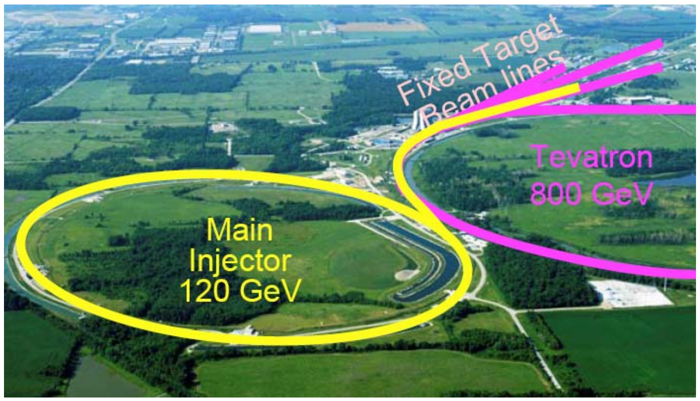
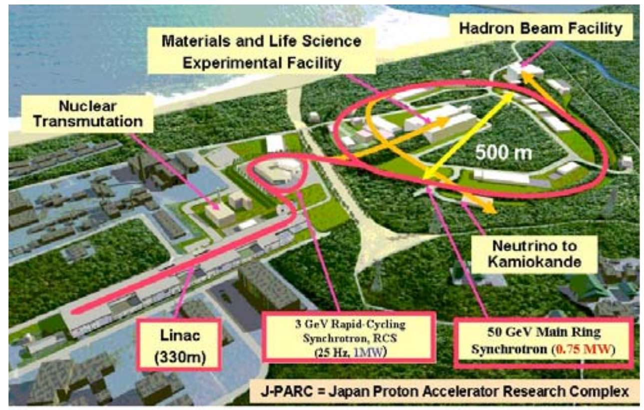
The First Precise Determination of Quark Energy Loss in Nuclei





Ivan Vitev (PI), Ming Liu (Co-PI), Patrick McGaughey, Benwei Zhang

T-16 and P-25 collaboration

E906 Collaboration Meeting, Fermilab, Batavia, IL

June 20-21, 2008

Stopping Power of Nuclear Matter for Quarks

- Stopping power of matter (radiative energy loss) $-\frac{dE}{dx} = \frac{E}{X_0}$
- Fundamental probe of the matter properties $\frac{1}{X_0} = \frac{4\alpha_{em} N_A Z(Z+1) r_e^2 \ln(183 Z^{-1/3})}{A}$

	Large Nuclei	***Electromagnetic***
Theory	Competing theories	Established theory
Phenomenology	Poorly known	Extremely successful
Experiment	Single attempt $0 \leq -dE/dx < (2.5-5)$ GeV/fm	Plentiful quality data
Need for improvement	**Urgent!!!**	Almost NONE

Recognized in the particle and nuclear theory communities need for a breakthrough in this area

