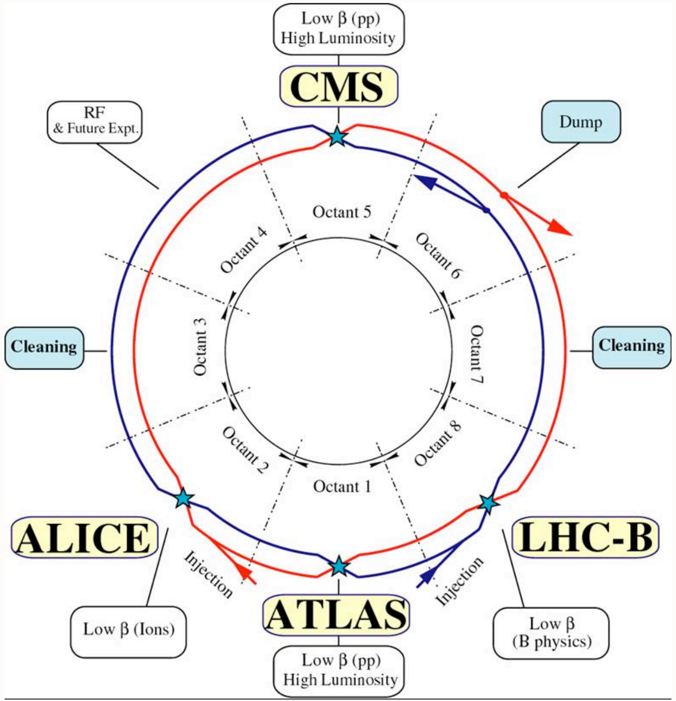
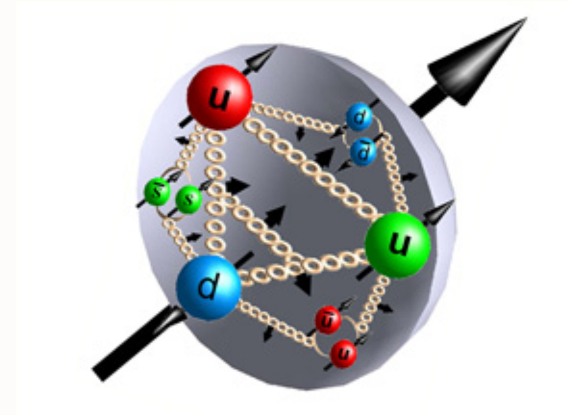
# Physics Flagships for AFTER: Fixed Target ExpeRiments @ the LHC




## AFTER @ LHC



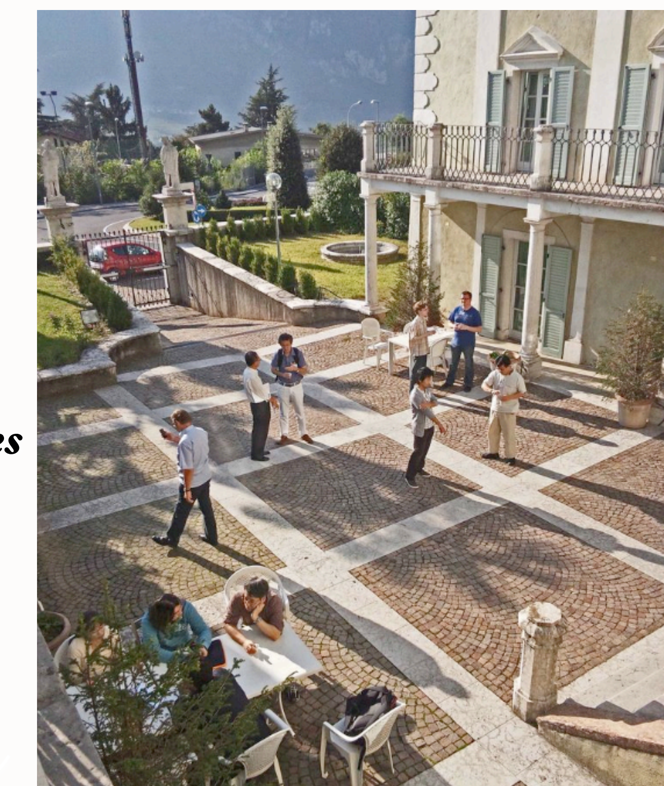

## ECT* Workshop

**February 4-8, 2013**

*European Center for Theoretical Studies in Nuclear Physics and Related Areas*


Stan Brodsky

SLAC NATIONAL ACCELERATOR LABORATORY


*Thanks to the France-Stanford Center for Interdisciplinary Studies*

***Thanks to: J.-P. Lansberg, F. Fleuret***

# A Compelling Idea for QCD:

*Utilize the High-Energy LHC proton and nuclear beams in a fixed-target mode*

- *Nuclear and Polarized Targets*

AFTER @ LHC

**A Fixed-Target ExpeRiment**

- *Study Dynamics at extreme rapidities: $X_F = -1$*

*A new hadron physics laboratory for studying and testing QCD*

AFTER @ LHC

- *7 TeV proton beam collisions on a proton or nuclear target -- Extract beam with Crystals -*
- *Minimal effects on the collider*
- *Equivalent to Ecm = 115 GeV*
- *Nuclear and Polarized Targets*
- *Nuclear Beams: Produce QGP in Rest Frame of Target Nucleus*
- *Study Dynamics at extreme rapidities: $X_F = -1$ New domain!*
- *Secondary Beams -- Even B and D*
- *Diffraction on Nucleons and Nucleus*
- *Cosmic Ray Simulations*

# Beam extraction

- **Beam extraction @ LHC**

… there are extremely promising possibilities to extract 7 TeV protons from the circulating beam by means of a bent crystal.

… The idea is to put a bent, single crystal of either Si or Ge (W would perform slightly better but needs substantial improvements in crystal quality) at a distance of $\simeq 7\sigma$ to the beam where it can intercept and deflect part of the beam halo by an angle similar to the one the foreseen dump kicking system will apply to the circulating beam.

… ions with the same momentum per charge as protons are deflected in a crystal with similar efficiencies

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ELSEVIER
Nuclear Instruments and Methods in Physics Research B 234 (2005) 31–39
NIM B
Beam Interactions with Materials & Atoms
www.elsevier.com/locate/nimb

Strong crystalline fields – a possibility for extraction from the LHC

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Available online 24 February 2005

If the crystal is positioned at the kicking section, the whole dump system can be used for slow extraction of parts of the beam halo, the particles that are anyway lost subsequently at collimators.

- Both $p$ and $Pb$ LHC beams can be extracted without disturbing the other experiments
- Extracting a few per cent of the beam $\rightarrow 5 \times 10^8$ protons per sec
- This allows for high luminosity $pp$, $pA$ and $PbA$ collisions at $\sqrt{s} = 115$ GeV and $\sqrt{s_{NN}} = 72$ GeV
- **Example**: precision quarkonium studies taking advantage of
  - high luminosity (reach in $y$, $P_T$, small BR channels)
  - target versatility (CNM effects, strongly limited at colliders)
  - modern detection techniques (e.g. $\gamma$ detection with high multiplicity)
- This would likely prepare the ground for $g(x, Q^2)$ extraction
- A wealth of possible measurements:
  DY, Open $b/c$, jet correlation, UPC... (not mentioning secondary beams)
- Planned LHC long shutdown ($<$ 2020 ?) could be used to install the extraction system
- Very good complementarity with electron-ion programs

# A Fixed Target ExperRiment

## Generalities

- *pp* or *pA* with a 7 TeV *p* beam : $\sqrt{s} \simeq 115$ GeV (+Fermi motion for *pA*)
- Same ballpark as electron-ion colliders → **complementary**
- For *pA*, a Fermi motion of 0.2 GeV would induce a spread of 10 % of $\sqrt{s}$

**S.Fredriksson, NPB 94 (1975) 337**

- The beam may be extracted using “Strong cristalline field”

**E. Huggerhøj, U.I Huggerhøj, NIM B 234 (2005) 31, Rev. Mod. Phys. 77 (2005) 1131** (see later)

- Expected luminosities with $5 \times 10^8$ *p*/s extracted (1cm-long target)

| Target | ρ (g.cm$^{-3}$) | A | $\mathcal{L}$ (μb$^{-1}$.s$^{-1}$) | $\mathcal{L}$ (pb$^{-1}$.y$^{-1}$) |
|---|---|---|---|---|
| Liq. $H_2$ | 0.07 | 1 | 21 | 210 |
| Liq. $D_2$ | 0.16 | 2 | 24 | 240 |
| Be | 1.85 | 9 | 60 | 600 |
| Cu | 8.96 | 64 | 40 | 400 |
| W | 19.1 | 185 | 30 | 300 |
| Pb | 11.35 | 207 | 16 | 160 |

(preliminary !)

- Using **NA51**-like 1.2m-long liquid $H_2$ & $D_2$ targets, $\mathcal{L}_{H_2/D_2} \simeq 20$ fb$^{-1}y^{-1}$
- For comparison, PHENIX recorded lumi for Run9 pp at 200 GeV: 16 pb$^{-1}$ & Run8 *d*Au at 200 GeV : 0.08 pb$^{-1}$

# AFTER @ LHC – Luminosity

- **Intensity: expect $5.10^8$ protons.$s^{-1}$**
  - **Beam:** 2808 bunches of $1.15\times10^{11}$ protons = **$3.2\times10^{14}$ protons**
  - **Bunch:** Each bunch passes IP at the rate: $3.10^5$km.$s^{-1}$/27 km ~ **11 kHz**
  - **Instantaneous extraction:** IP sees 2808 x 11000~$3.10^7$ bunches passing every second
    ➔ extract $5.10^8/3.10^7$ ~ **extract 16 protons in each bunch at each pass**
  - **Integrated extraction:** Over a 10h run: extract $5.10^8$p x 3600s.$h^{-1}$ x 10h=1.8 $10^{13}$p.$run^{-1}$
    ➔ extract 1.8 x $10^{13}$/(3.2 x $10^{14}$)~**5.6% of the protons stored in the beam**
- **Instantaneous Luminosity**

  $\mathcal{L} = N_{beam} \times N_{Target} = N_{beam} \times (\rho \times e \times \mathcal{N}_A)/A$
  - $N_{beam}$=5 x $10^8$ $p^+$/s
  - **e** (target thickness) = 1 cm
- **Integrated luminosity**
  - 9 months running/year
  - ➔ 1year ~ $10^7$ s
  - ➔ $\int_{year}\mathcal{L} = \mathcal{L}_{inst}\times10^7$

**p+A**

| Targ | ρ ($g.cm^{-3}$) | A | $\mathcal{L}_{inst}$ ($\mu b^{-1}.s^{-1}$) | $\int_{year}\mathcal{L}$ ($pb^{-1}.y^{-1}$) |
|---|---|---|---|---|
| **Liq H** | 0.068 | 1 | **20** | **200** |
| **Liq D** | 0.16 | 2 | **24** | **240** |
| **Be** | 1.85 | 9 | **62** | **620** |
| **Cu** | 8.96 | 64 | **42** | **420** |
| **W** | 19.1 | 185 | **31** | **310** |
| **Pb** | 11.35 | 207 | **16** | **160** |

- **Pb+A intensity : expect $7.10^5$Pb.$s^{-1}$**
  - PHENIX @ RHIC recorded in 2010
    - Au+Au @ 200 GeV : 1.3 $nb^{-1}$
    - Au+Au @ 62 GeV: 0.11 $nb^{-1}$

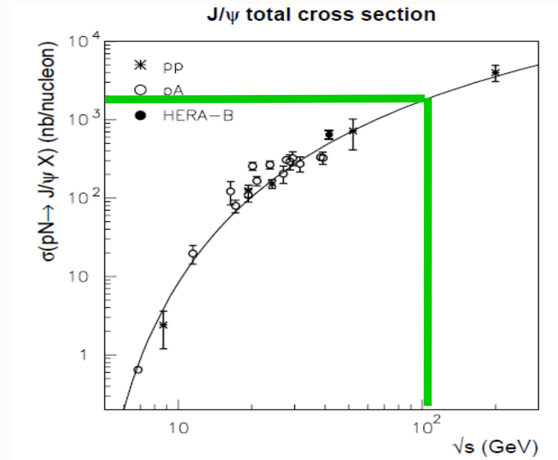
**Pb+A**

| Target | ρ ($g.cm^{-3}$) | A | $\mathcal{L}$ ($mb^{-1}.s^{-1}$)=$\int\mathcal{L}$ ($nb^{-1}.yr^{-1}$) |
|---|---|---|---|
| **Liq. $H_2$** | 0.07 | 1 | **28** |
| **Liq. $D_2$** | 0.16 | 2 | **34** |
| **Be** | 1.85 | 9 | **84** |
| **Cu** | 8.96 | 64 | **56** |
| **W** | 19.1 | 185 | **42** |
| **Pb** | 11.35 | 207 | **22** |

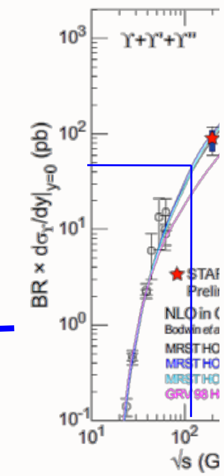
# AFTER @ LHC – Luminosity

- **Typical numbers**
  - **J/Ψ @ √s=115 GeV**
    - **$\sigma_\Psi$ ~ 1.5 $10^3$ nb**

    ➔ **$Br_{\Psi\to e+e-}\, d\sigma_\Psi/dy(y=0)$ ~ 30 nb**




  - **ϒ @ √s=115 GeV**
    - **$Br_{\Upsilon\to e+e-}\, d\sigma_\Upsilon/dy(y=0)$@ 115 GeV ~ 50 pb**




With 1 cm thick target

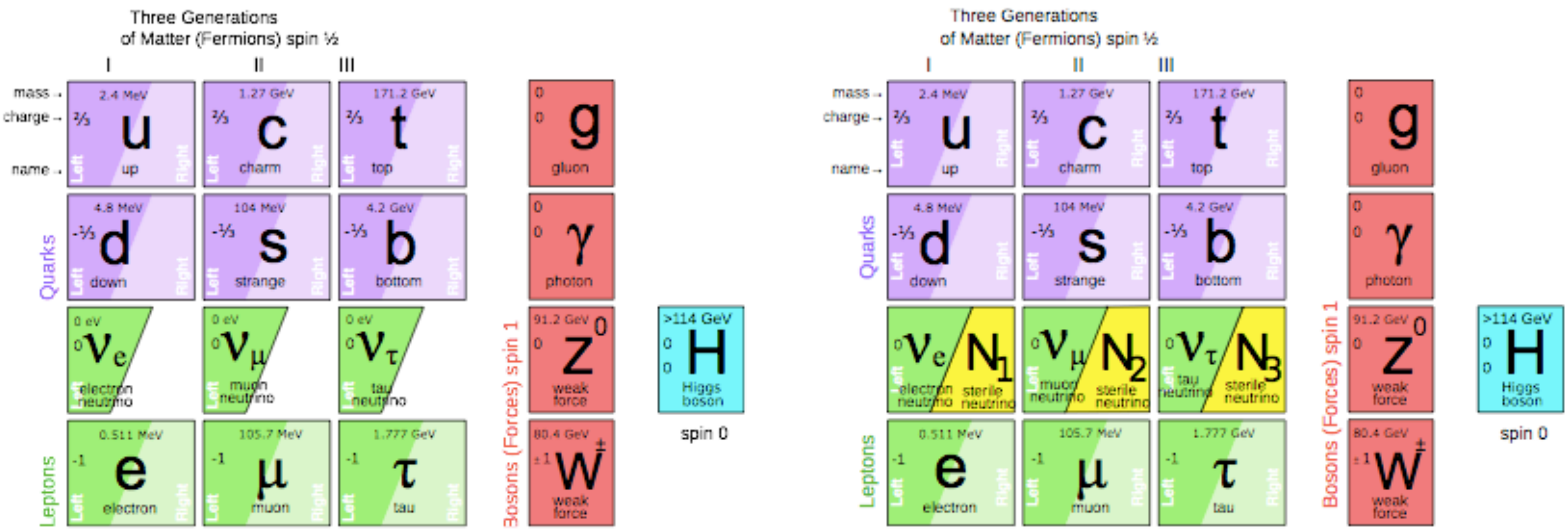
| Target | ρ (g.cm$^{-3}$) | A | $\mathcal{L}$ (μb$^{-1}$.s$^{-1}$) | $\mathcal{L}$ (pb$^{-1}$.y$^{-1}$) | $N_{J/\Psi}\|_{y=0}$ (y$^{-1}$) $N_{J/\Psi} = A\mathcal{L}\sigma_\Psi$ | $N_\Upsilon\|_{y=0}$ (y$^{-1}$) $N_\Upsilon = A\mathcal{L}\sigma_\Upsilon$ |
|---|---|---|---|---|---|---|
| Liq H | 0.068 | 1 | 20 | 200 | 6 $10^6$ | 1. $10^5$ |
| Liq D | 0.16 | 2 | 24 | 240 | 1.4 $10^7$ | 2.4 $10^5$ |
| Be | 1.85 | 9 | 62 | 620 | 1.6 $10^8$ | 2.8 $10^5$ |
| Cu | 8.96 | 64 | 42 | 420 | 8.1 $10^8$ | 1.3 $10^6$ |
| W | 19.1 | 185 | 31 | 310 | 1.7 $10^9$ | 2.9 $10^6$ |
| Pb | 11.35 | 207 | 16 | 160 | 1. $10^9$ | 1.7 $10^6$ |

# Fixed-Target Physics with the LHC Beams

- 7 TeV proton beam, 3 TeV nuclear beams
- Full Range of Nuclear and Polarized Targets
- Cosmic Ray simulations
- Sterile Neutrinos -- Dark Matter Candidates
- Single-Spin Asymmetries, Transversity Studies, $A_N$
- High-$x_F$ Dynamics --Correlations, Diffraction
- High-$x_F$ Heavy Quark and quarkonium phenomena
- Production of ccq to ccc to bbb baryons
- Quark-Gluon Plasma in Nuclear Rest System:
  e.g. Ridge Physics at Extreme Rapidities
- Anti-Shadowing: Flavor Specific?
- Higgs at Threshold using nuclear Fermi motion

***Search for GeV-scale sterile neutrinos responsible for active neutrino oscillations and baryon asymmetry of the Universe***

