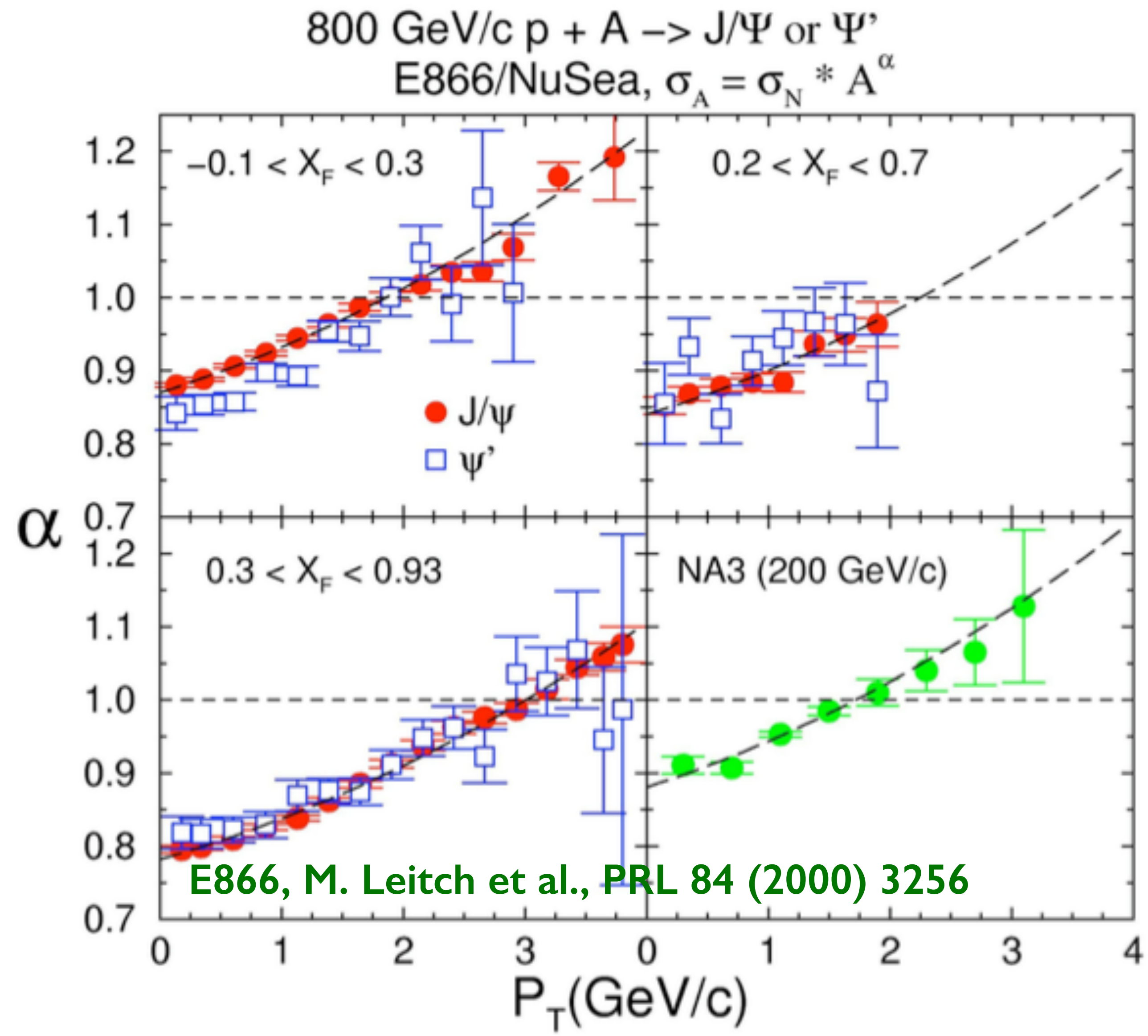
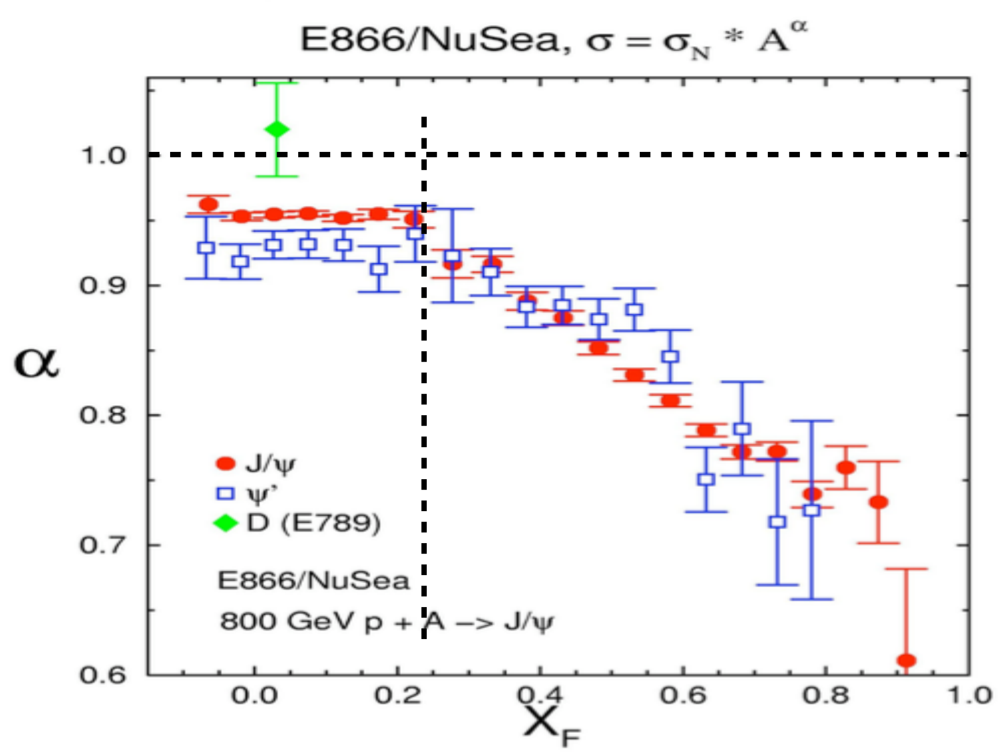
Nuclear effects in charmonia production