A Fundamental Probe

Stopping power $-dE/dx$ at high energies is dominated by radiative energy loss

$$-\frac{dE}{dx} = \frac{E}{X_0}$$

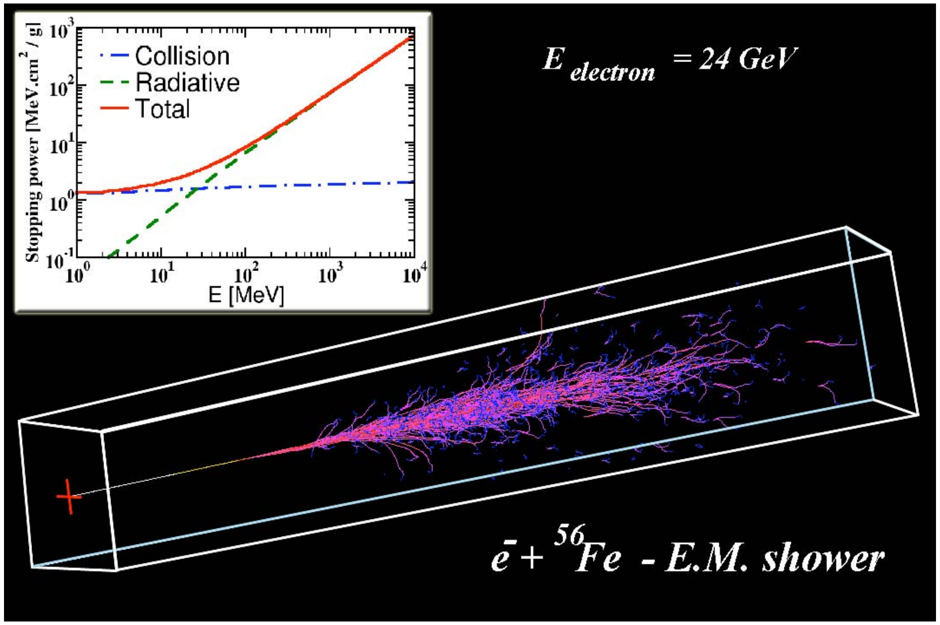
- Fundamental probe of the matter properties

$$\frac{1}{X_0} = \frac{4\alpha_{\rm em} N_A Z(Z+1) r_e^2 \ln(183 Z^{-1/3})}{A}$$

J.D. Jackson, John Wiley & Sons (1975)

- In electrodynamics (classical and quantum) it is know to a few %

- Utility: muon radiography, X-ray tomography, detector development



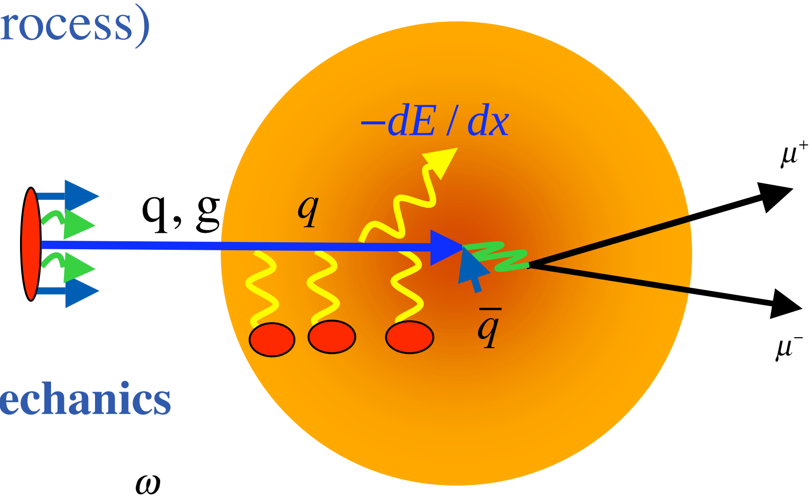
http://physics.nist.gov/PhysRefData/Star/Text/contents.html

http://www.mppmu.mpg.de/~menke/elss/description.shtml

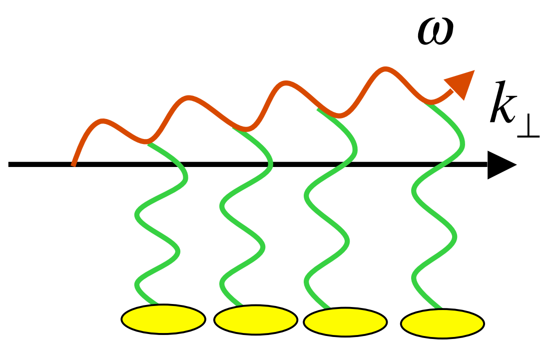
http://www2.slac.stanford.edu/vvc/egs/basicsimtool.html

The Basic Idea of Initial-State Energy Loss

$$q+\bar{q} \rightarrow \gamma^* \rightarrow \mu^+ + \mu^-$$ (Drell-Yan Process)



- Minimal final-state interactions of the detected particles.