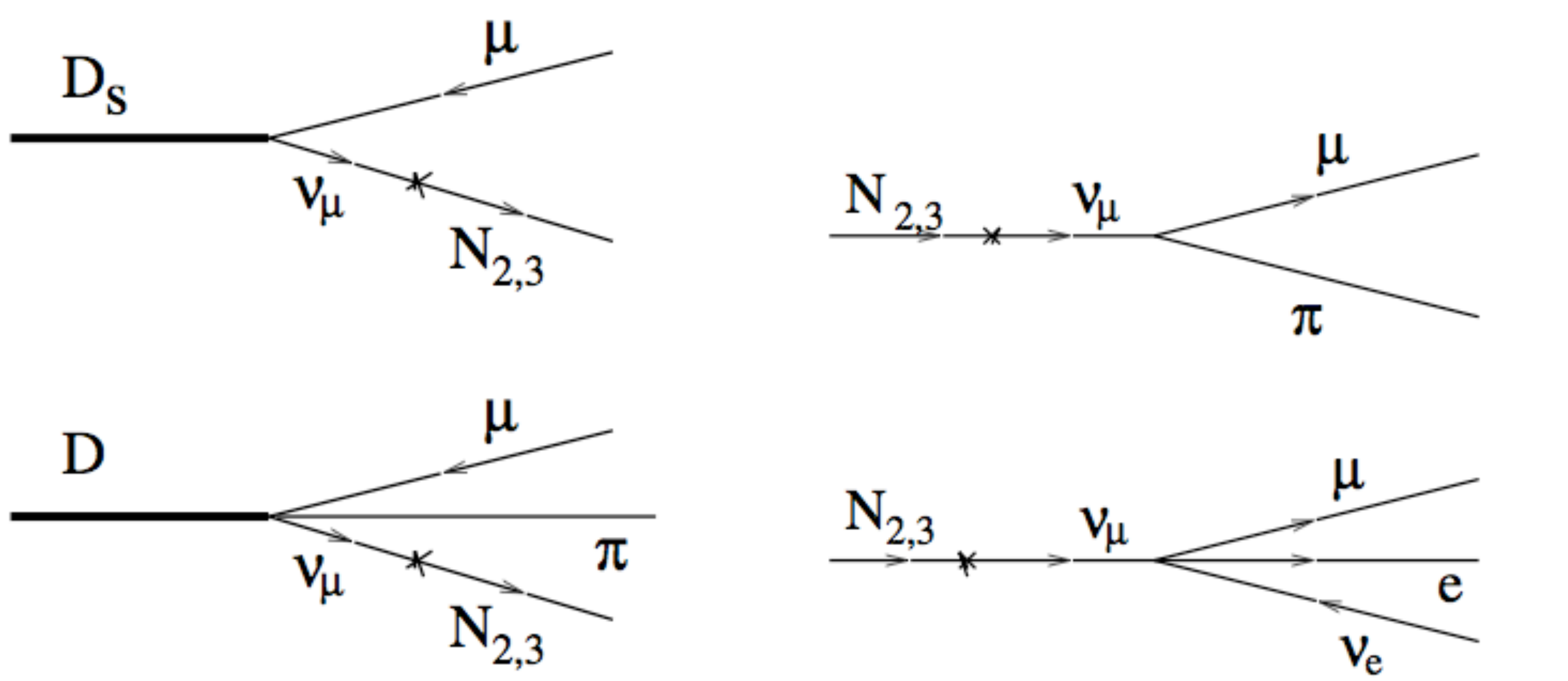
**Gninenko, Gorbunov and Shaposhnikov**

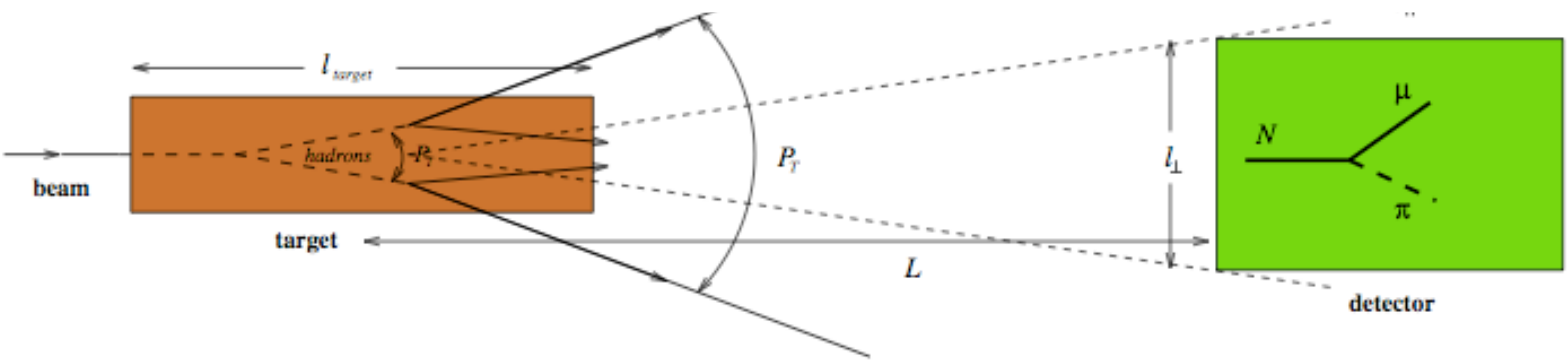



Particle content of the SM and its minimal extension in neutrino sector. In the SM (left) the right-handed partners of neutrinos are absent. In the $\nu$MSM (right) all fermions have both left and right-handed components.

*Search for GeV-scale sterile neutrinos responsible for active neutrino oscillations and baryon asymmetry of the Universe*

Gninenko, Gorbunov and Shaposhnikov



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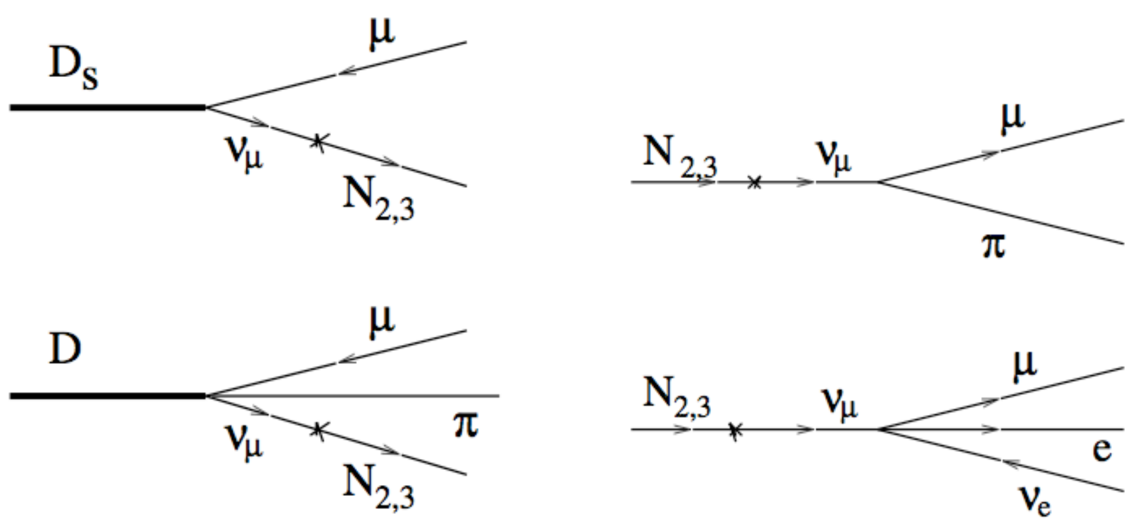


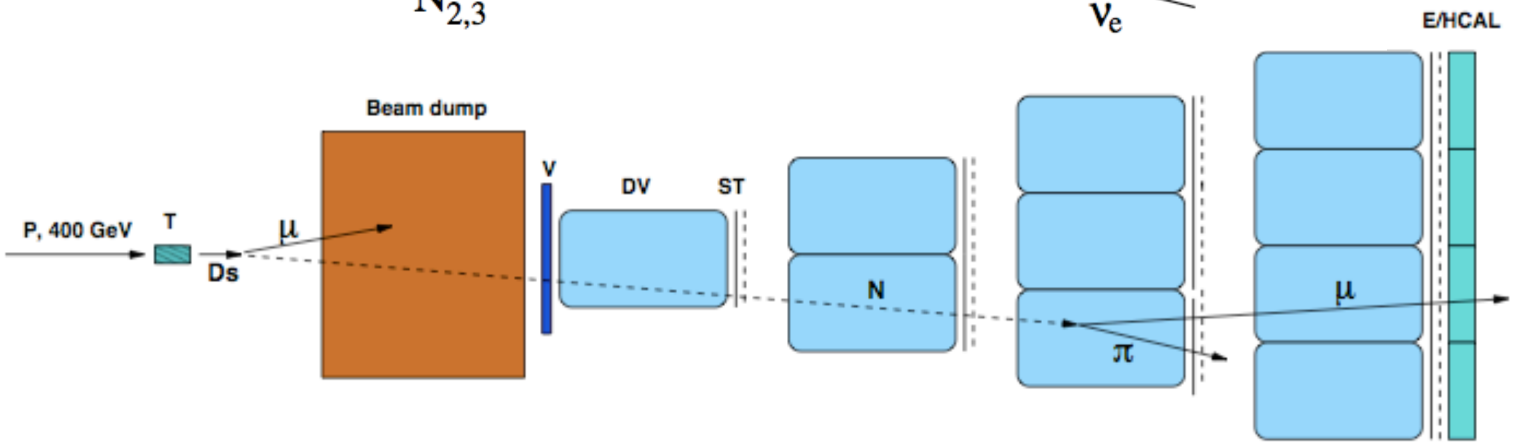


Schematic illustration of a proton beam dump experiment on search for $D_s \to \mu N$, $N \to \mu\pi$ decay chain: charm mesons $D_s$ generated by the proton beam in the target (T) produce a flux of high energy $N$'s through the $U_{\mu N}$ mixing in the decay $D_s \to \mu\nu_\mu$, which penetrate the downstream shielding and decay into $\mu\pi$ pair in a neutrino decay volume (DV). The same setup can be used to search for the process $N \to \mu e \nu$. See text.

# A Fixed Target ExperRiment

## Generalities

- *Pbp* or *PbA* with a 2.75 TeV Pb beam : $\sqrt{s} \simeq 72$ GeV
- Cristal channeling is also possible (to extract a few per cent of the beam)
- Requires cristals highly resistant to radiations: progress with diamonds

**P. Ballin** *et al.*, **NIMB 267 (2009) 2952**

- Expected luminosities with $7 \times 10^5$ Pb/s extracted (1cm-long target)

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(Preliminary !)

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  AuAu at 200 GeV: 1.3 nb$^{-1}$ & AuAu at 62 GeV: 0.11 nb$^{-1}$

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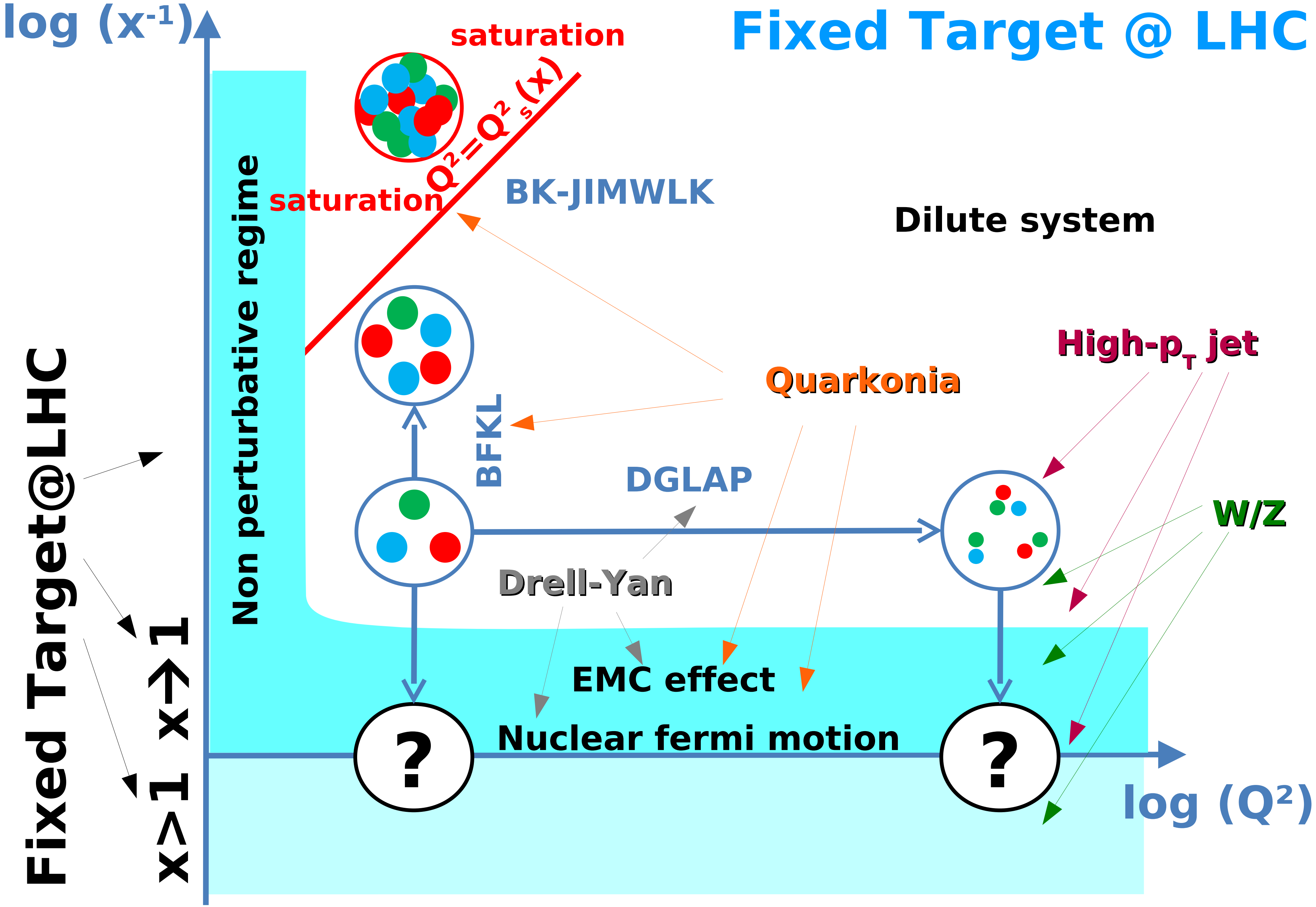
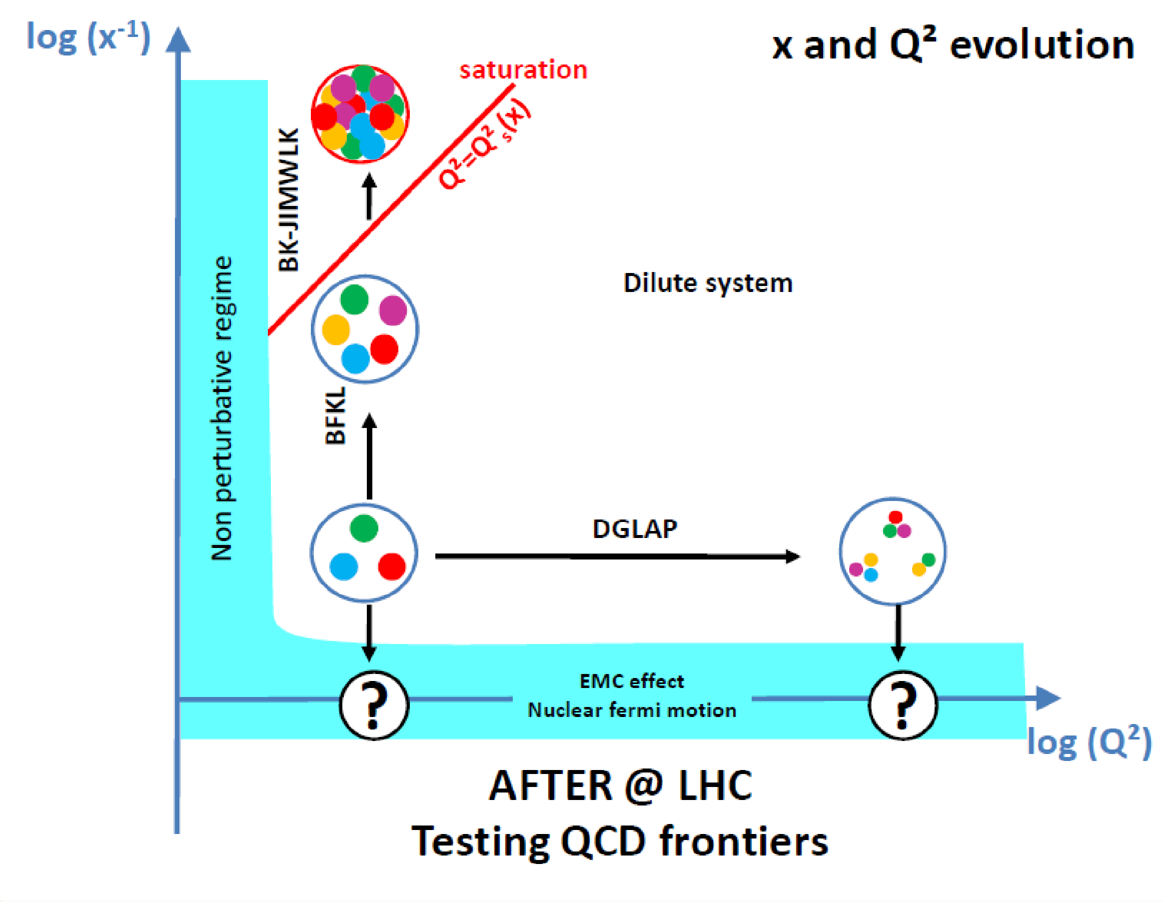
# Fixed Target @ LHC



# AFTER @ LHC – Physics

- **Idea : use LHC beam on fixed target**
  - *7 TeV proton beam*
  - *2.75 TeV Pb beam*

- ***High boost and luminosity giving access to***
  - *QCD at large x*
  - *nPDF and shadowing*
  - *Spin physics ...*