E866, M. Leitch et al., PRL 84 (2000) 3256



- Nuclear effects scale with x_F, but not x_T
- 'Universal' behavior for $\alpha(p_T)$ and $\alpha(x_F)$,
- E906 will probe this behavior at much lower energy
  - production mechanism changes with $\sqrt{s}$
  - formation time could also change

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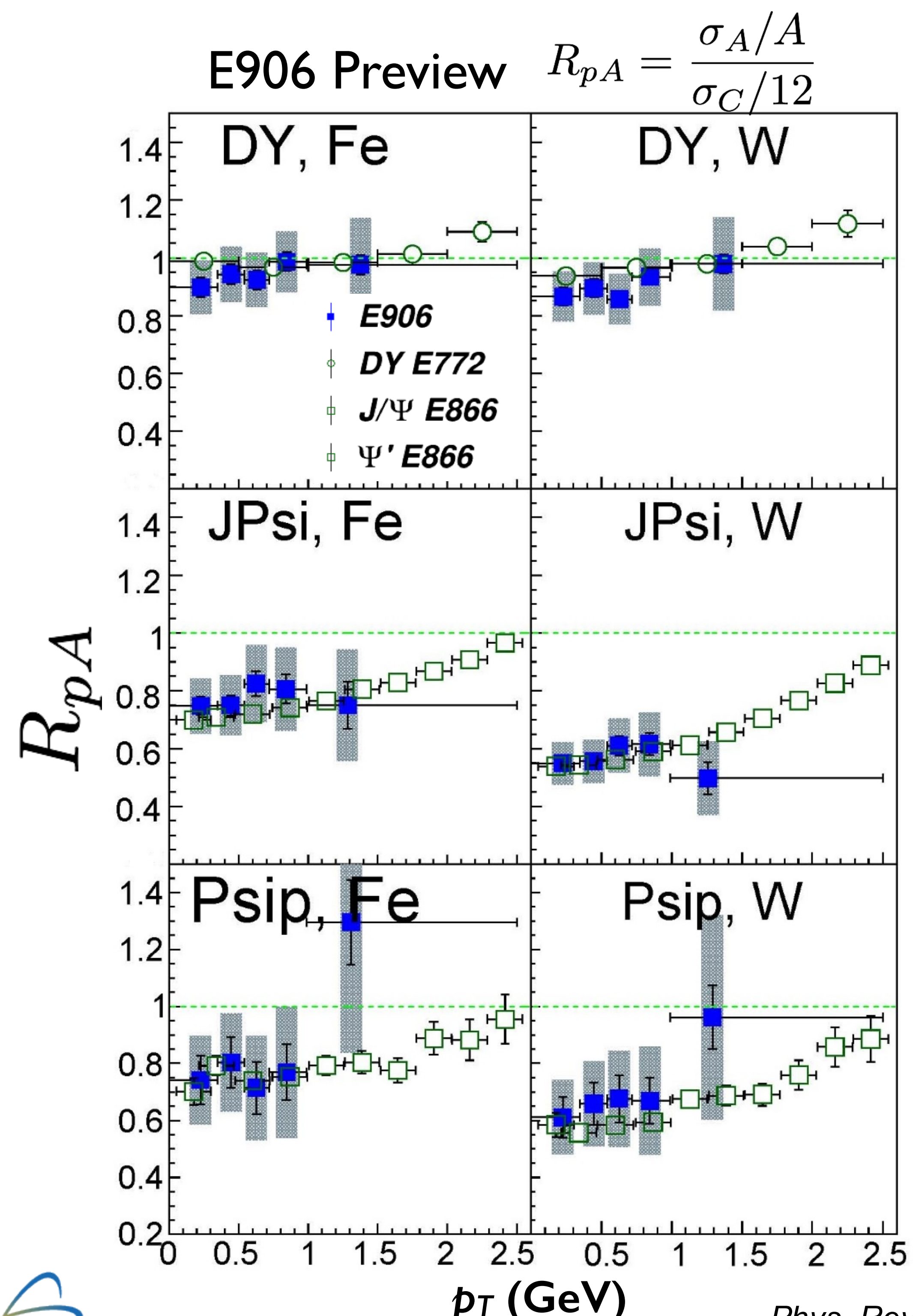
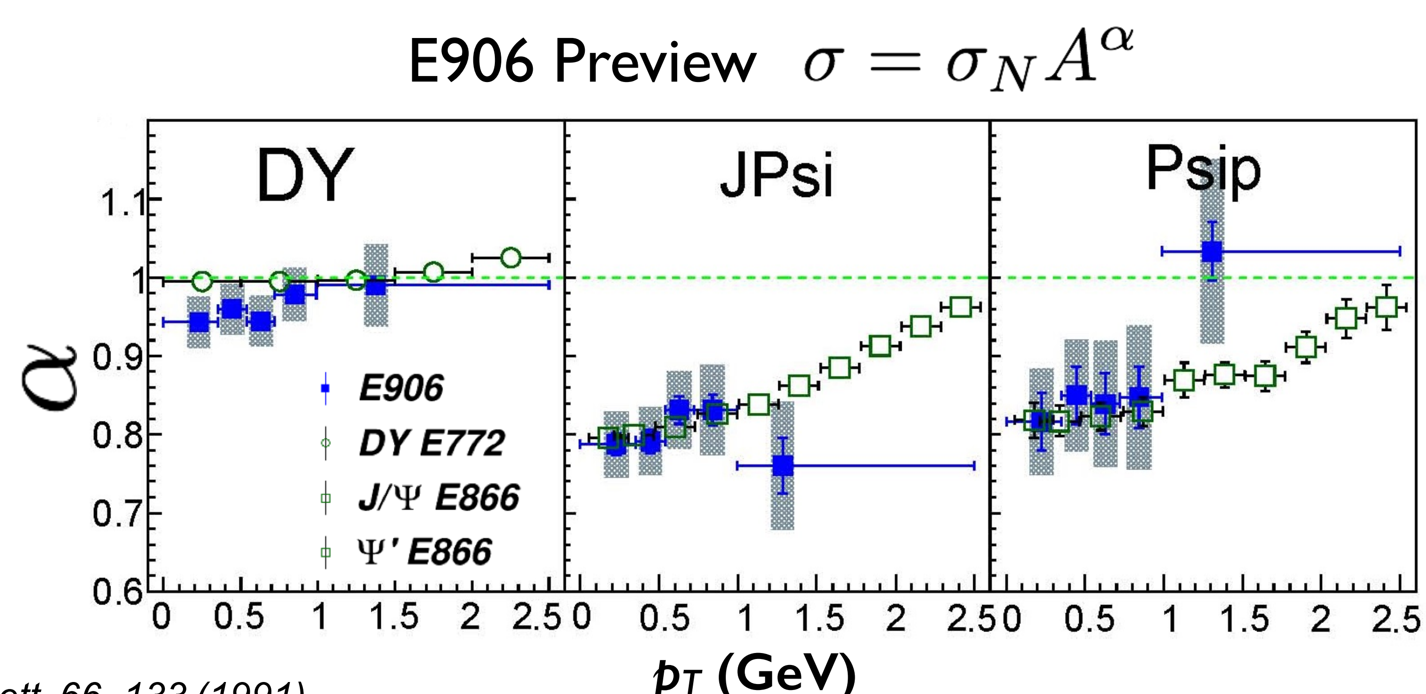
Preliminary p_T measurement at E906