Quantum mechanics

$$\tau_{formation} = \frac{1}{E_{final} - E_{initial}} = \frac{\omega}{k_\perp^2}$$

- Coherent multiple scattering - suppression of radiation by 1/n coherent collisions

$$\frac{1}{X_0} \sim \frac{\alpha_s}{\pi} \frac{1}{\kappa} \frac{\xi^2}{Q_0} \frac{1}{0.2\ GeV.fm}$$

Strong coupling (0.3)

Color magnetic field² (0.1 GeV²)

Conversion factor

Suppression (5)

Form factor (Q~1 GeV)

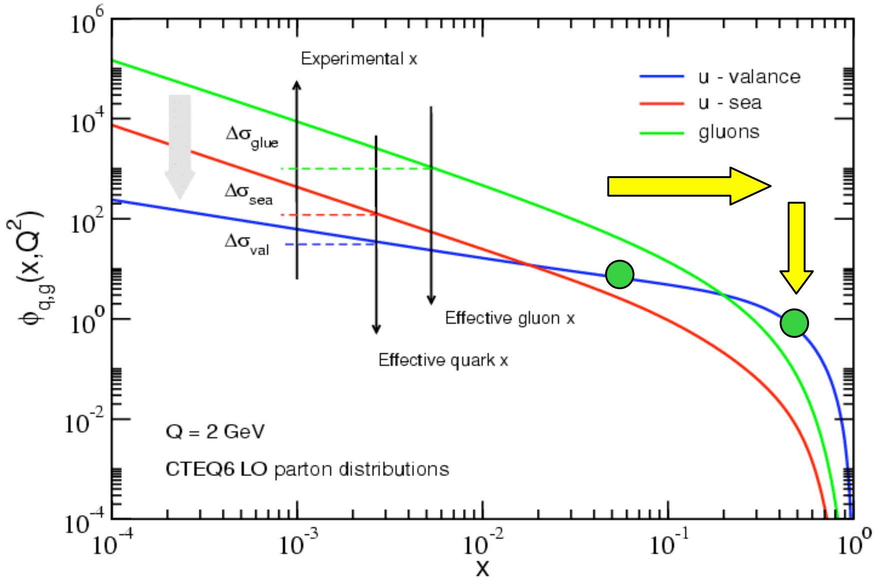
$X_0 \sim 10^{-13} m$

- Shortest radiation length in nature!!!

Experimental Signature

Multiplicity density for quarks and gluons to carry a fraction of the proton momentum

$$d\sigma \sim \phi_1(x_1,Q^2)\otimes\phi_2(x_2,Q^2)\otimes\frac{1}{2\hat{s}}|M|^2$$



Stopping power

of large nuclei:

suppressed cross sections

Maximum sensitivity in the large-x region

$$x_1 = p_{\text{quark}} / p_{\text{proton}}$$

$$p_{\text{quark}}(p+A) > p_{\text{quark}}(p+p)$$

- Unambiguous experimental signature

Experimental Sensitivity to Quark Energy Loss

- For radiation lengths X_0 = 1 x 10^{-13} m achieve sensitivity ~ 20%

$$X_0(W)=3.5\text{x}10^{-3}\ \text{m}$$

- Clearly distinguish between leading models for L dependence of E-loss (5σ)

$$-\Delta E \sim A^{1/3} \ (\text{or} \ \sim L)$$

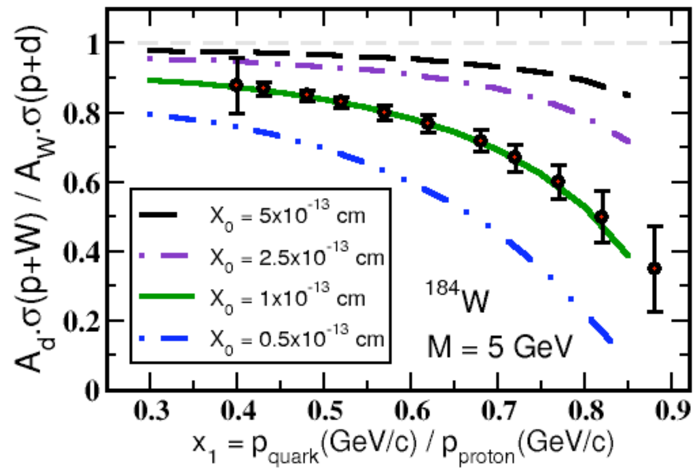
$$-\Delta E \sim A^{2/3} \ (\text{or} \ \sim L^2)$$