# Nuclear Collisions with AFTER

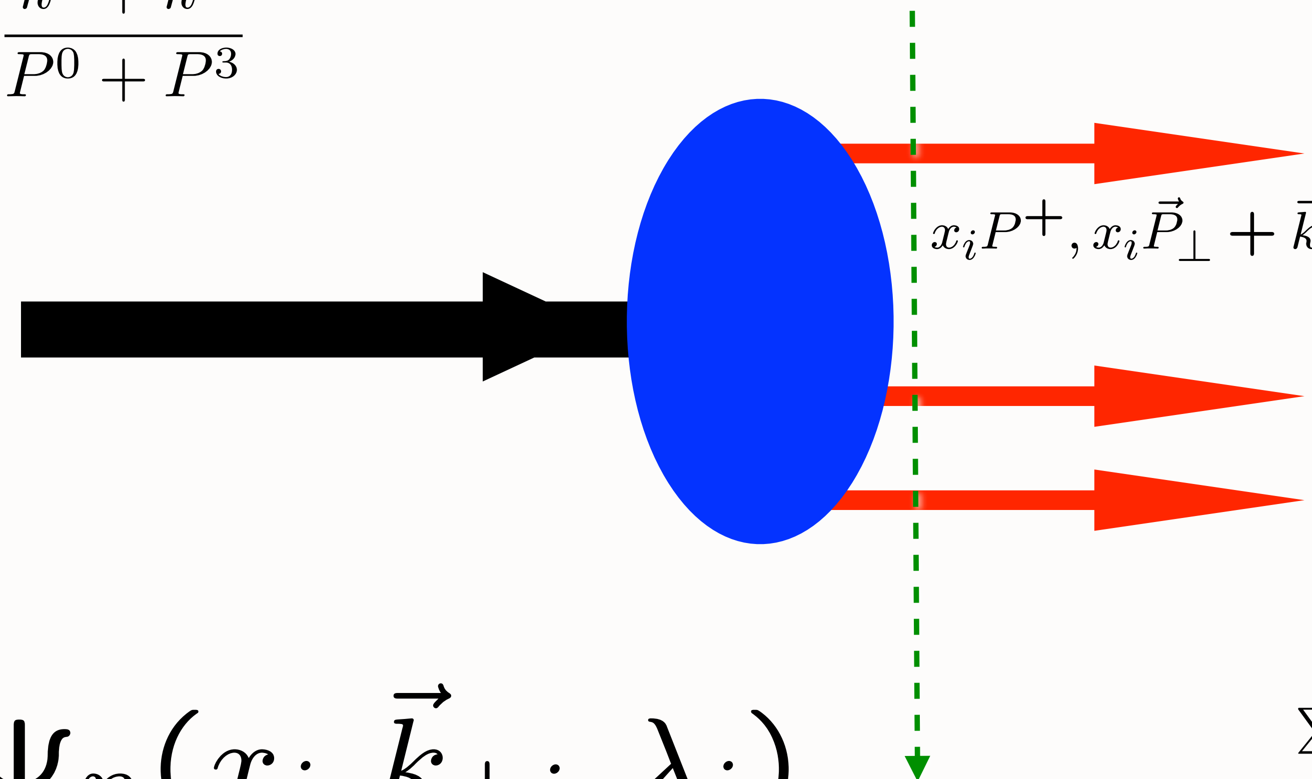
- **Nucleus-Nucleus and Proton-Nucleus Scattering in Lab Frame Look at Target Fragmentation Region $x_F=-1$**
- **What happens to Target Nucleus when QGP is formed?**
- **pp pA AA Ridge at extreme rapidity**
- **What are the critical parameters for the onset of QGP**
- **Light-Front Description: Frame-Independent**
- **Use Fool's ISR Frame -- No Lorentz Contraction of LFWF**
- **Energy Loss Studies, LPM, Non-Abelian**
- **Quarkonium Production, Polarization**
- **Open charm, bottom**

# Light-Front Wavefunctions: rigorous representation of composite systems in quantum field theory

Fixed $\tau = t + z/c$

$$x = \frac{k^+}{P^+} = \frac{k^0 + k^3}{P^0 + P^3}$$

$P^+, \vec{P}_\perp$



$x_i P^+, x_i \vec{P}_\perp + \vec{k}_{\perp i}$

$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

$\sum_i^n x_i = 1$

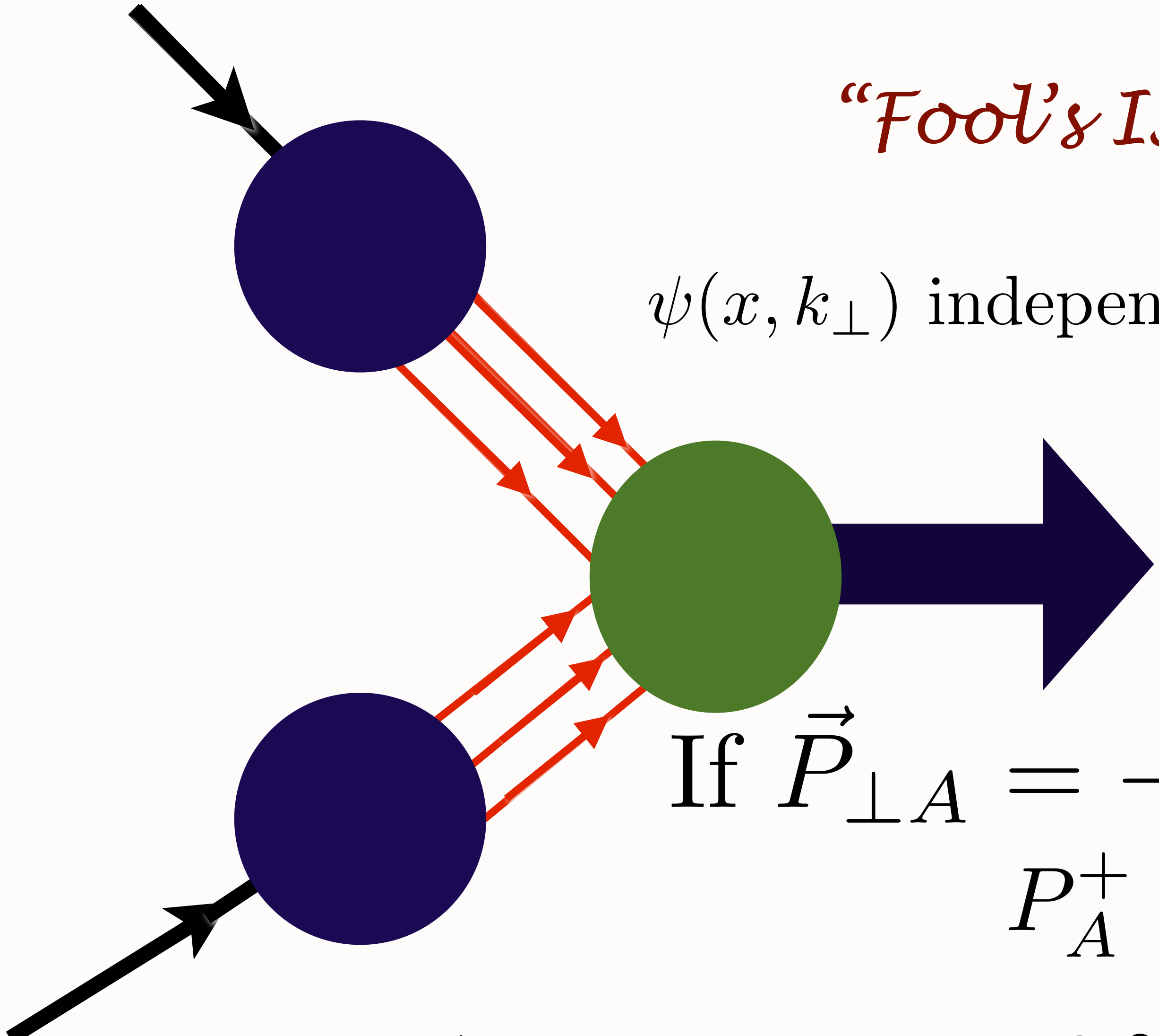
$\sum_i^n \vec{k}_{\perp i} = \vec{0}_\perp$

*Invariant under boosts! Independent of $P^\mu$*

$$P_A^\mu = (P_A^+, P_A^-, \vec{P}_{\perp A})$$

$$P^- = \frac{P_\perp^2 + M^2}{P^+}$$

*"Fool's ISR Frame"*



$\psi(x, k_\perp)$ independent of $P^+, \vec{P}_\perp$

$$\text{If } \vec{P}_{\perp A} = -\vec{P}_{\perp B} = \vec{P}_\perp$$

$$P_A^+ = P_B^+$$

$$s \simeq 4P_\perp^2$$

$$P_B^\mu = (P_B^+, P_B^-, \vec{P}_{\perp B})$$

$$s = (P_A + P_B)^2 = M_A^2 + M_B^2 + \frac{P_{\perp A}^2 + M_A^2}{P_A^+} P_B^+ + \frac{P_{\perp B}^2 + M_B^2}{P_B^+} P_A^+ - 2\vec{P}_{\perp A} \cdot \vec{P}_{\perp B}$$

# High $x_F$ at AFTER

- Drell Yan at high $x_F$
- W, Z
- Structure Functions at High x
- Direct Processes
- Polarization Correlations
- Intrinsic Heavy Quark Studies
- Diffractive Channels
- Proton Diffraction to 3 Jets
- Quarkonium Dynamics
- Open Flavor, B and D

# Novel Physics at AFTER,

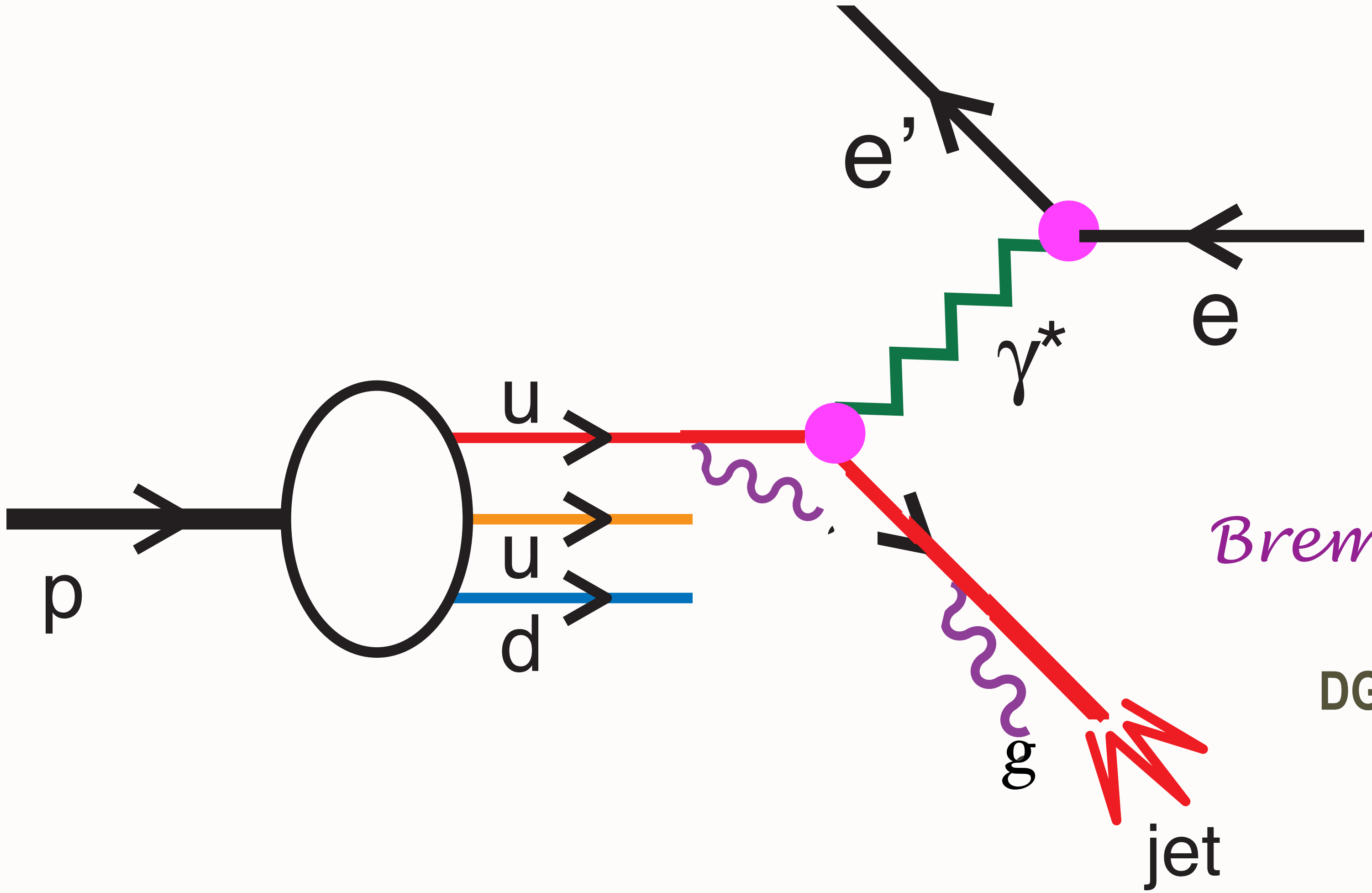
- **Secondary Beams: Pions Kaons, Muons, even B and D**
- **Pion Exchange: Effective Pion Collisions**
- **Deuteron Target: Hidden Color**
- **Spin-Correlations with Polarized Targets**
- **Huge single spin asymmetries at high xF**
- **pA to Quarkonium -- non-factorizing nuclear dependence**
- **Breakdown of Factorization: Double Boer-Mulders**
- **Photon plus Heavy Quark Anomalies**
- **Shadowing, Antishadowing**
- **Odderon Search**

# Target Polarization Studies with AFTER

AFTER @ LHC

- T-Odd Sivers, Boer-Mulders Effects
- Non-Factorization
- Strong Effects at Charm, Bottom, Thresholds
- Study Anomalously Large $A_N$ for Hadron Production at high $x_F$
- Quarkonium Spin and Correlations

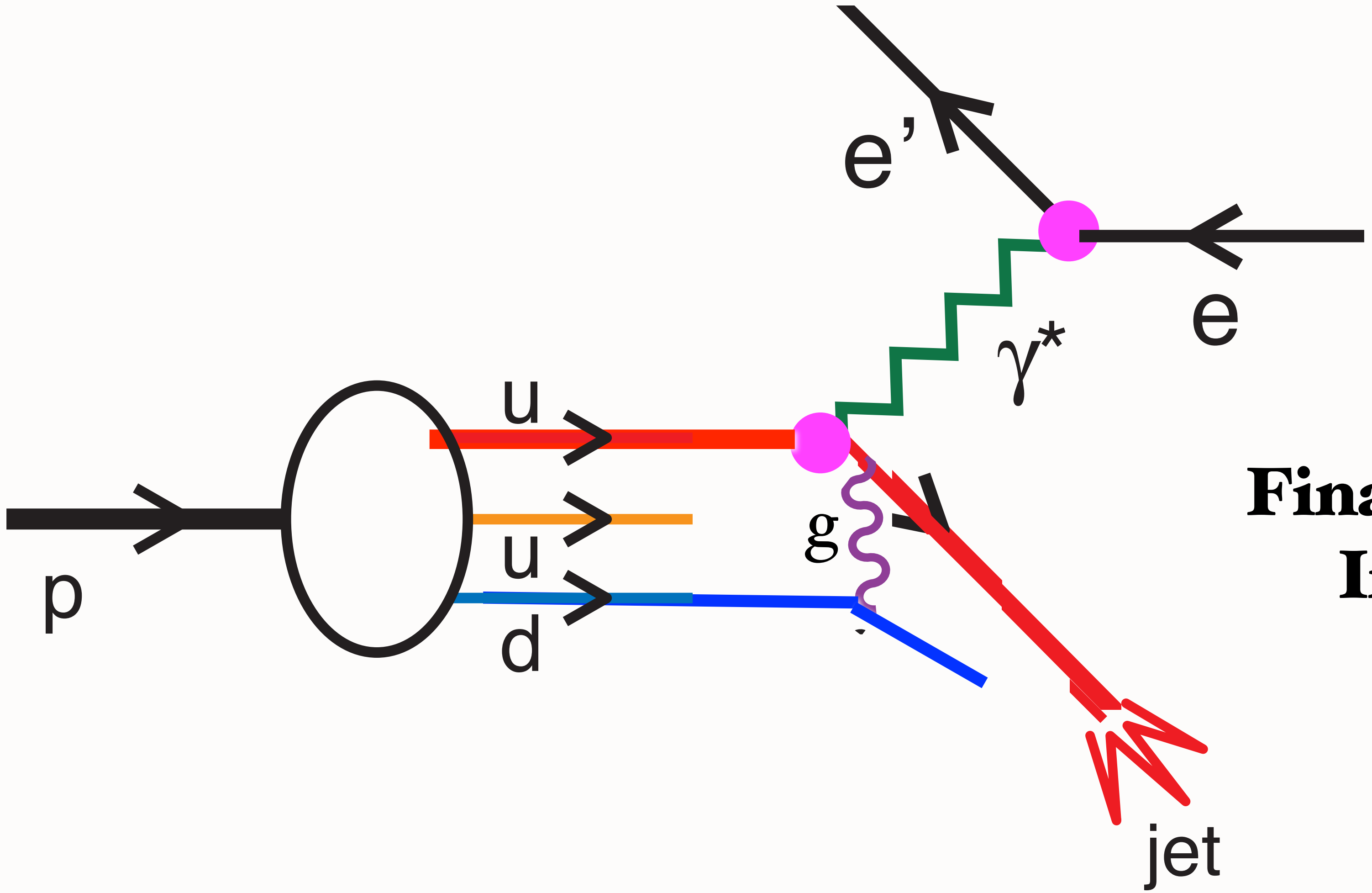
# Deep Inelastic Electron-Proton Scattering




Gluonic Bremmstrahlung

DGLAP Evolution

# *Deep Inelastic Electron-Proton Scattering*




**Final-State QCD Interaction**

*Conventional wisdom:*
*Final-state interactions of struck quark can be neglected*