- Only 30% of final data set, and very conservative systematic error estimation
- Both DY and charmonia suppression shows very similar scale/shape compared to previous experiments with 800 GeV beam.
- J/ψ and ψ' shows very similar p_T dependence, where they both correspond to ccbar traversing the nucleus.



Phys. Rev. Lett. 66, 133 (1991)
Phys. Rev. D52, 4251 (1995)
Phys. Rev. Lett. 84, 3256-3260

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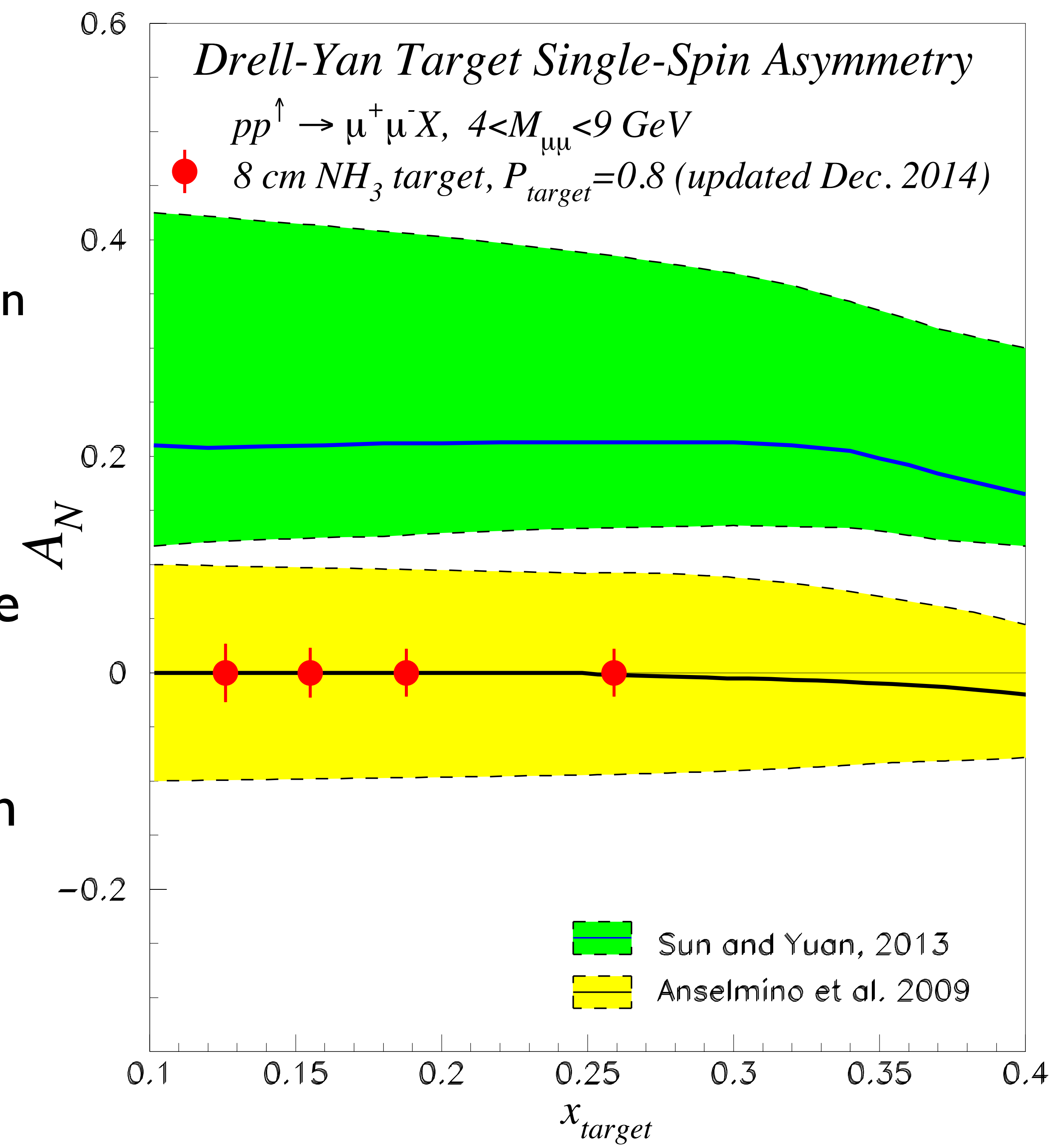
Summary