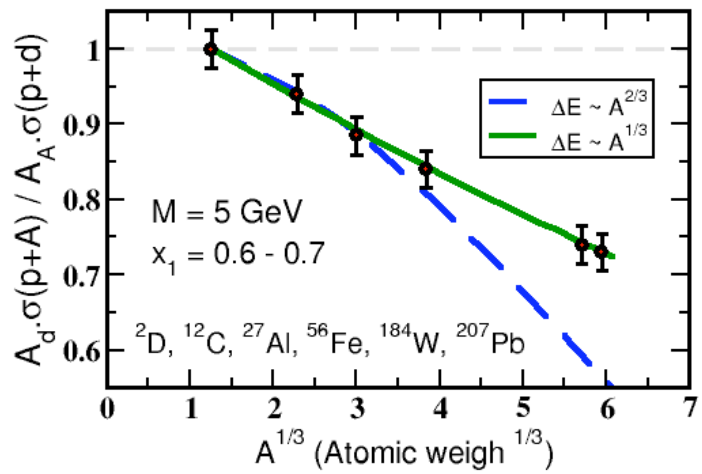
- Theory guided optimization of the E906 p+A program:

  Need 2 targets (^{27}Al,^{184}W) / high statistics versus many targets / low statistics

⇨ **Cut costs in design and operation**

Quark energy loss only





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Progress: Baseline Cross Sections

- NLO codes are ready (collinear factorization). Comparison to E772 data shown as an example

  - good description (room for 10-30 % improvement)