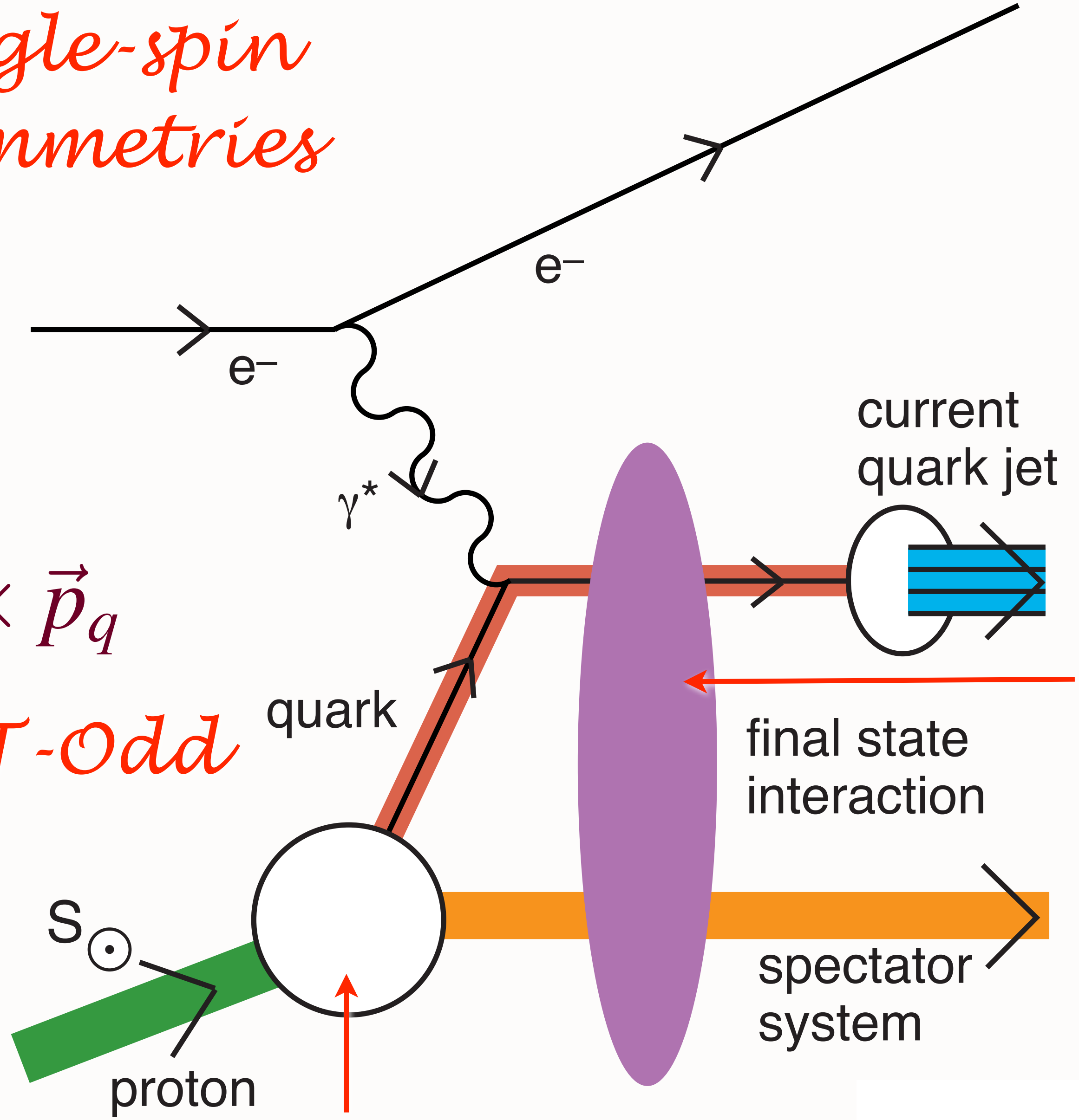
# Single-spin asymmetries

# Leading Twist Sivers Effect

Dae Sung Hwang, Ivan Schmidt, sjb

$$i\ \vec{S}_p \cdot \vec{q} \times \vec{p}_q$$

Pseudo-T-Odd




QCD S- and P-Coulomb Phases --Wilson Line

Light-Front Wavefunction S and P- Waves

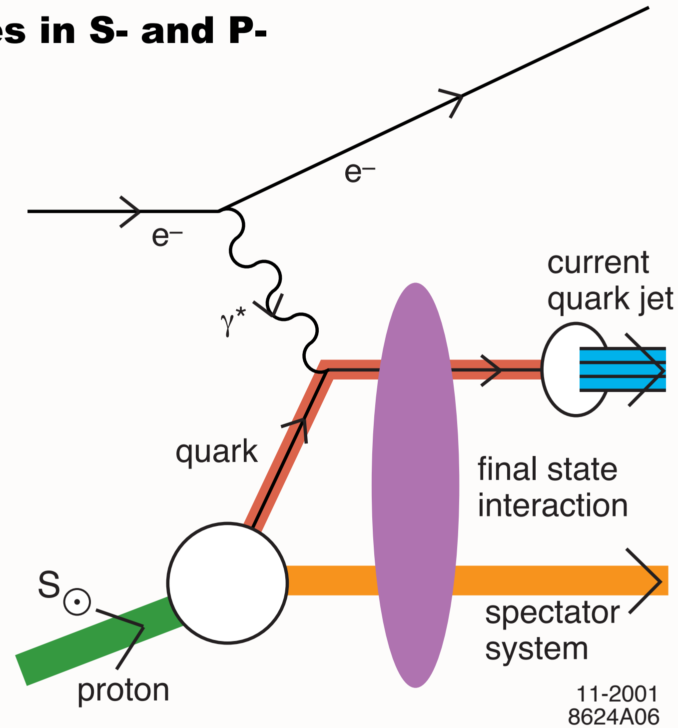
Leading-Twist Rescattering Violates pQCD Factorization!

# Final-State Interactions Produce Pseudo T-Odd (Sivers Effect)

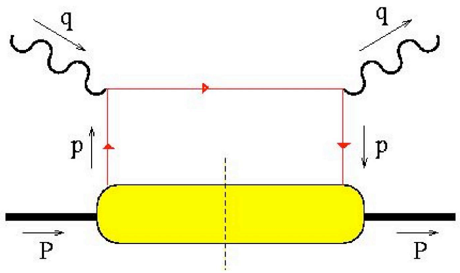
**Hwang, Schmidt, sjb**
**Collins**

$$\mathbf{i}\ \vec{S} \cdot \vec{p}_{jet} \times \vec{q}$$

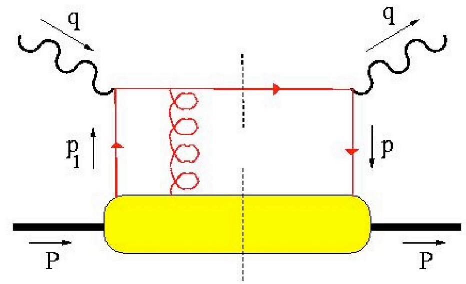
- **Leading-Twist Bjorken Scaling!**
- **Requires nonzero orbital angular momentum of quark**
- **Arises from the interference of Final-State QCD Coulomb phases in S- and P-waves;**
- **Wilson line effect -- gauge independent**
- **Relate to the quark contribution to the target proton anomalous magnetic moment and final-state QCD phases**
- **QCD phase at soft scale!**
- **New window to QCD coupling and running gluon mass in the IR**
- **QED S and P Coulomb phases infinite -- difference of phases finite!**
- **Alternate: Retarded and Advanced Gauge: Augmented LFWFs**




**Pasquini, Xiao, Yuan, sjb**
**Mulders, Boer** **Qiu, Sterman**



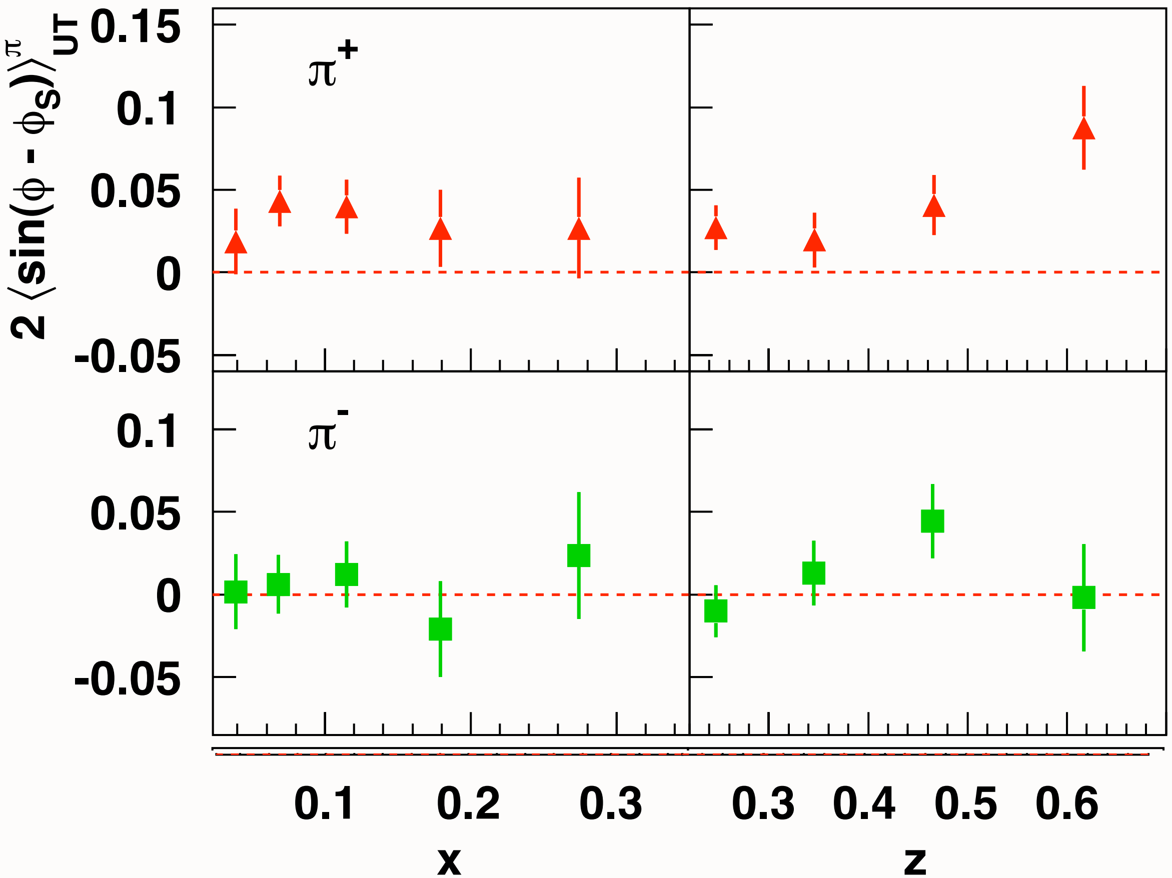

can interfere with




and produce a T-odd effect! (also need $L_z \neq 0$)

HERMES coll., A. Airapetian et al., Phys. Rev. Lett. 94 (2005) 012002.

## Sivers asymmetry from HERMES

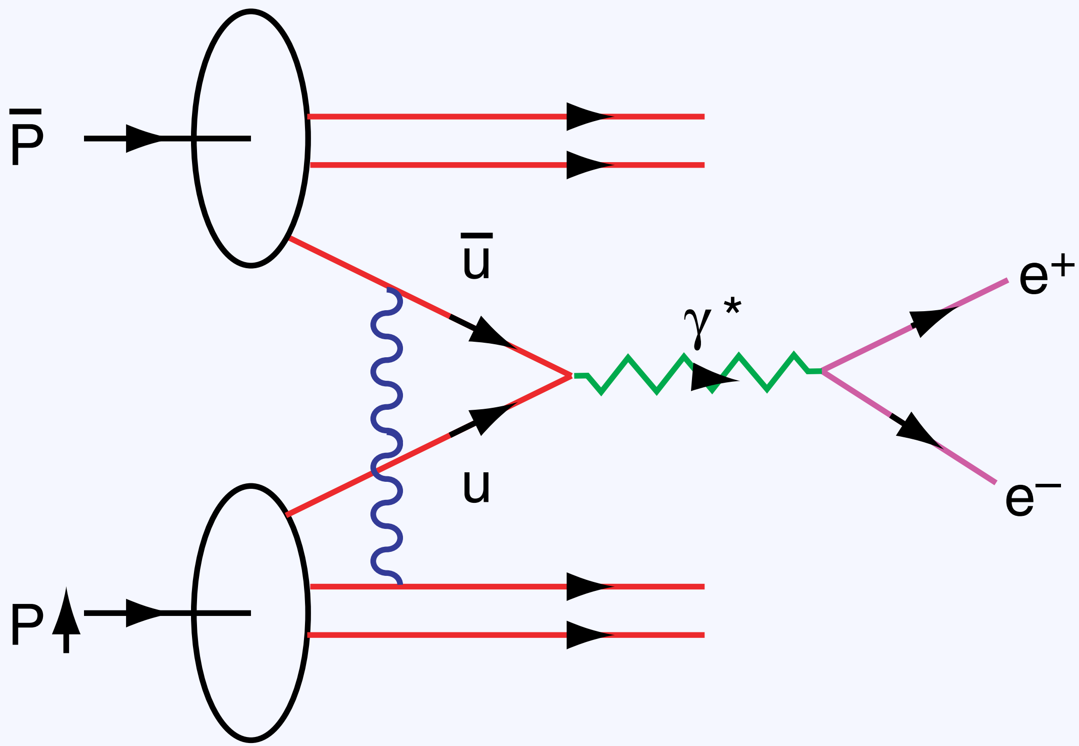



- First evidence for non-zero Sivers function!
- ⇒ presence of non-zero **quark orbital angular momentum**!
- Positive for **π⁺**... Consistent with zero for **π⁻**...

**Gamberg: Hermes data compatible with BHS model**

**Schmidt, Lu:**
***Asymmetry ratios should follow quark contributions to anomalous moment***

# Predict Opposite Sign SSA in DY !




**Collins**

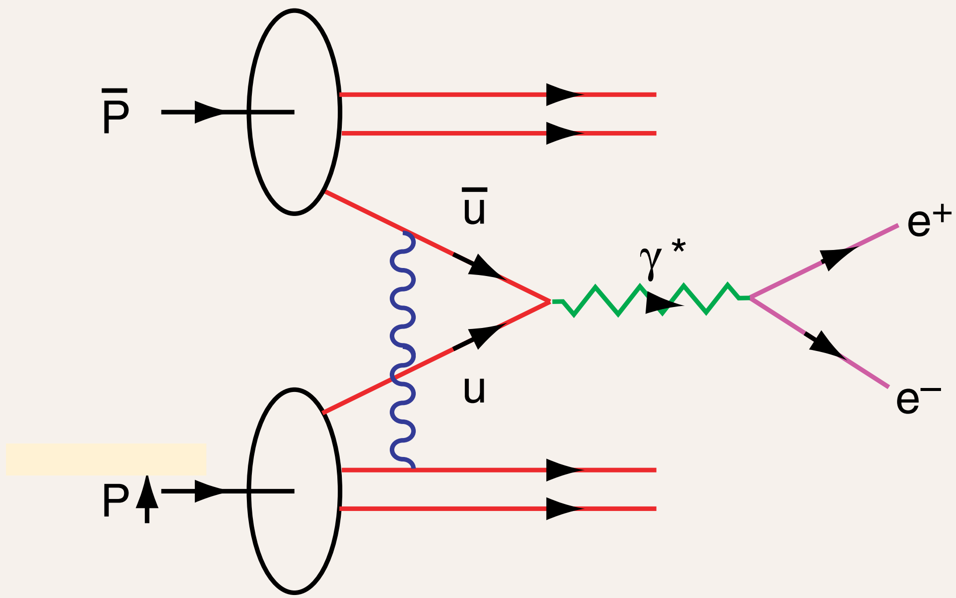
**Hwang**
**Schmidt**
**sjb**

Single Spin Asymmetry In the Drell Yan Process
$\vec{S}_p \cdot \vec{\bar{p}} \times \vec{q}_{\gamma^*}$
Quarks Interact in the Initial State
Interference of Coulomb Phases for *S* and *P* states
Produce Single Spin Asymmetry [Siver's Effect]Proportional to the Proton Anomalous Moment and $\alpha_s$.
Opposite Sign to DIS! No Factorization

# Key QCD Experiment

Collins; Hwang, Schmidt. sjb

Measure single-spin asymmetry $A_N$ in Drell-Yan reactions




Leading-twist Bjorken-scaling $A_N$ from $S, P$-wave initial-state gluonic interactions

Predict: $A_N(DY) = -A_N(DIS)$
Opposite in sign!

$$\bar{p}p_{\uparrow} \to \ell^+\ell^- X$$

$\vec{S} \cdot \vec{q} \times \vec{p}$ correlation

- A further undisputable property of fixed-target experiments is
  the possibility of polarising the target

  see COMPASS, HERMES, CLAS, ...

- The polarisation can be longitudinal and transverse
- Single Transverse Spin Asymmetries unravel the correlations
  between the parton $k_T$ and the proton spin
  $\rightarrow$ **information on orbital motion of partons in the proton !**
- Double Longitudinal Spin Asymmetries allow for the extraction of
  polarised PDFs
- Double Transverse Spin Asymmetries probe transversity
- The beam may become transversely polarised during the crystal extraction

  M. Ukhanov, Nucl. Instrum. Meth. A 582 (2007) 378.

  $\rightarrow$ to be experimentally checked . . .

# Spin Asymmetries and quarkonia

*Large Range of Target Single-Spin Asymmetry Phenomena*

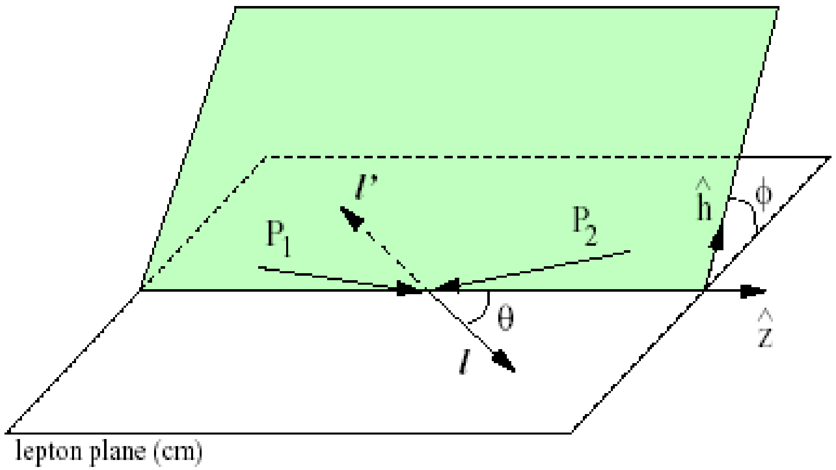
- For now, such Transverse SSA can be used to discrimate between production mechanism
- The situation is likely to change in the future, allowing us to measure gluon Sivers function from quarkonia ($J/\psi$, $\chi_c$, $\Upsilon$)
- It remains to be investigated how quarkonium polarisation can be used to form DSA

Attempt in: J. L. Cortes, B. Pire, Phys. Rev. **D38**, 3586 (1988).