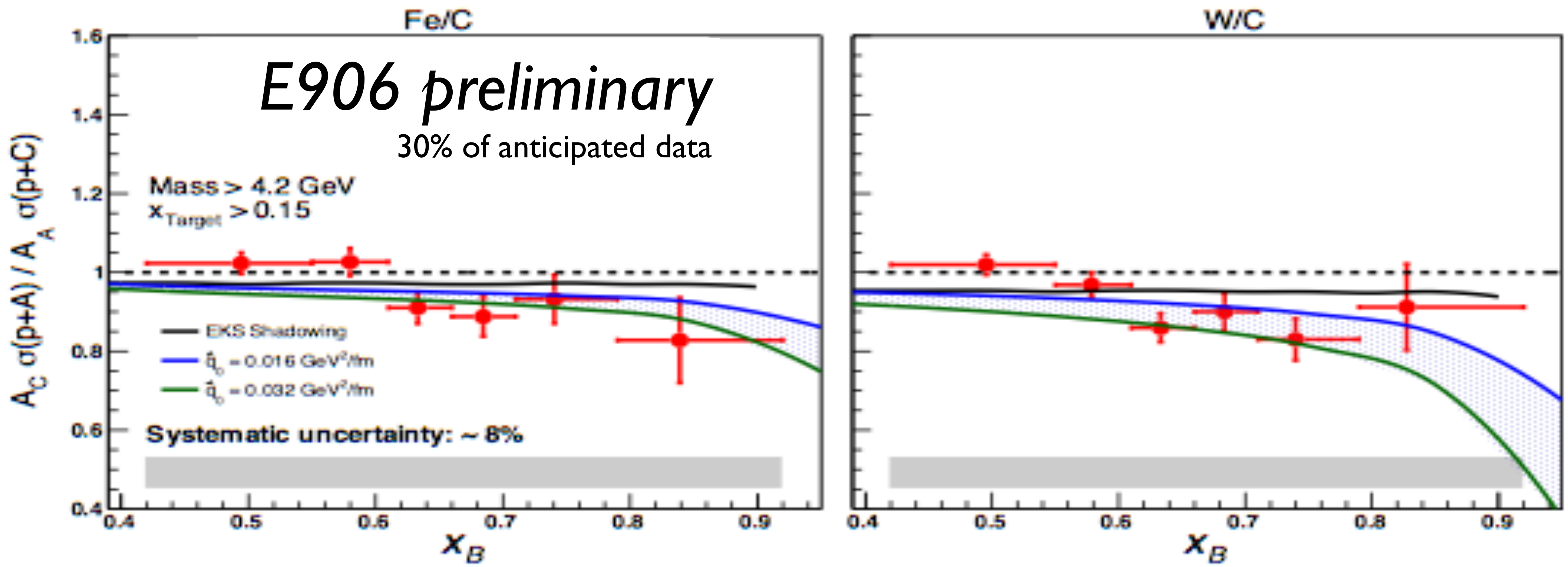
- Being a fixed target experiment, E906/SeaQuest and the extension E1039 provide very unique access to the sea quark TMDs in DY:
  - ➢ first measurement of sea quark Sivers function in DY, long missing piece of the nucleon spin
  - ➢ much more accurate measurement of the Boer-Mulders function in proton-induced DY
- On pA physics side, E906 is able to extend the previous DY and charmonia measurement to lower c.m. energy and larger kinematics, to constrain the extraction of QGP properties in heavy-ion collisions
- Other physics programs at E906 and beyond:
  - ➢ light sea quark flavor asymmetry
  - ➢ search for dark photon/higgs produced in beam dump
  - ➢ …