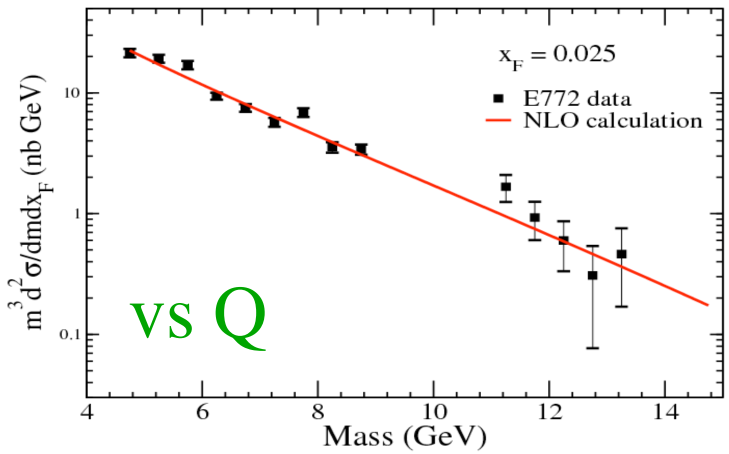
  - isospin corrections are included

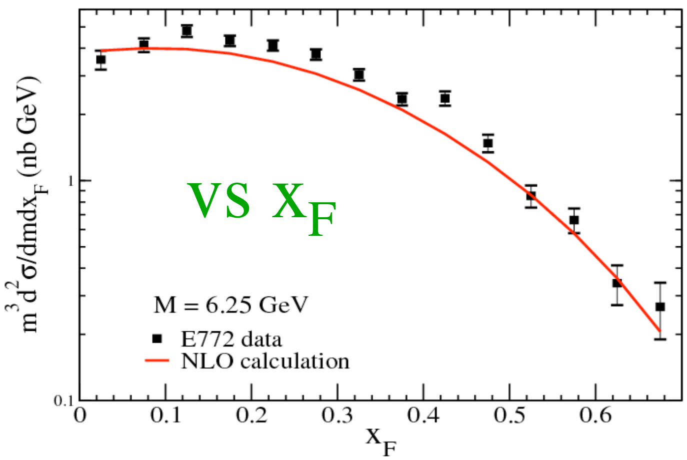
- To do list

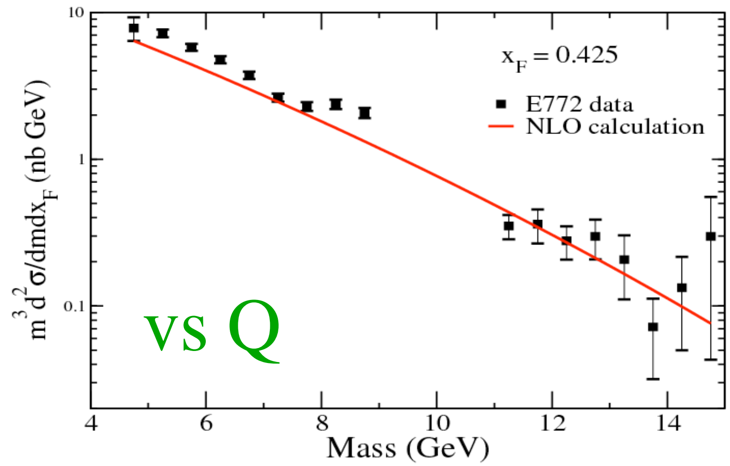
  - Incorporate k_T broadening (critical for p+A)

  - Calculate baseline cross sections for E906, JPARC, RHIC, LHC

Vitev, I., Zhang, B.W. (2008)



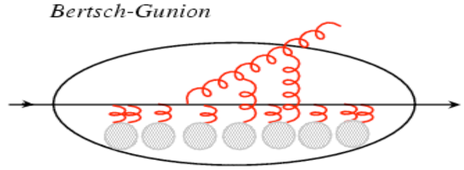




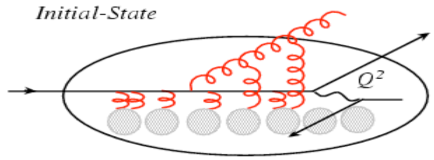
Progress: Stopping Power of Cold Nuclei

- Initial-state E-loss

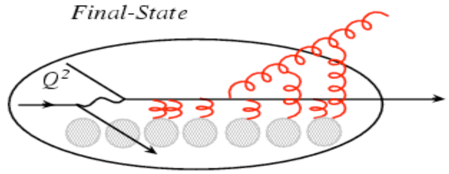
$$\frac{\omega dN^g}{d\omega d^2k_\perp} = \frac{C_R\alpha_s}{\pi^2}\int_0^{s/4} d^2q_\perp \frac{\mu_{eff}^2}{(q_\perp^2+\mu^2)^2}\left[\frac{L}{\lambda_g}\frac{q_\perp^2}{k_\perp^2(k_\perp-q_\perp)^2} - 2\frac{q_\perp^2 - 2k_\perp\cdot q_\perp}{k_\perp^2(k_\perp-q_\perp)^2}\frac{k^+}{k_\perp^2\lambda_g}\sin\frac{k_\perp^2 L}{k^+}\right]$$



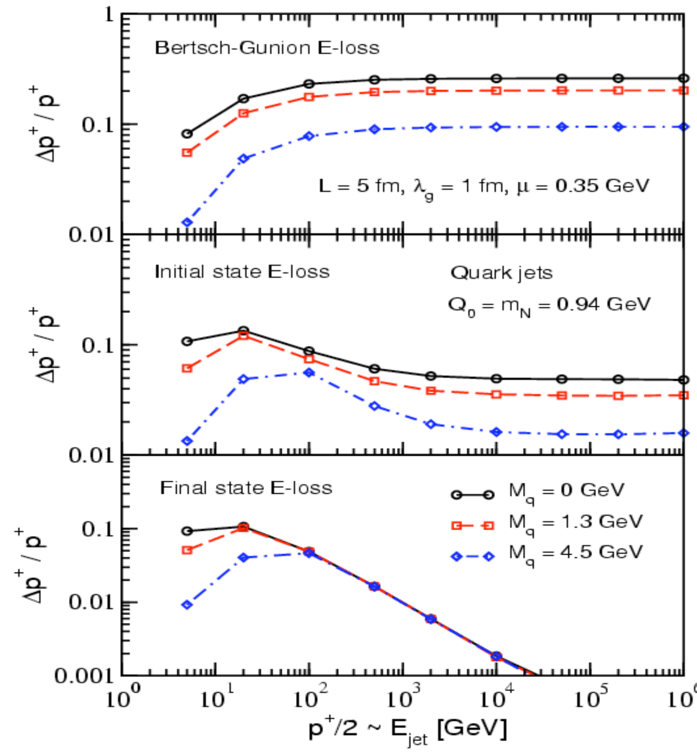
Academic case (probably inapplicable)