- Of course, transverse SSA can be studied in parallel for other mesons (*D*, *B*, ...)
- In general, the backward region is the most favourable allowing for measurements in the large *x* region of the polarised nucleon

# Drell-Yan angular distribution

*Unpolarized DY*




$\mathrm{Lam-Tung\ SR:}\ 1-\lambda=2\nu$

$\mathrm{NLO\ pQCD:}\ \lambda\approx 1\ \mu\approx 0\ \nu\approx 0$

- Experimentally, a violation of the Lam-Tung sum rule is observed by sizeable cos2Φ moments
- Several model explanations
  - higher twist
  - spin correlation due to non-triva QCD vacuum
  - Non-zero Boer Mulders function

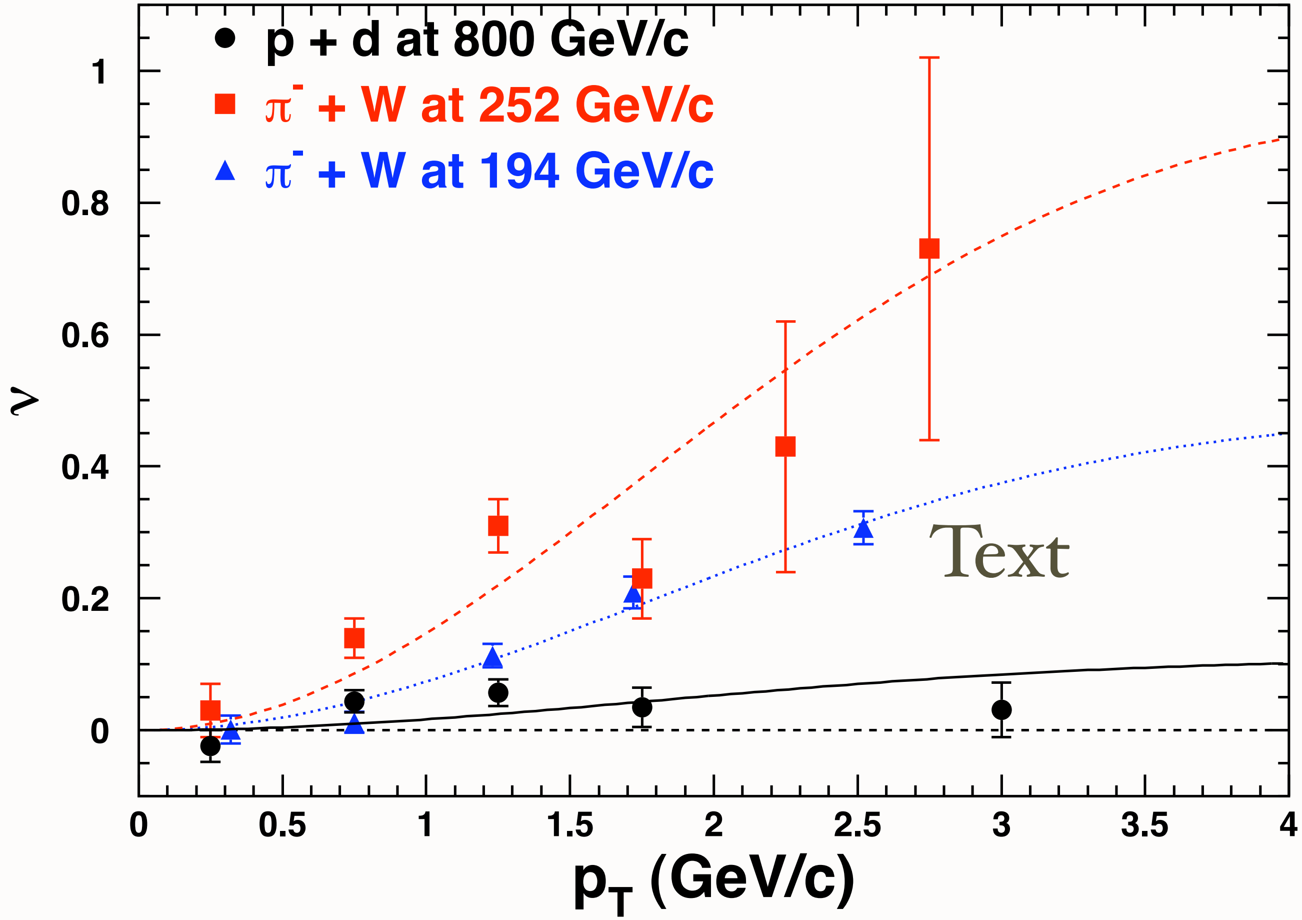
$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega}=\frac{3}{4\pi}\frac{1}{\lambda+3}\left(1+\lambda\cos^2\theta+\mu\sin2\theta\cos\phi+\frac{\nu}{2}\sin^2\theta\cos2\phi\right)$$

$$\mathrm{Experiment:}\ \nu\simeq 0.6$$

**B. Seitz**

Measurement of Angular Distributions of Drell-Yan Dimuons in $p + d$ Interaction at 800 GeV/c

(FNAL E866/NuSea Collaboration)



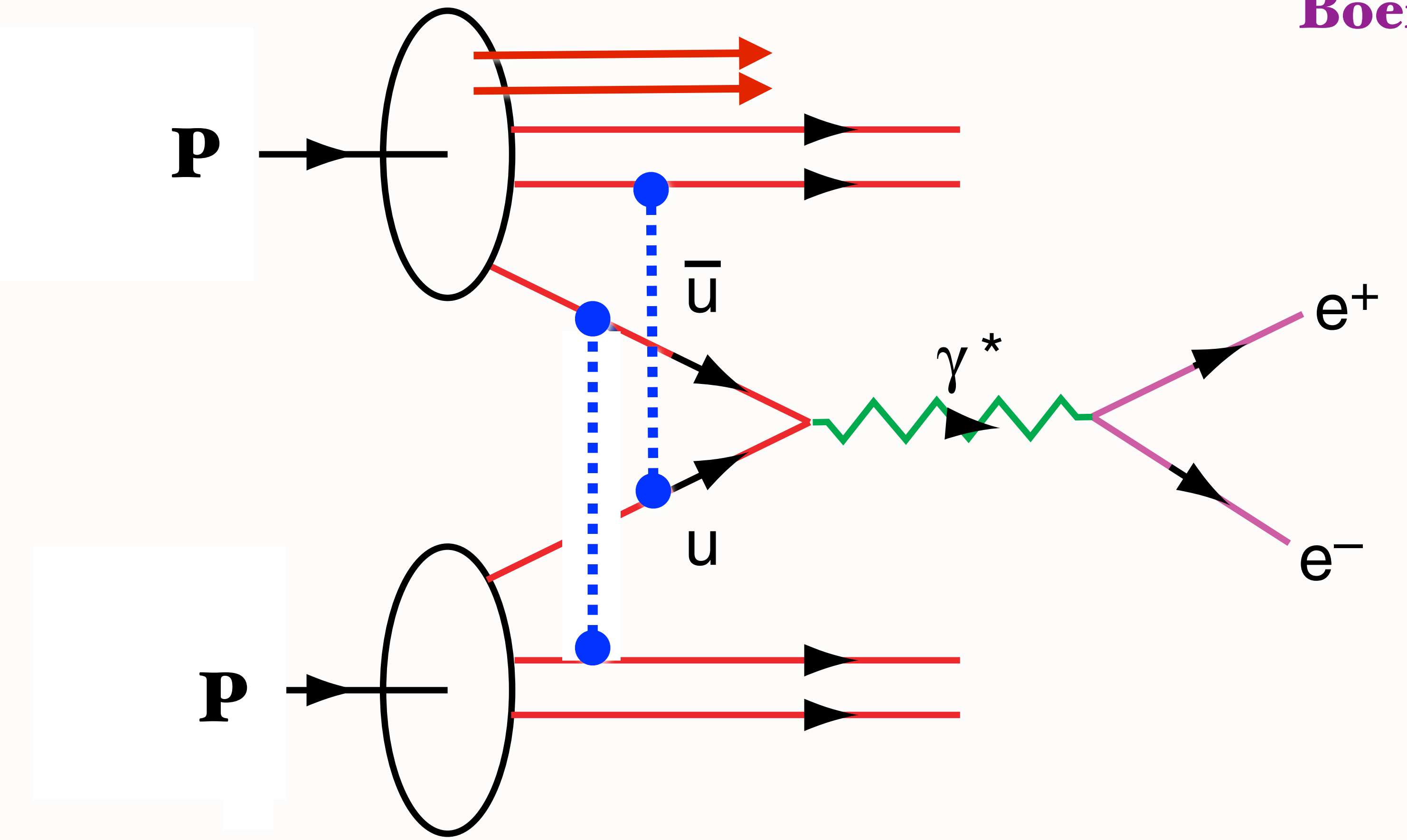

Parameter $\nu$ vs. $p_T$ in the Collins-Soper frame for three Drell-Yan measurements. Fits to the data using Eq. 3 and $M_C = 2.4$ GeV/c$^2$ are also shown.

Huge Effect in
$\pi W \to \mu^+ \mu^- X$
Negligible Effect in
$pd \to \mu^+ \mu^- X$

**Boer: Sudakov suppression at high Q**

# AFTER Experiment

Boer, Hwang, sjb




**DY $\cos 2\phi$ correlation at leading twist from double ISI**

Product of Boer - Mulders Functions

$$h_1^{\perp}(x_1, \boldsymbol{p}_\perp^2) \times \bar{h}_1^{\perp}(x_2, \boldsymbol{k}_\perp^2)$$

# Double Initial-State Interactions generate anomalous $\cos 2\phi$

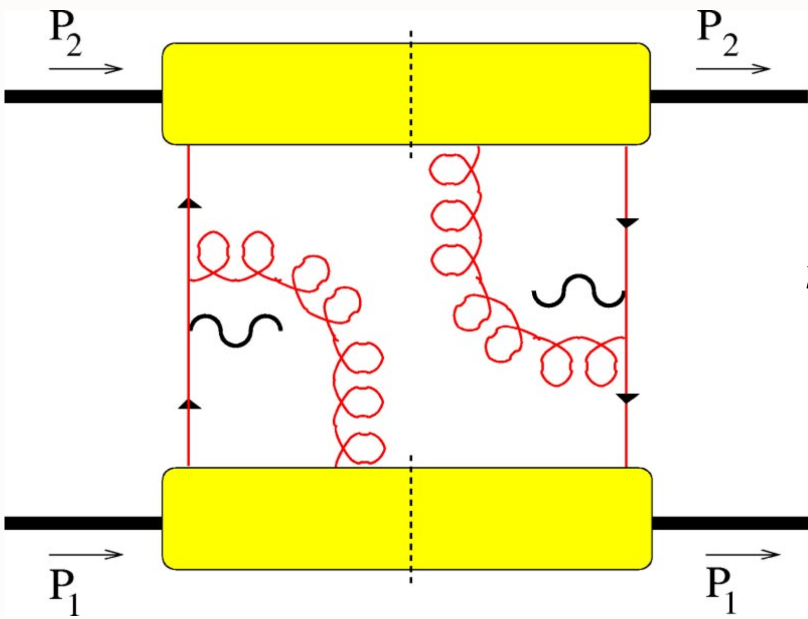
Boer, Hwang, sjb

## Drell-Yan planar correlations

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

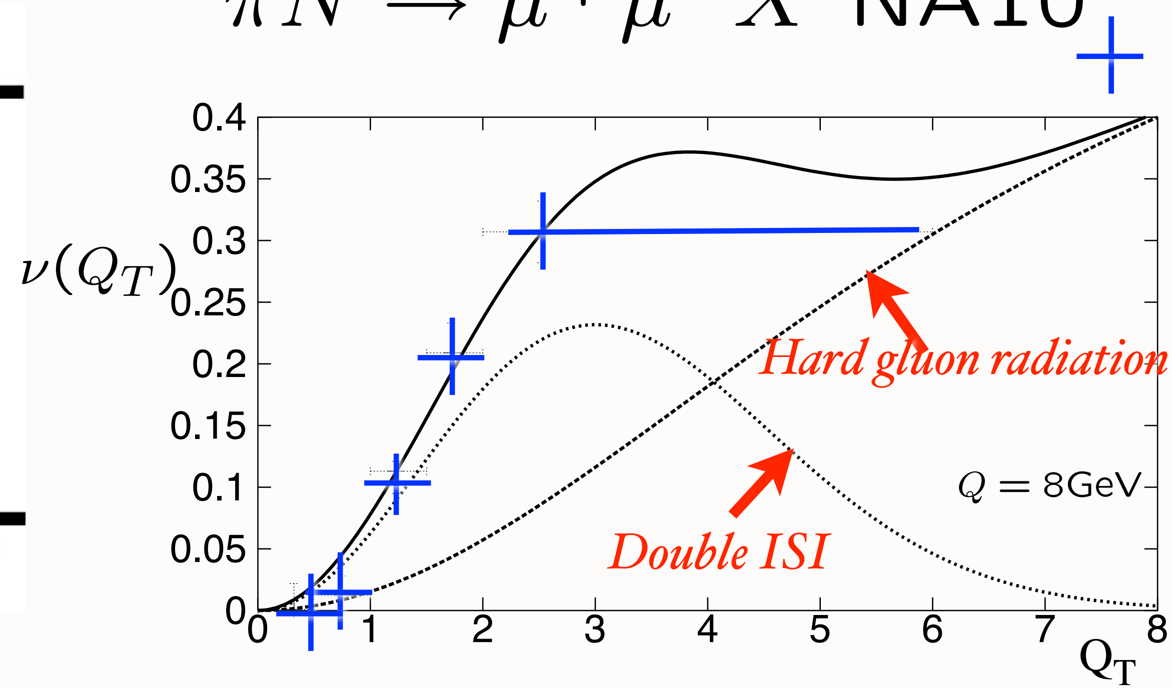
PQCD Factorization (Lam Tung): $1 - \lambda - 2\nu = 0$