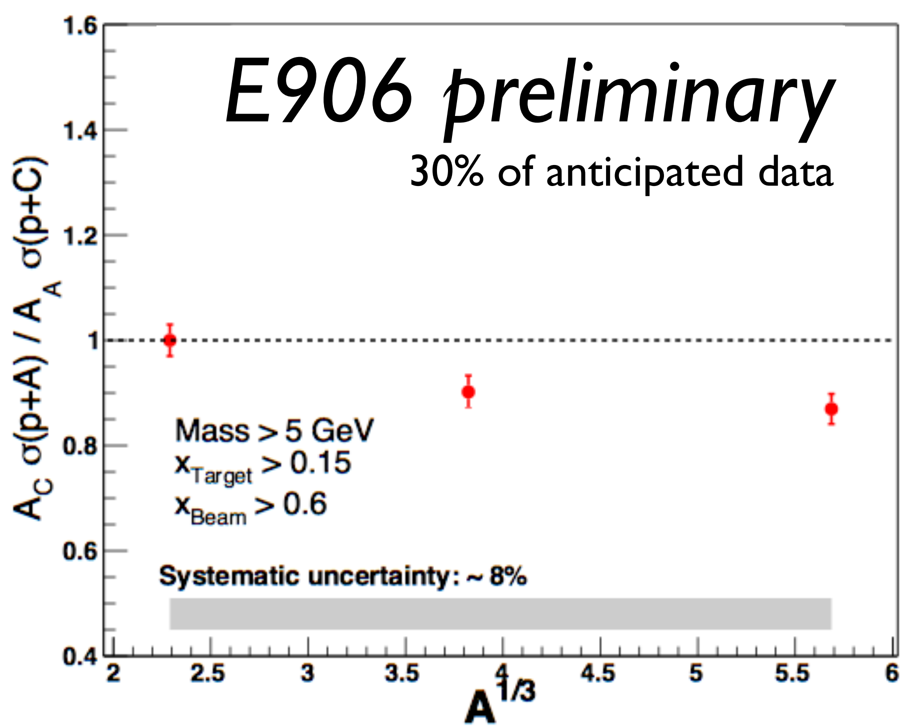


Thanks very much!

Backup slides: challenges, other physics programs

Quark energy loss in DY





- A clear indication of suppression beyond the shadowing strength is observed in p+Fe and p+W data, which agrees well with the theory prediction.
- E906's measurement in return proves the large suppression observed in E866 has a large shadowing contribution
- We are working closely with leading theorists to interpret our latest results (I. Vitev Z-B Kang and H-X Xing from LANL, R. Vogt, B-W Zhang *et al* from outside)
- With the complete data set, we will be able to clearly distinguish between:
  - ➢ $-dE \propto A^{1/3}$ (or $\propto L$)
  - ➢ $-dE \propto A^{2/3}$ (or $\propto L^2$)

This is the first unambiguous sign of quark energy loss in cold nuclear matter!

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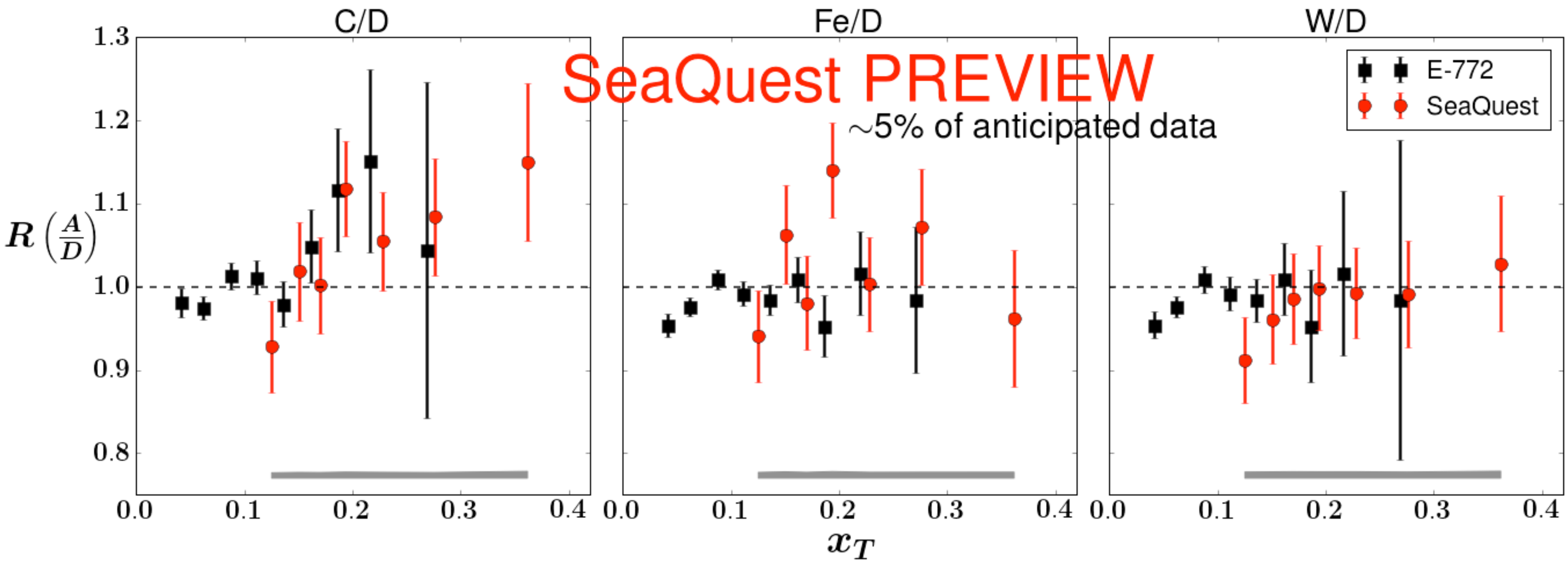
EMC effect in DY from E906