DY process



SDIS, QGP



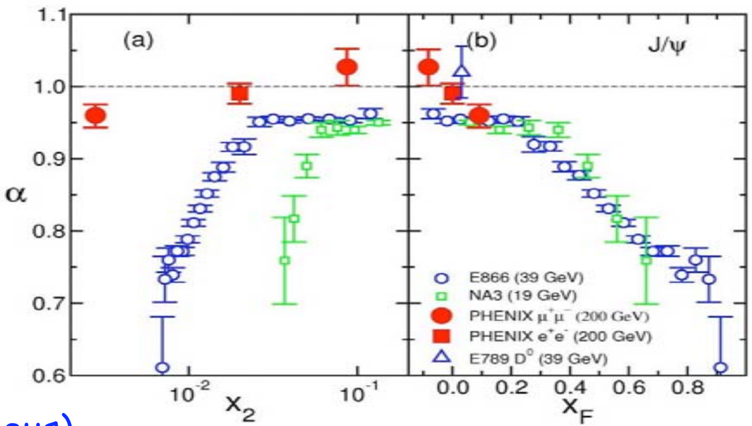
Vitev, I. (2007)

$E = p_T \cosh(y_{\rm jet} - y_{\rm target})$

- Partons can loose a few % of their energy at any parton E

Relation to Other Fields

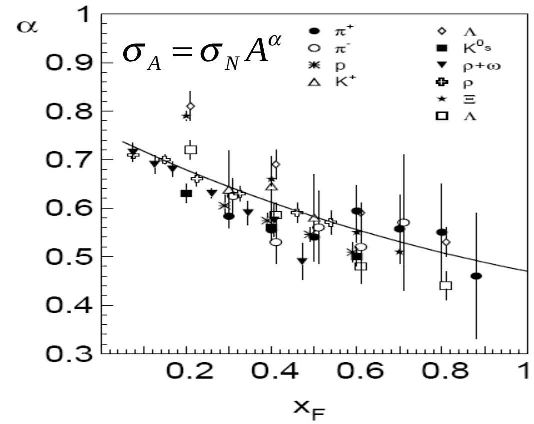
Scaling with x_F (x_1), not x_2, indicates initial state energy loss



(in nucleus)

Gavin, S. et al. (1992)