$$\frac{\nu}{2} \propto h_1^{\perp}(\pi)\, h_1^{\perp}(N)$$

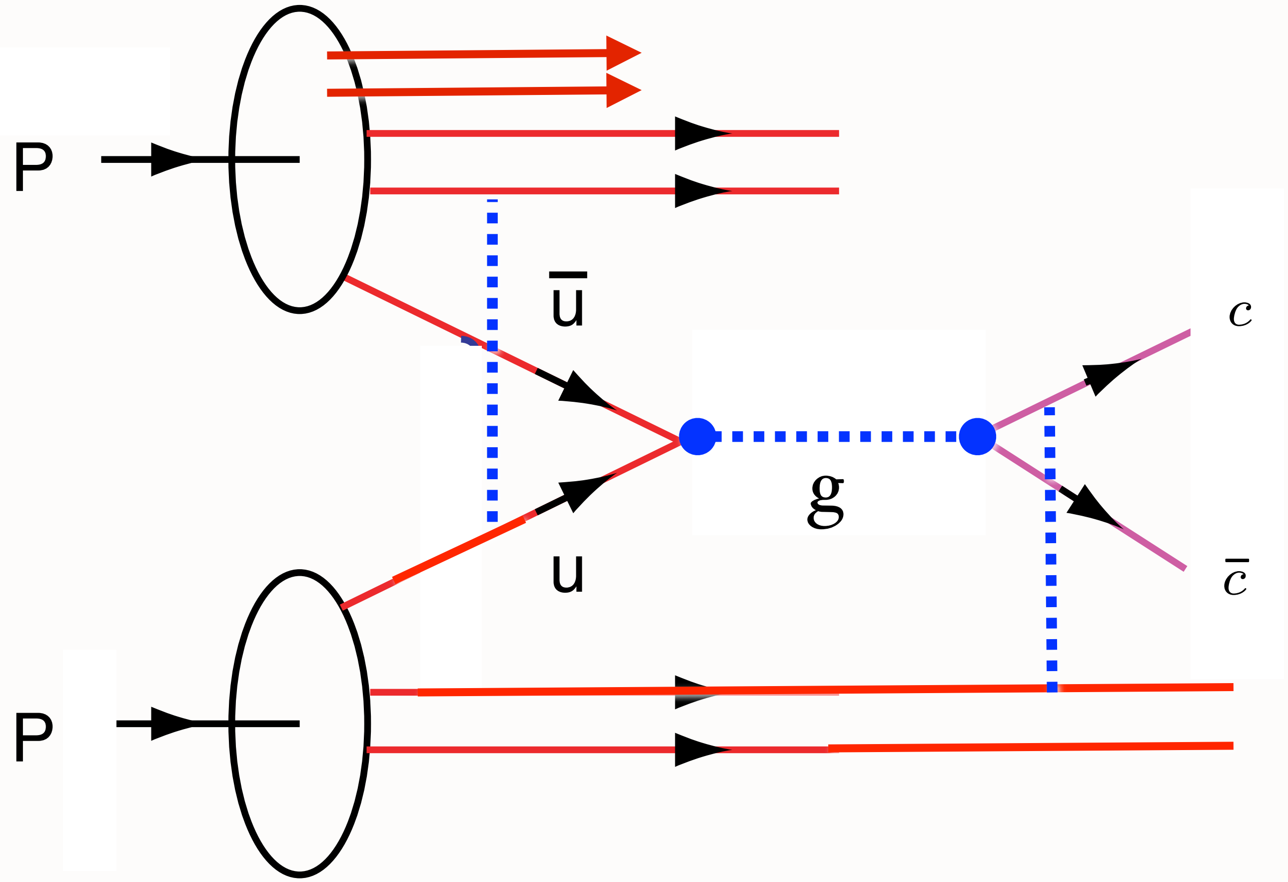



**Violates Lam-Tung relation!**

$\pi N \to \mu^+\mu^- X$ NA10




Model: Boer,

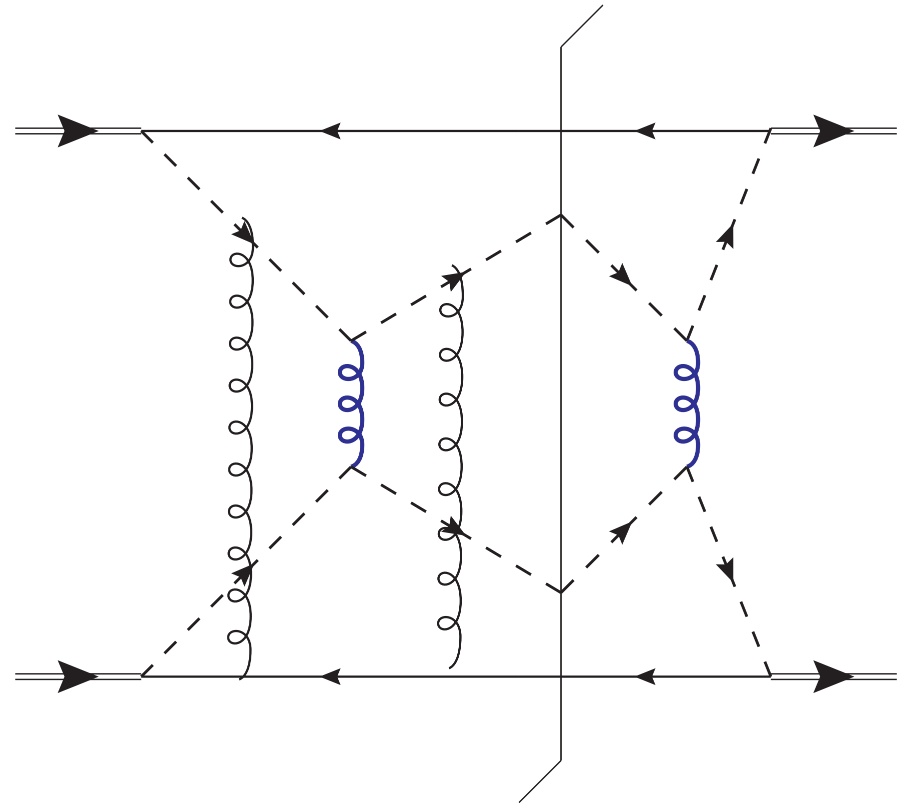



*Problem for factorization when both ISI and FSI occur*

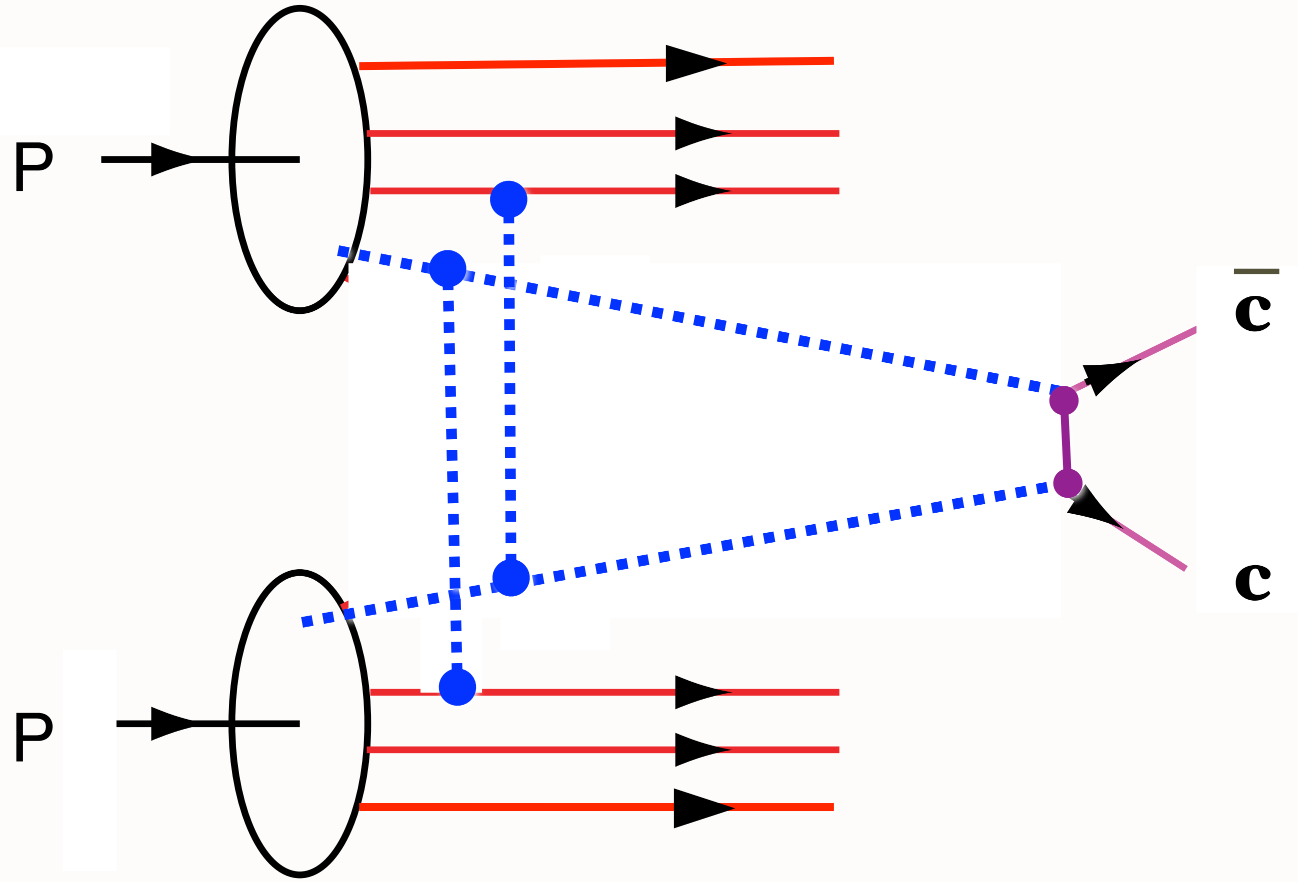
# Factorization is violated in production of high-transverse-momentum particles in hadron-hadron collisions

John Collins, Jian-Wei Qiu . ANL-HEP-PR-07-25, May 2007.

e-Print: **arXiv:0705.2141** [hep-ph]



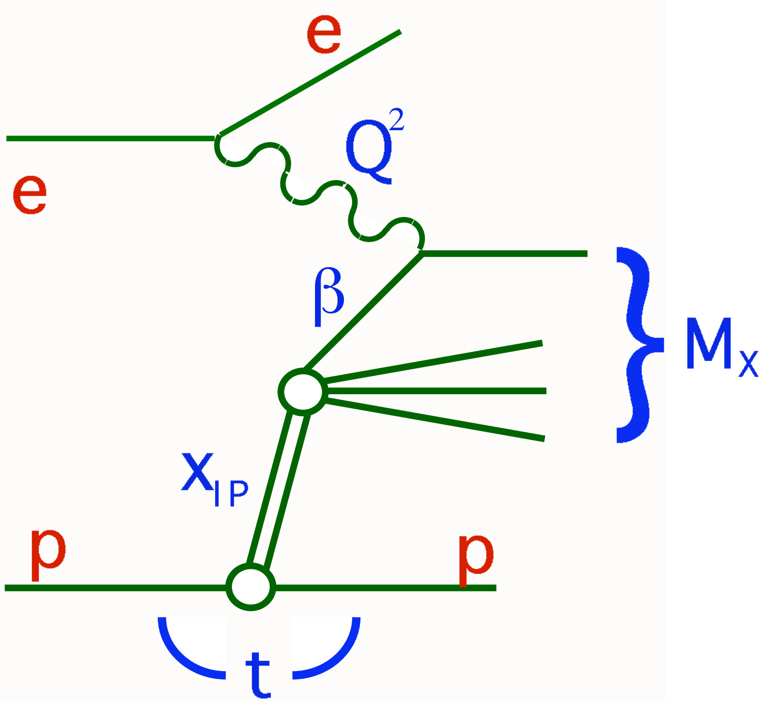
The exchange of two extra gluons, as in this graph, will tend to give non-factorization in unpolarized cross sections.

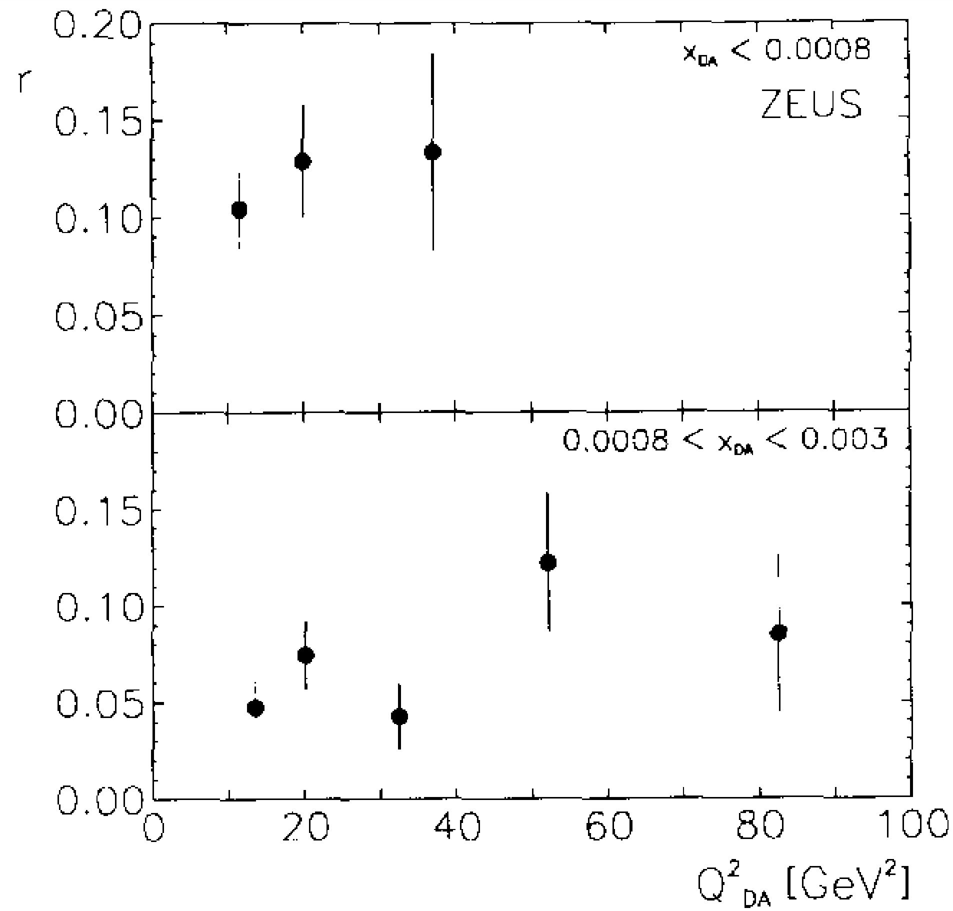



$\cos 2\phi$ correlation for quarkonium production at leading twist from double ISI

**Enhanced by gluon color charge**

# Remarkable observation at HERA



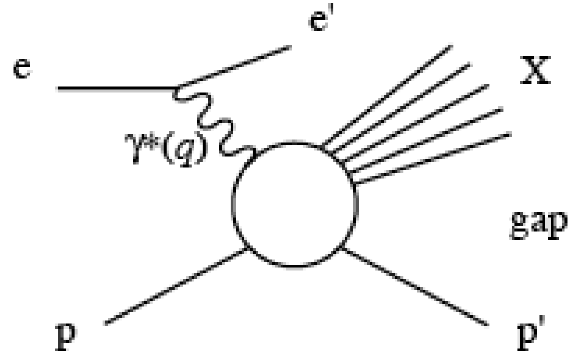




Fraction $r$ of events with a large rapidity gap, $\eta_{max} < 1.5$, as a function of $Q^2_{DA}$ for two ranges of $x_{DA}$. No acceptance corrections have been applied.

10% to 15%
of DIS events
are
diffractive !

M. Derrick et al. [ZEUS Collaboration], Phys. Lett. B 315, 481 (1993)

# DDIS

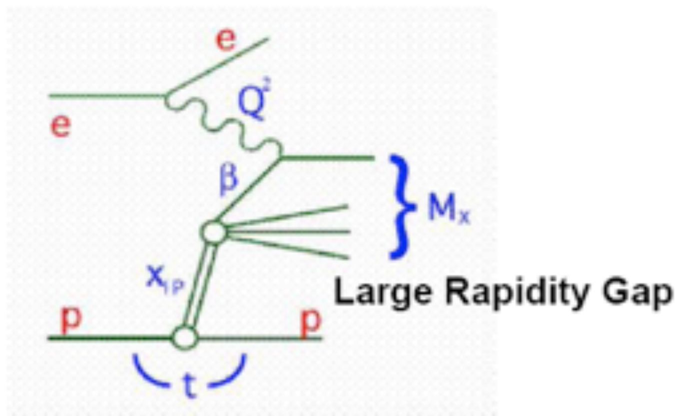


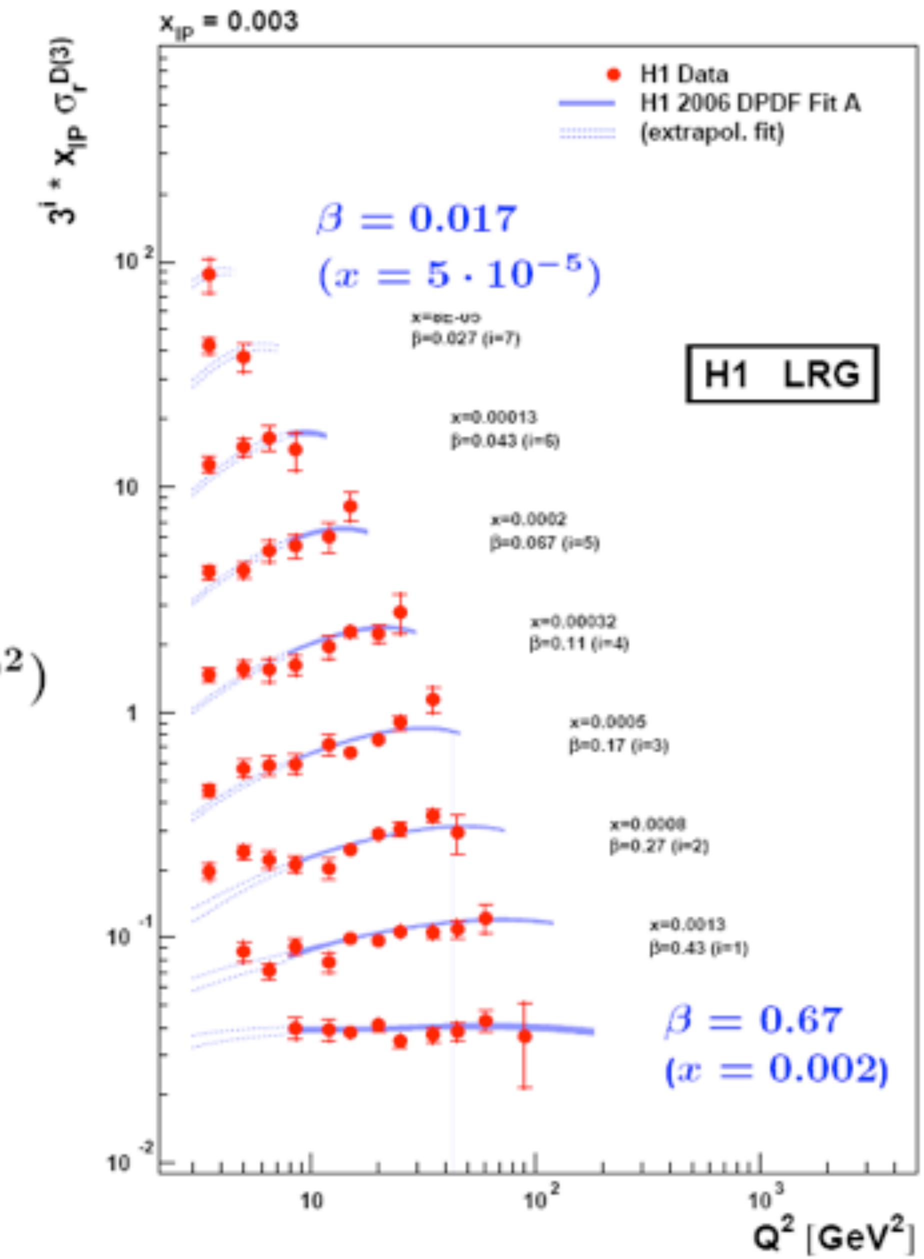

- In a large fraction ($\sim$ 10–15%) of DIS events, the proton escapes intact, keeping a large fraction of its initial momentum
- This leaves a large *rapidity gap* between the proton and the produced particles
- The $t$-channel exchange must be *color singlet* $\rightarrow$ a pomeron??

*Diffractive Deep Inelastic Lepton-Proton Scattering*

ISR, Tevatron: Single and Double Diffractive Events

# Diffractive Structure Function $F_2^D$




**Diffractive inclusive cross section**

$$\frac{d^3\sigma_{NC}^{diff}}{dx_{I\!P}\, d\beta\, dQ^2} \propto \frac{2\pi\alpha^2}{xQ^4} F_2^{D(3)}(x_{I\!P}, \beta, Q^2)$$

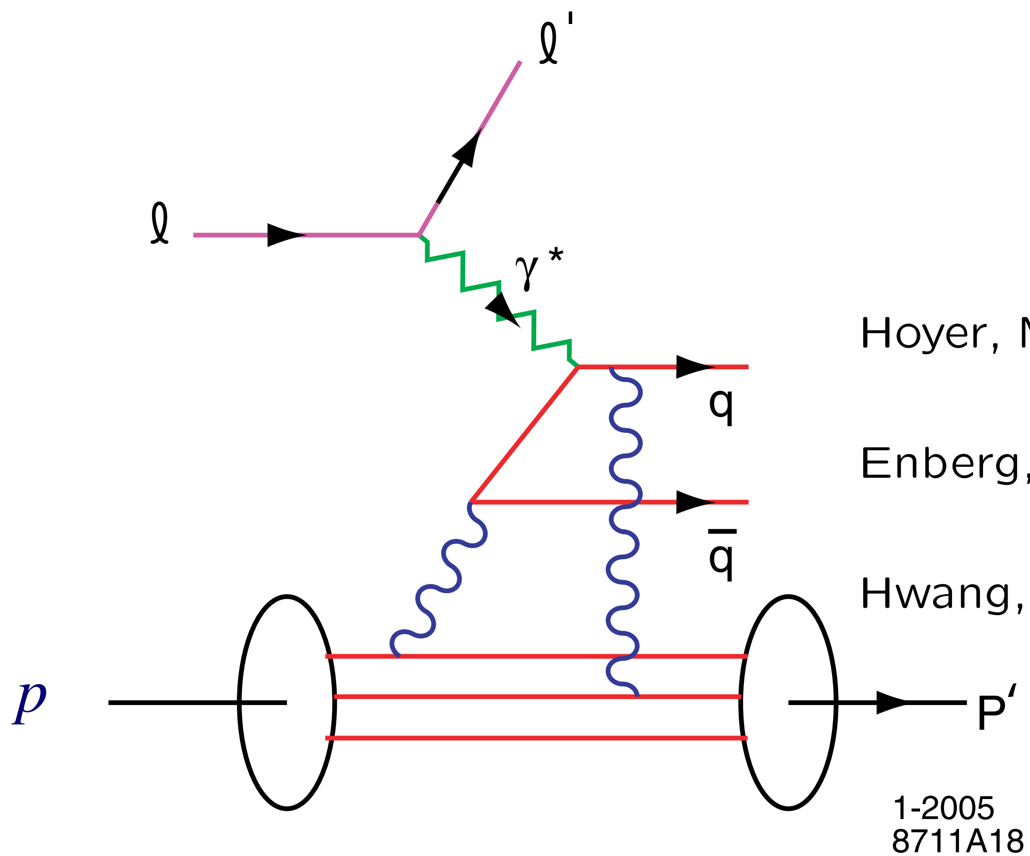
$$F_2^D(x_{I\!P}, \beta, Q^2) = f(x_{I\!P}) \cdot F_2^{I\!P}(\beta, Q^2)$$

**extract DPDF and $xg(x)$ from scaling violation**

*Large kinematic domain* $3 < Q^2 < 1600\ \mathrm{GeV}^2$

*Precise measurements* *sys 5%, stat 5–20%*

# Final-State Interaction Produces Diffractive DIS




Quark Rescattering

Hoyer, Marchal, Peigne, Sannino, SJB (BHMPS)