- Only consists of 5% of the total expected statistics
- Well consistent with E772 results at low x_T
- Pushing into x_T range (0.3 - 0.6) where DIS sees clear depletion parton densities (*what will the sea do?*)
- Current systematic error mainly comes from LD_2 impurity and unresolved rate-dependence. We expect final systematic uncertainty to be ~1%

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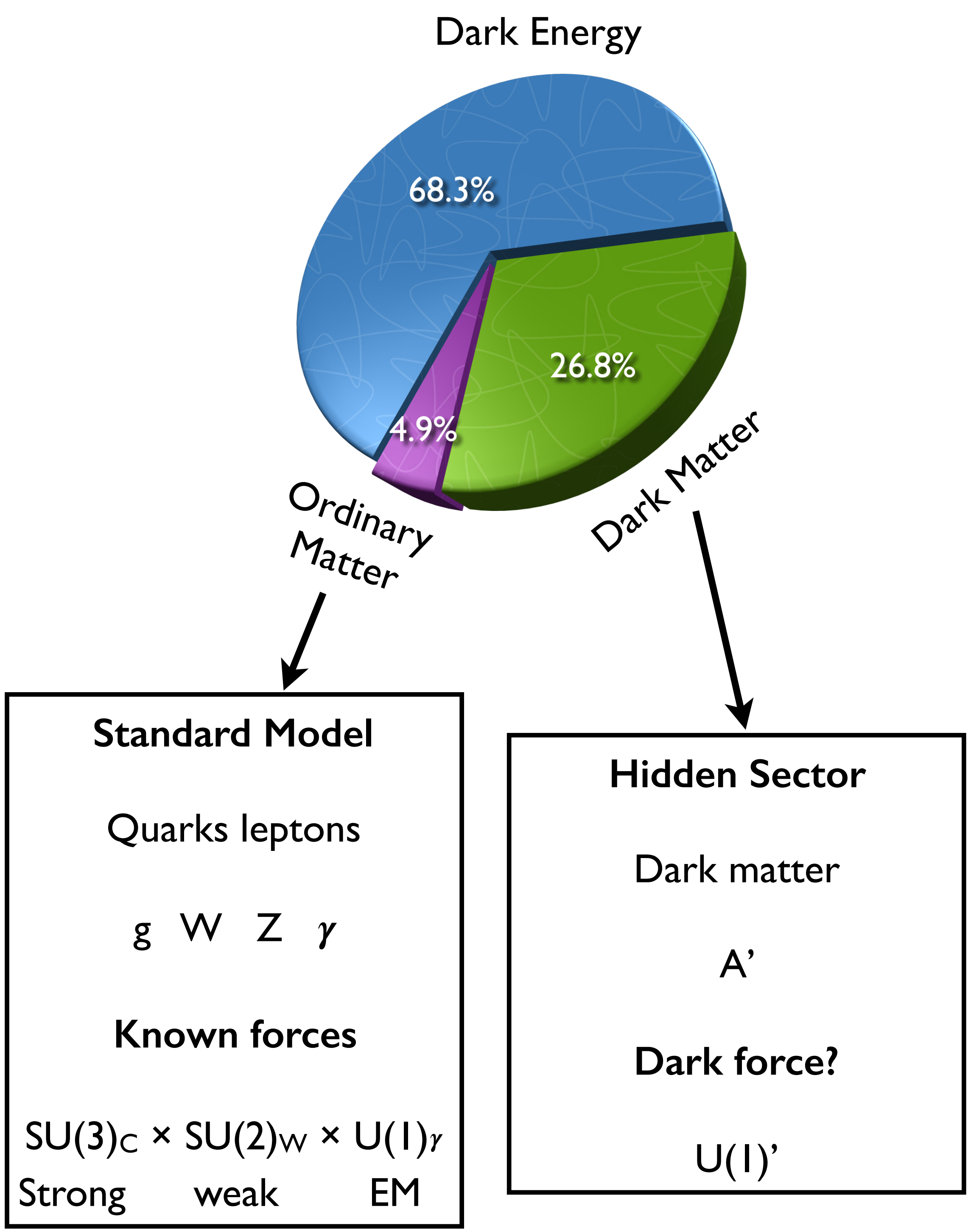
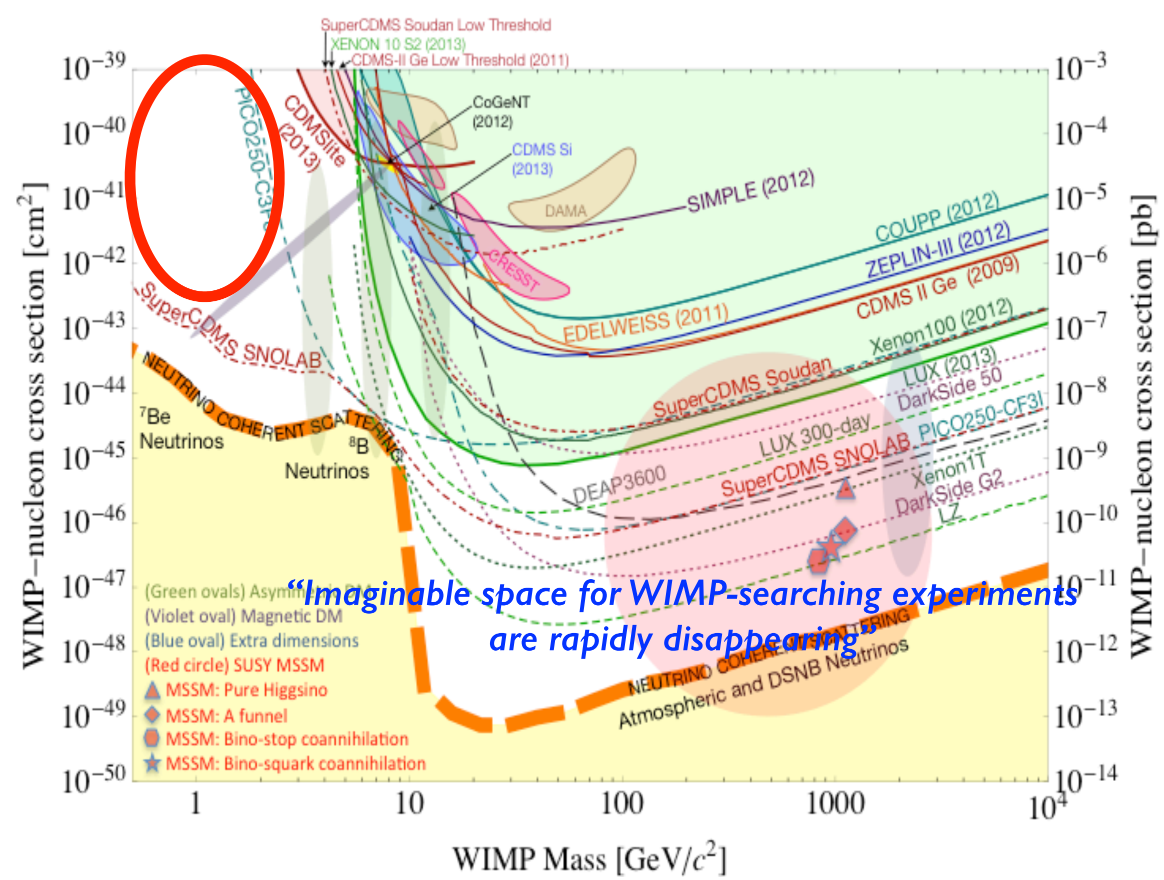
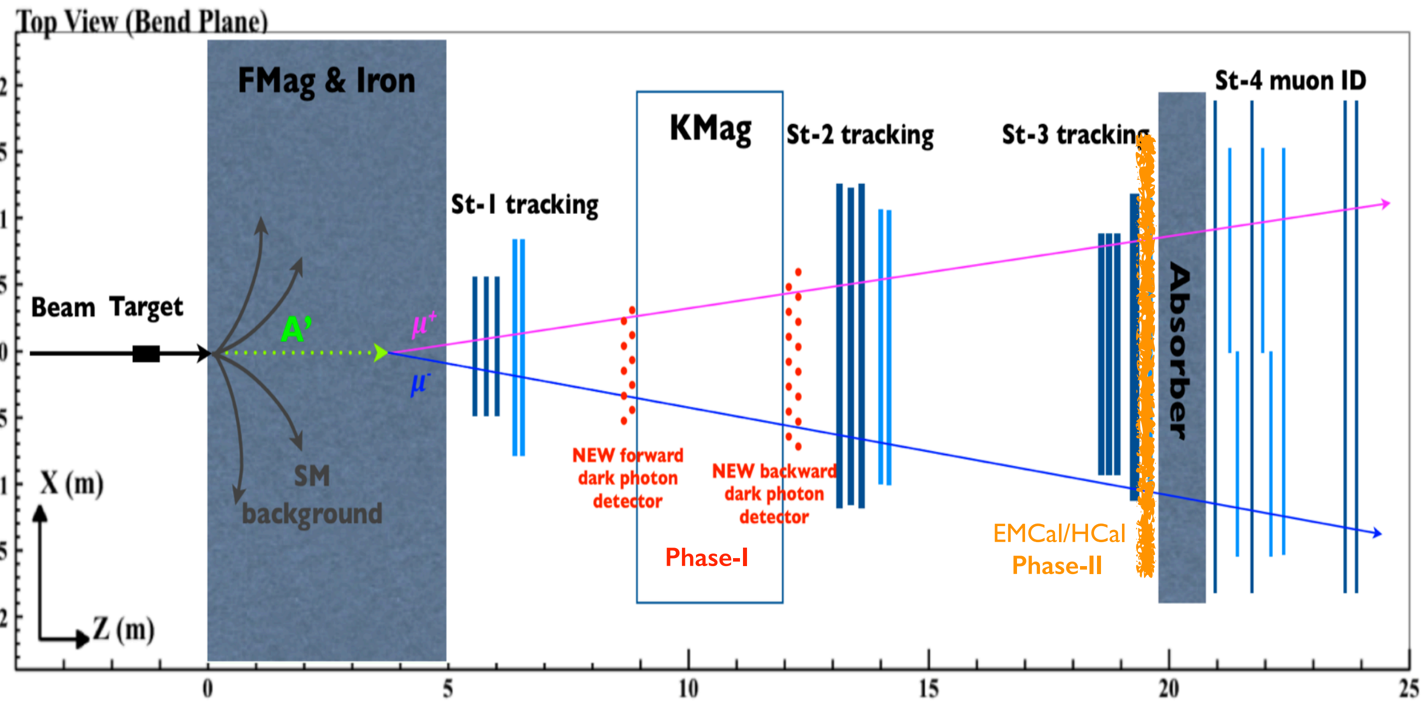
Post-E906: searching for dark photon