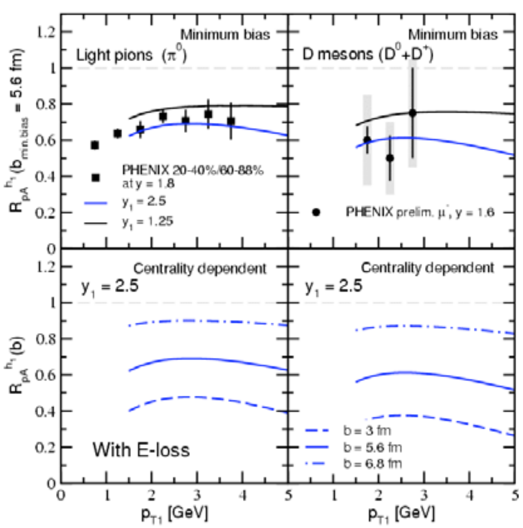
$= X_1 - X_2$

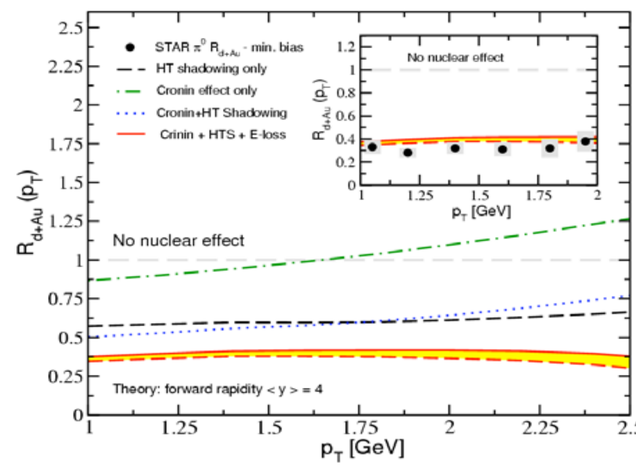


Kopeliovich, B. et al. (2005)

Forward rapidity suppression

Vitev, I. (2006)



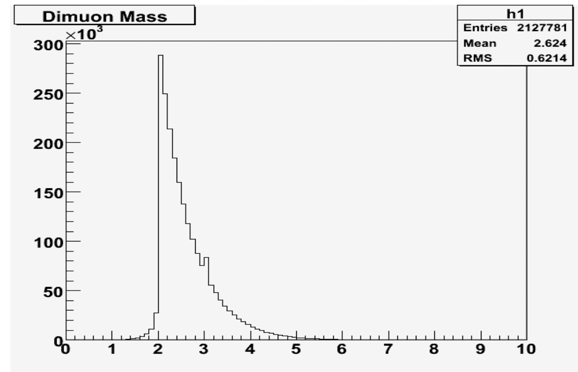


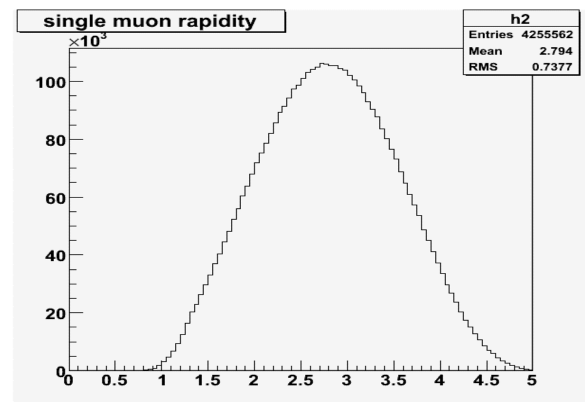
Vitev, I. in preparation

MC Modelling Effort

Progress

- Developed and debugged event simulation code based on PYTHIA package. The code is working now.
- Simulated 100 Million DY events in p+p collisions in the fixed target mode to study the kinematic distributions of the high momentum muons
- Also simulated other processes, open charm, and minimum biased events to study dimuon background in Drell-Yan measurements.





To do list

- Include the E906 detector acceptance in the simulation once the magnet design is finalized.
- Add detector resolution effects in the simulation.
- Need to run more simulations to match the expected luminosity in the high dimuon mass region
- Interface to GEANT detector response package once it is developed.
- Do “physics analysis” for optimal parton energy loss measurements.

PYTHIA simulation,
Full acceptance,
E_{lab} = 120 GeV p+p,
100 M events

Conclusions

- There is pressing need for a benchmark determination of the energy loss of quarks in large nuclei
- We have theoretical tools and computational power to carry out the technically challenging pQCD calculations
- Experiment E906 will provide the ideal platform with upgraded muon identifier and target optimization
- We will likely establish the shortest radiation length known in nature
- Also critical for the interpretation of the data from current and future heavy ion experiments
- Progress has been made in setting up baseline NLO DY calculations and theoretical determinetion of the stopping power of large nuclei, MC simulations groundwork