Enberg, Hoyer, Ingelman, SJB

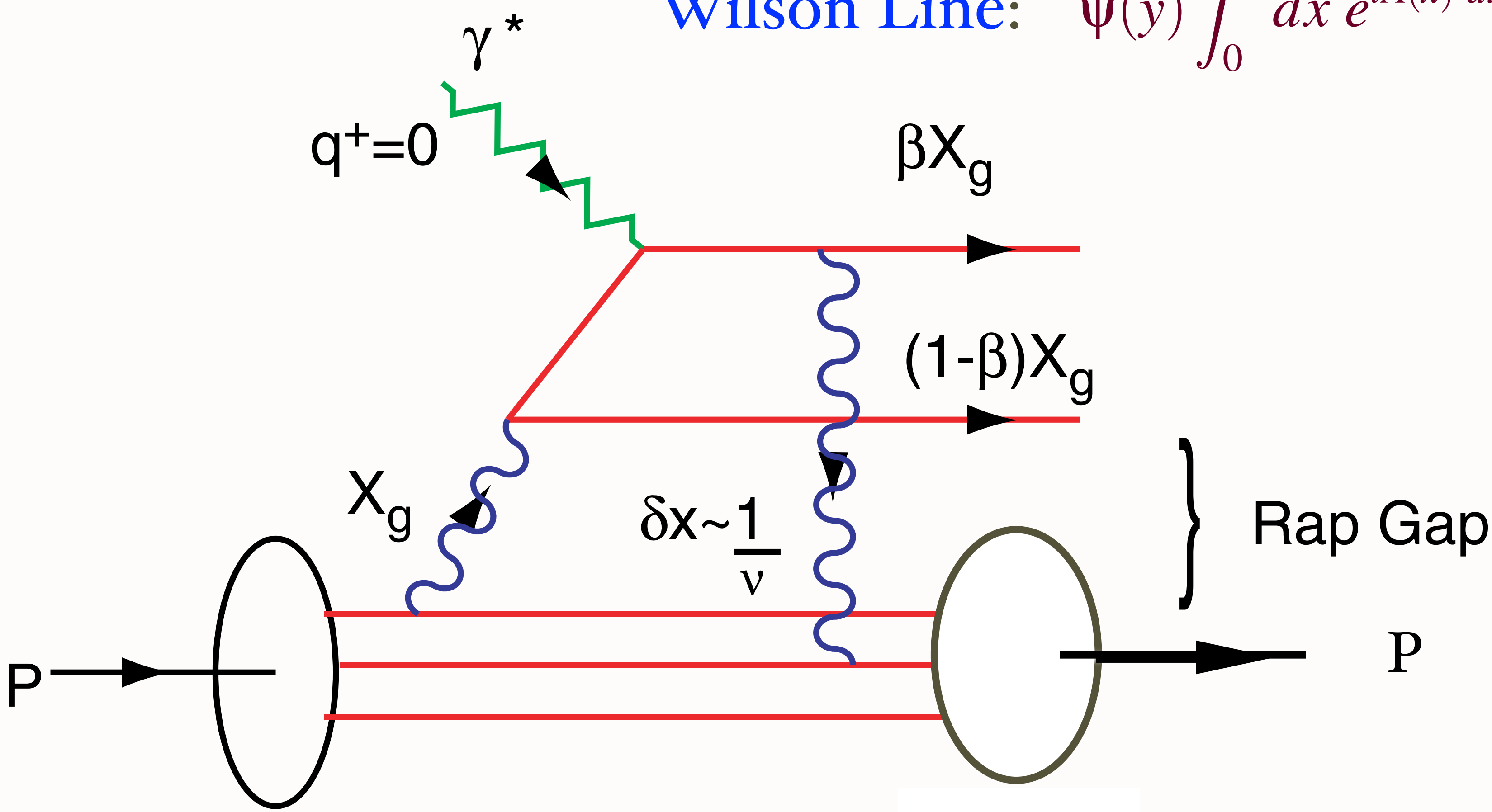
Hwang, Schmidt, SJB

**Low-Nussinov model of Pomeron**

Hoyer, Marchal, Peigne, Sannino, sjb

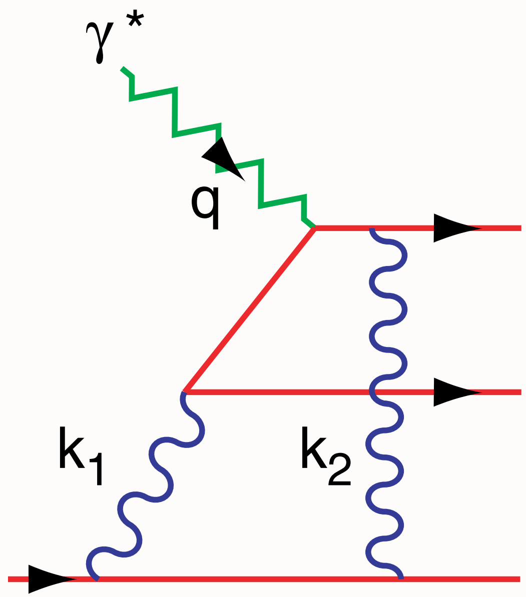
# QCD Mechanism for Rapidity Gaps

Wilson Line: $\overline{\psi}(y) \int_0^y dx\, e^{iA(x)\cdot dx}\, \psi(0)$

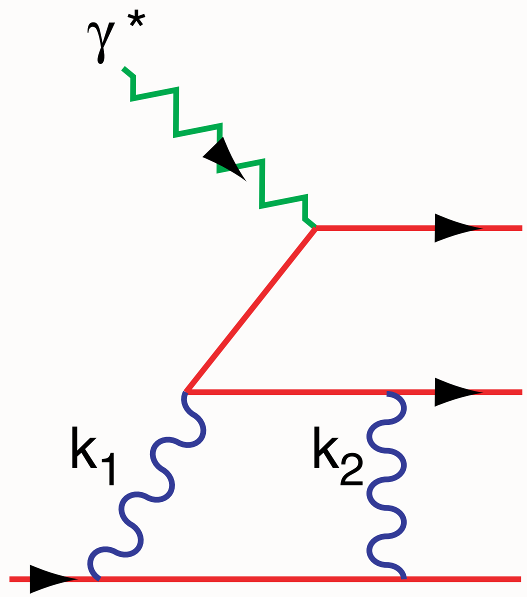



**Reproduces lab-frame color dipole approach**

# Final State Interactions in QCD

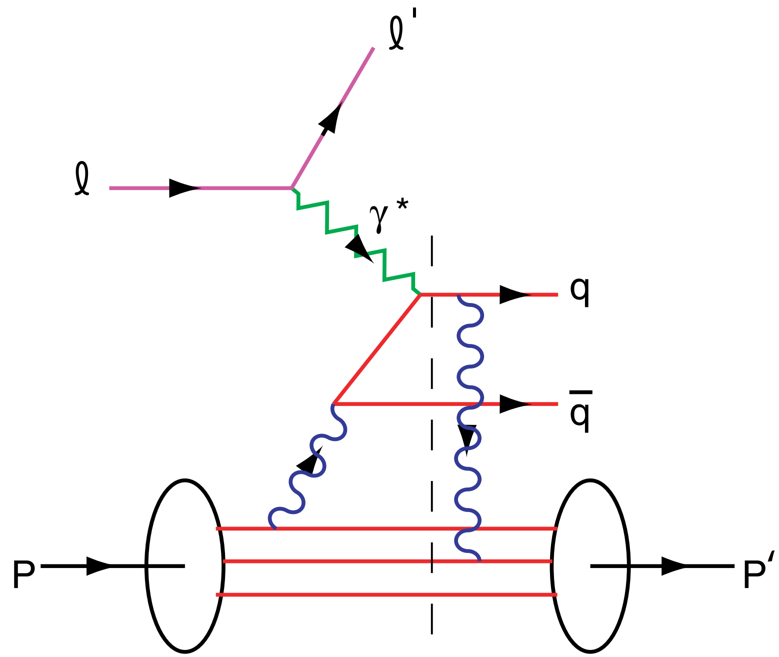



Feynman Gauge




Light-Cone Gauge

**Result is Gauge Independent**




Integration over on-shell domain produces phase i

Need Imaginary Phase to Generate Pomeron and DDIS

Need Imaginary Phase to Generate
T-Odd Single-Spin Asymmetry

*Physics of FSI not in Wavefunction of Target!*

# Physics of Rescattering

- Sivers Asymmetry and Diffractive DIS: New Insights into Final State Interactions in QCD
- Origin of Hard Pomeron
- Structure Functions not Probability Distributions! *Not square of LFWFs*
- T-odd SSAs, Shadowing, Antishadowing
- Diffractive dijets/ trijets, doubly diffractive Higgs
- Novel Effects: Color Transparency, Color Opaqueness, Intrinsic Charm, Odderon

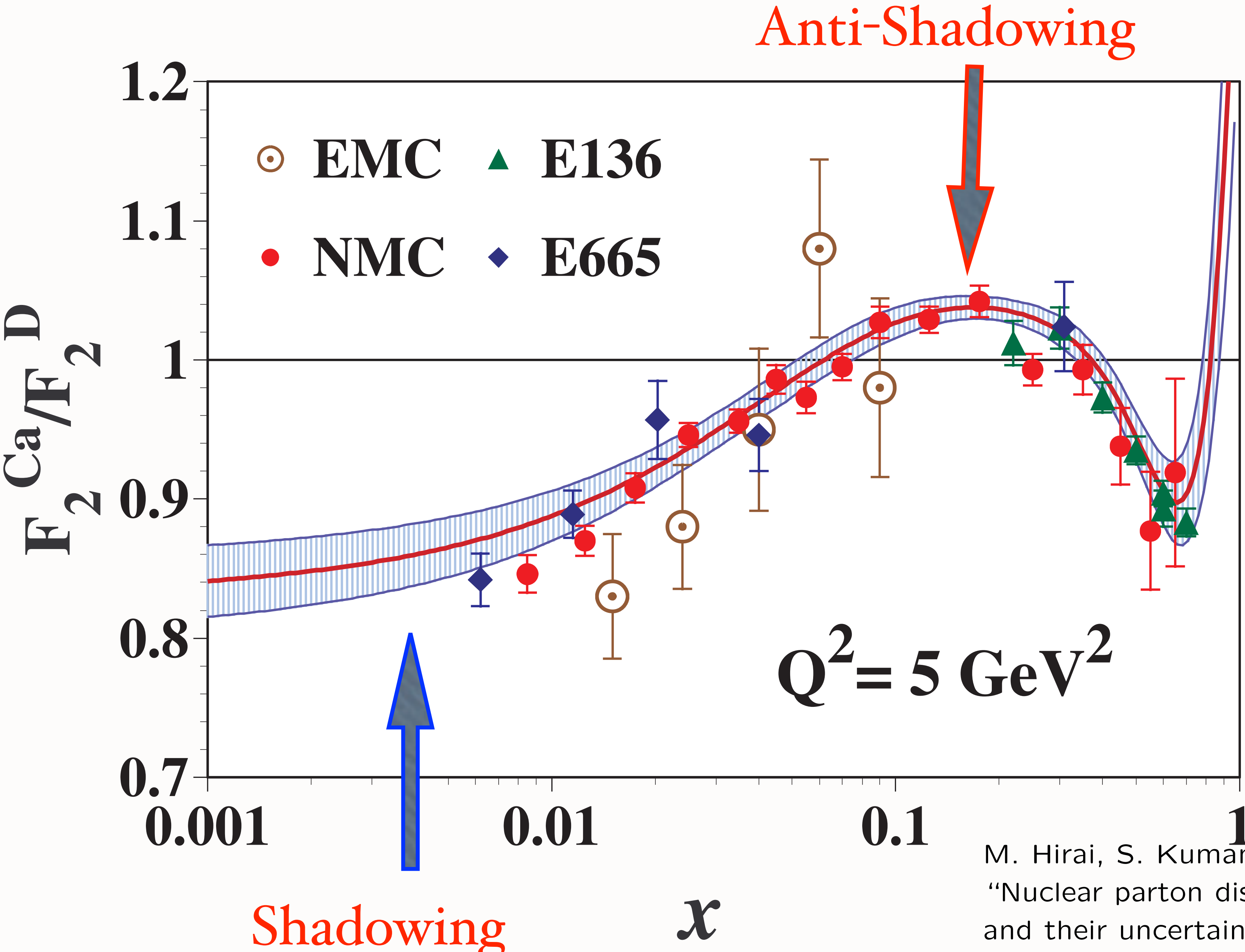
# Applications of Nonperturbative Running Coupling from AdS/QCD

- Sivers Effect in SIDIS, Drell-Yan
- Double Boer-Mulders Effect in DY
- Diffractive DIS
- Heavy Quark Production at Threshold

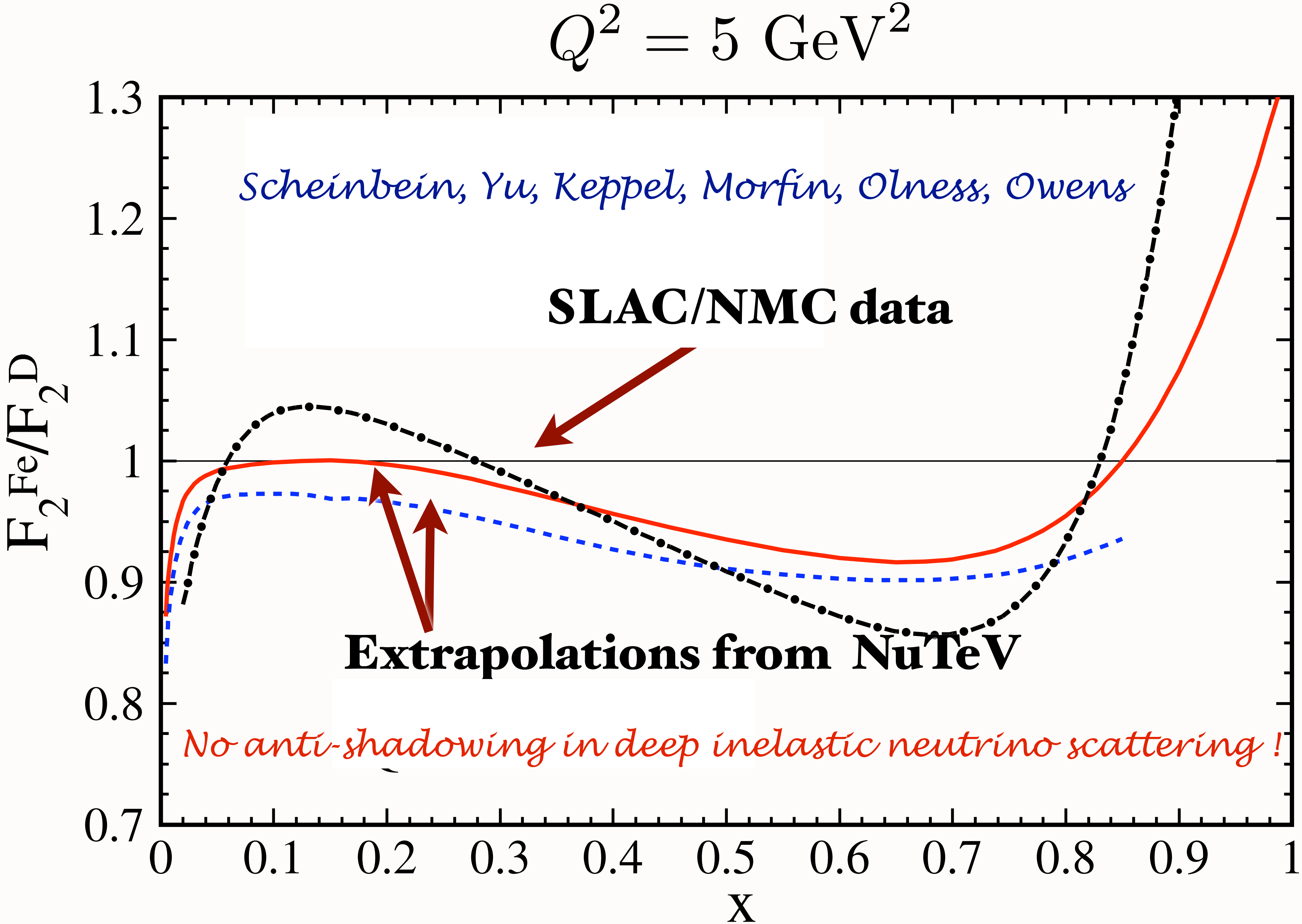
*All involve gluon exchange at small momentum transfer*

# Diffraction at AFTER

- Multi-gluon exchange leaves target intact
- Many Channels
- Nucleus remains intact at high energy
- Many types of Diffractive Channels
- Odderon Search in $pp \to c\bar{c}X$
- Look for heavy quark asymmetry
- Proton Diffracts to 3 Jets -- measures valence LFWF

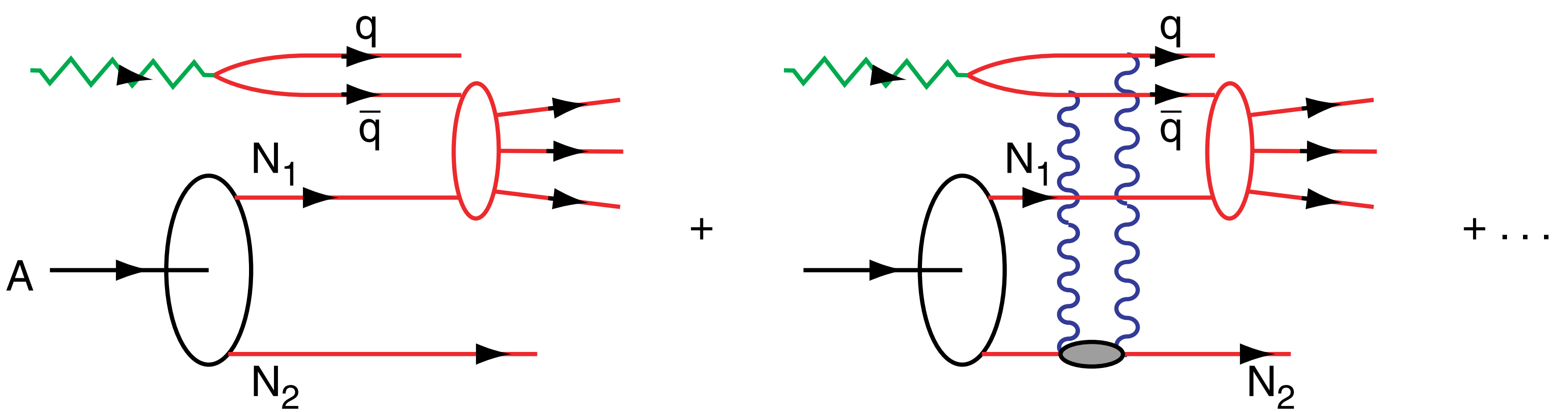



M. Hirai, S. Kumano and T. H. Nagai, "Nuclear parton distribution functions and their uncertainties," Phys. Rev. C **70**, 044905 (2004) [arXiv:hep-ph/0404093].