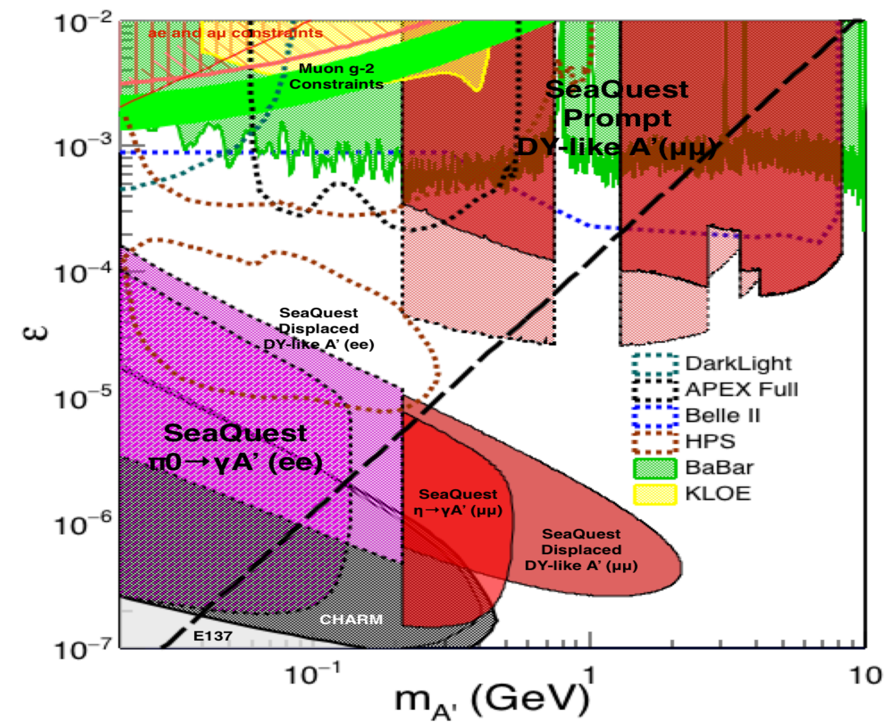


- Dark matter consists of 27% of the universe, yet only interacts very weakly with SM particles.
- WIMPs are considered to be the prime candidate of dark matter, the gap of un-excluded parameter space are quickly closing
- Sub-GeV low mass weakly interacting particles becomes the next target



Modest upgrade with great discovery potential



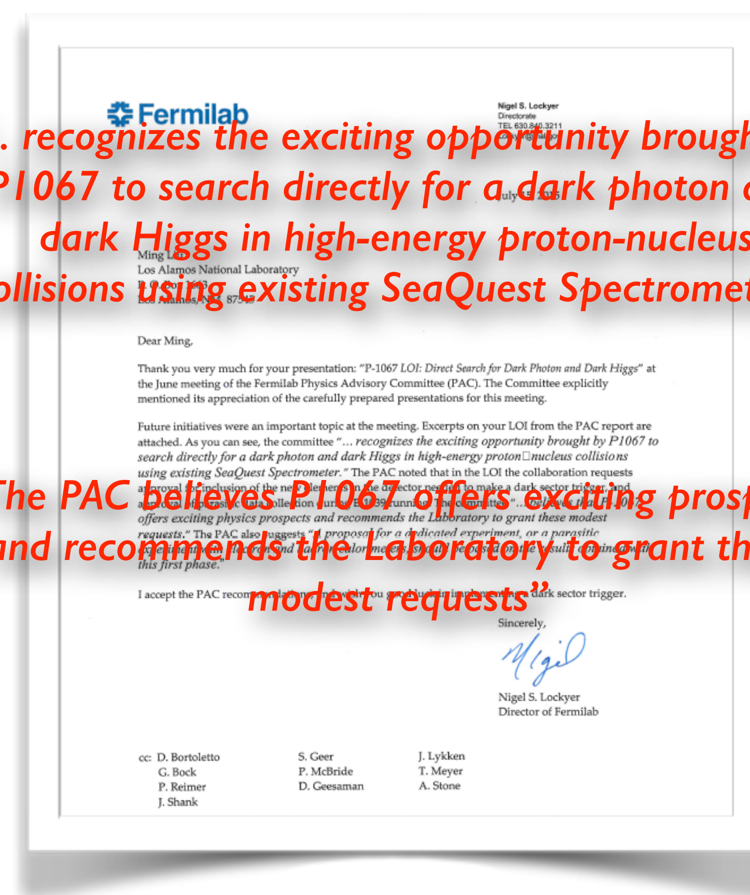


Phase-I:

- Addition of new displaced dimuon trigger to tag long-lived downstream decayed dark photon/higgs
- Runs *parasitically* with E1039 (pol. target) and any future upgrades
- Supported by LANL LDRD-ER (joint effort of P and T division, M. Liu and Z-B Kang as co-PIs)
- The experiment E-1067 was initiated by LANL (M. Liu and P. Reimer as co-spokespersons) and endorsed by Fermilab PAC

Phase-II:

- Dedicated beam time if phase-I is successful, with EMCal/HCal upgrades for $e^{+/-}$ and $h^{+/-}$ capabilities
- Cover full parameter phase space allowed by beam energy and luminosity
- Cesar has submitted his early career proposal for EMCal/HCal detector
- An open lab for all possible target physics


Fermilab

Nigel S. Lockyer

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.

Sincerely,

Nigel S. Lockyer
Director of Fermilab

"… 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 believes P1067 offers exciting prospects and recommends the Laboratory to grant these modest requests"

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