$Q^2 = 5 \text{ GeV}^2$
Scheinbein, Yu, Keppel, Morfin, Olness, Owens
SLAC/NMC data
Extrapolations from NuTeV
No anti-shadowing in deep inelastic neutrino scattering !
$F_2^{Fe}/F_2^D$
x
1.3
1.2
1.1
1
0.9
0.8
0.7
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

Stodolsky
Pumplin, sjb
Gribov

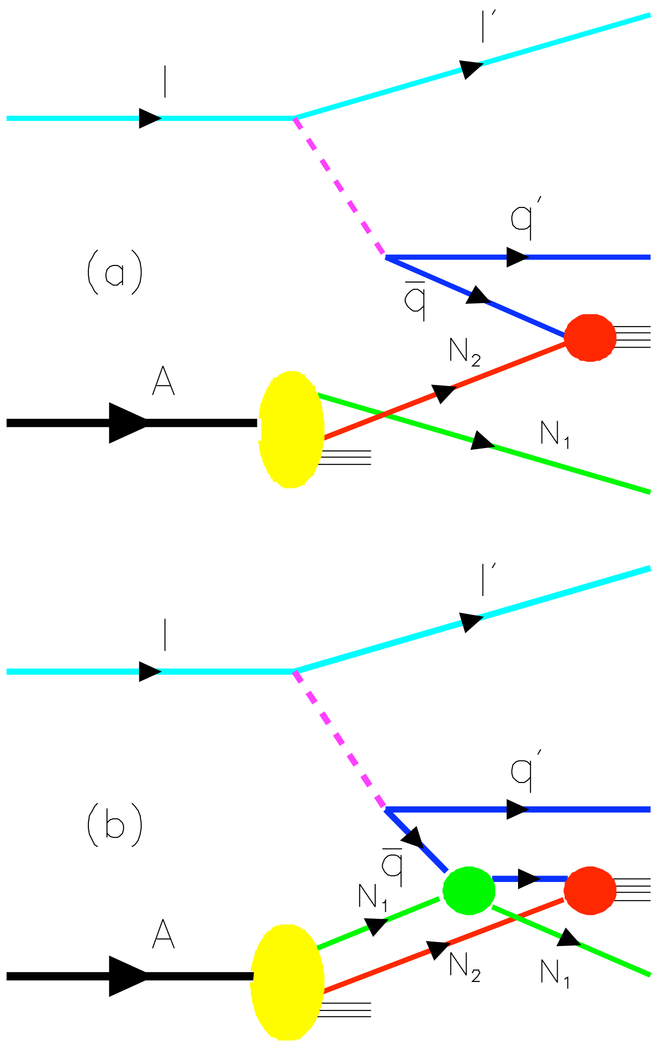
# *Nuclear Shadowing in QCD*




*Shadowing depends on understanding leading twist-diffraction in DIS*

**Nuclear Shadowing not included in nuclear LFWF !**

**Dynamical effect due to virtual photon interacting in nucleus**



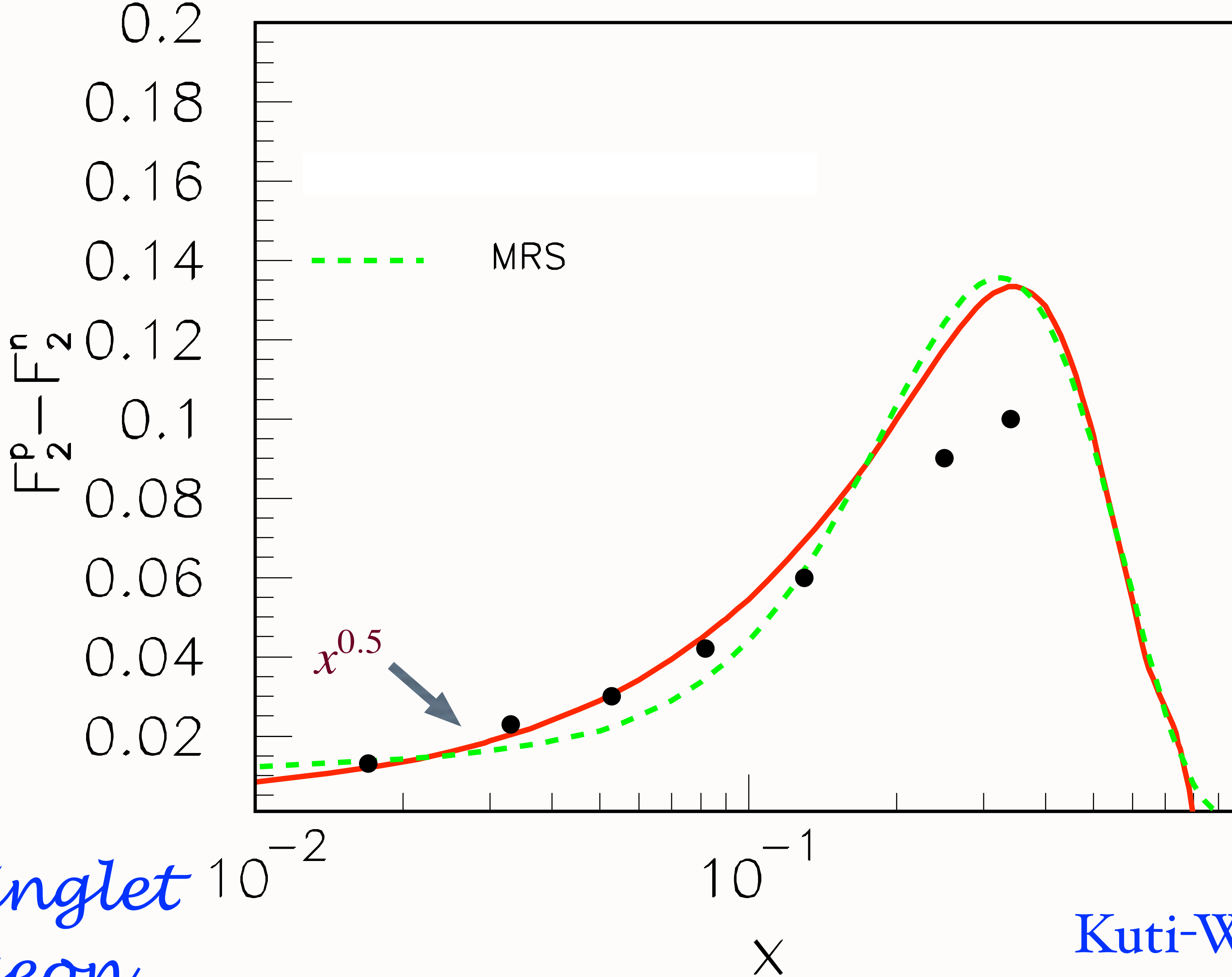

The one-step and two-step processes in DIS on a nucleus.

Coherence at small Bjorken $x_B$ :
$1/Mx_B = 2\nu/Q^2 \geq L_A$.

If the scattering on nucleon $N_1$ is via pomeron exchange, the one-step and two-step amplitudes are opposite in phase, thus diminishing the $\overline{q}$ flux reaching $N_2$.

$\rightarrow$ Shadowing of the DIS nuclear structure functions.

**Observed HERA DDIS produces nuclear shadowing**




*Non-singlet Reggeon Exchange*

Kuti-Weisskopf behavior

# Reggeon Exchange

Phase of two-step amplitude relative to one step:

$$\frac{1}{\sqrt{2}}(1-i) \times i = \frac{1}{\sqrt{2}}(i+1)$$

Constructive Interference

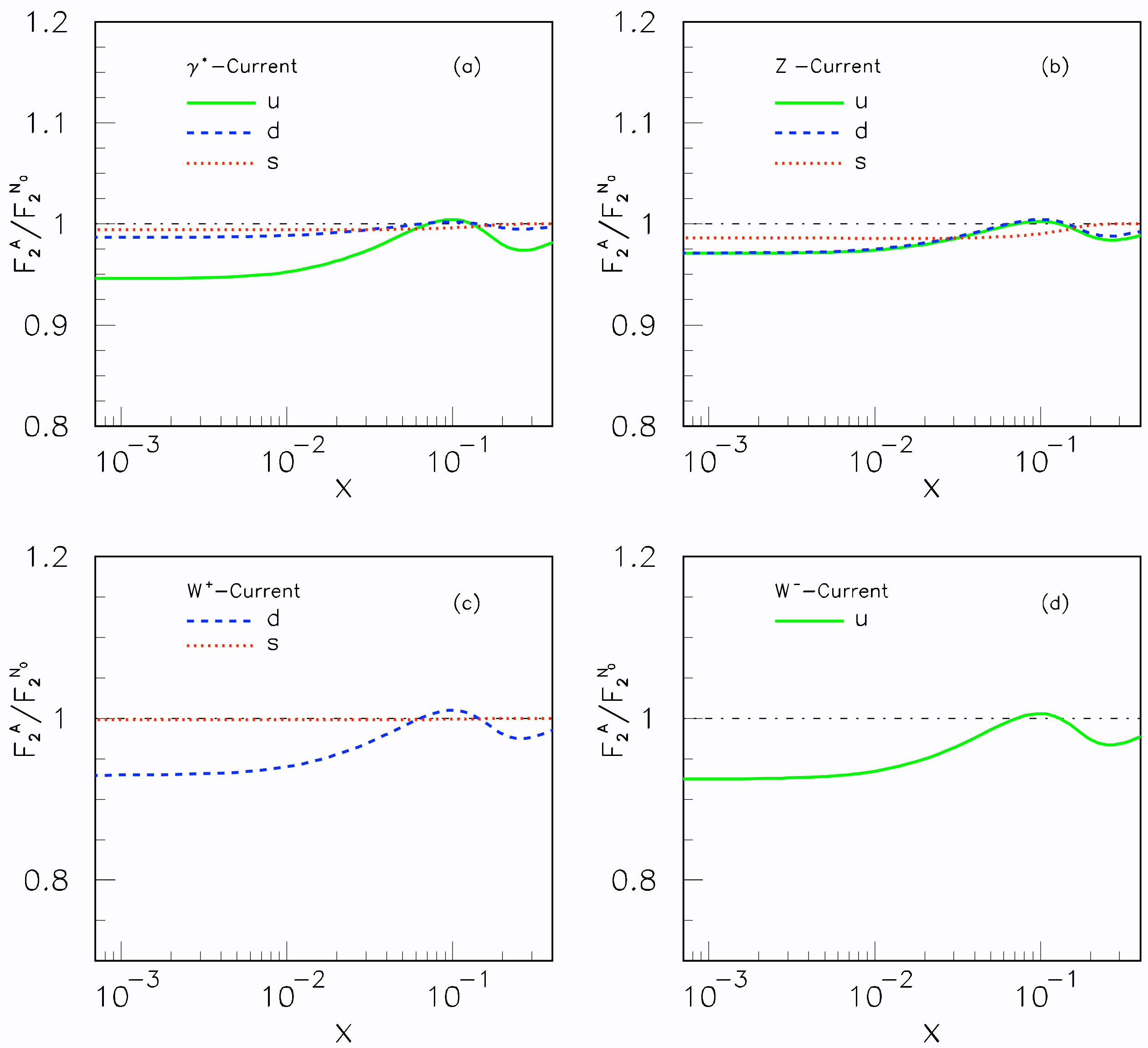
Depends on quark flavor!

Thus antishadowing is not universal

Different for couplings of $\gamma^*, Z^0, W^\pm$

*Critical test: Tagged Drell-Yan*

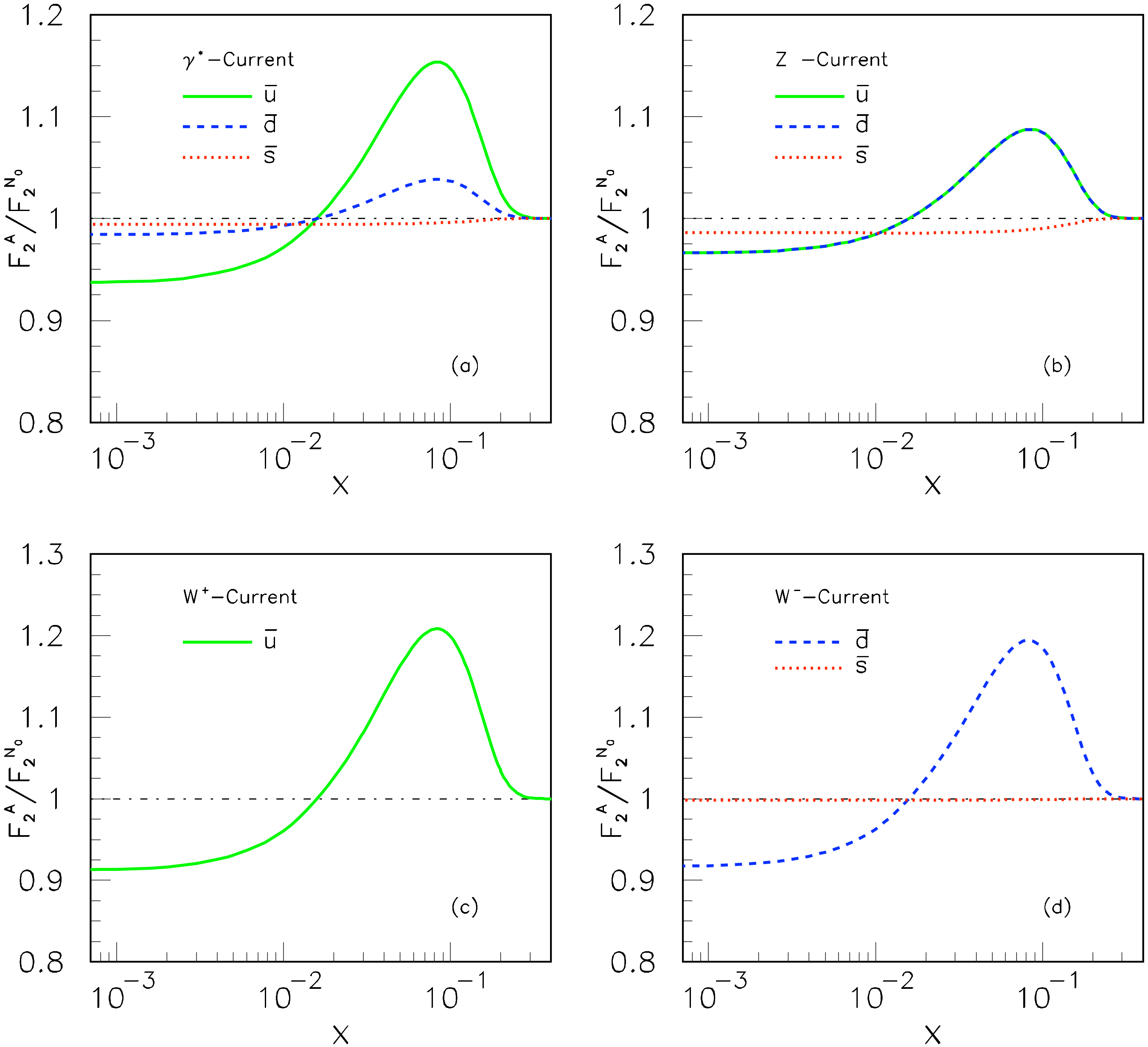
# Shadowing and Antishadowing of DIS Structure Functions




S. J. Brodsky, I. Schmidt and J. J. Yang, "Nuclear Antishadowing in Neutrino Deep Inelastic Scattering," Phys. Rev. D 70, 116003 (2004) [arXiv:hep-ph/0409279].

**Modifies NuTeV extraction of** $\sin^2\theta_W$

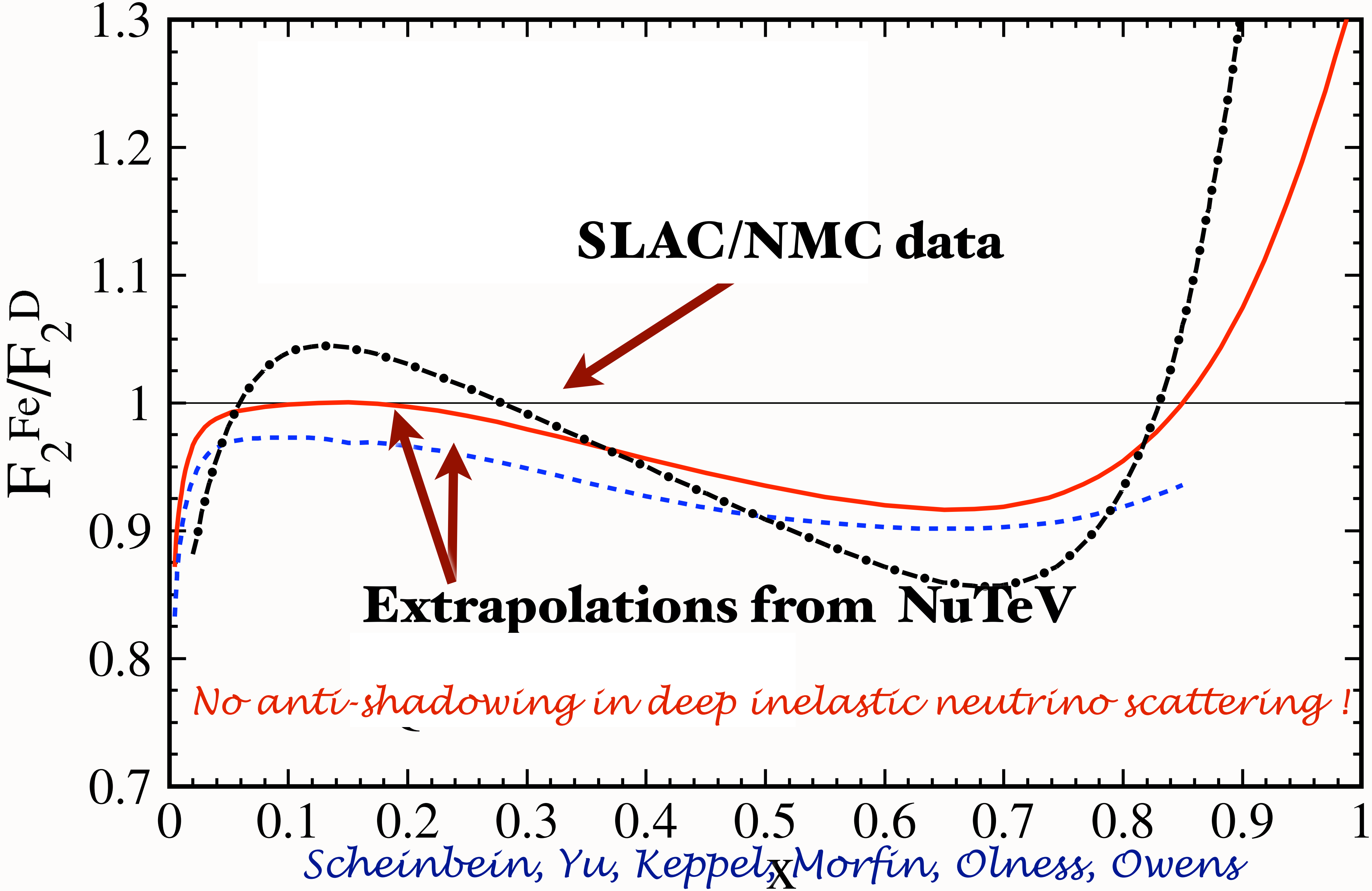
**Test in flavor-tagged lepton-nucleus collisions**




**Schmidt, Yang; sjb**

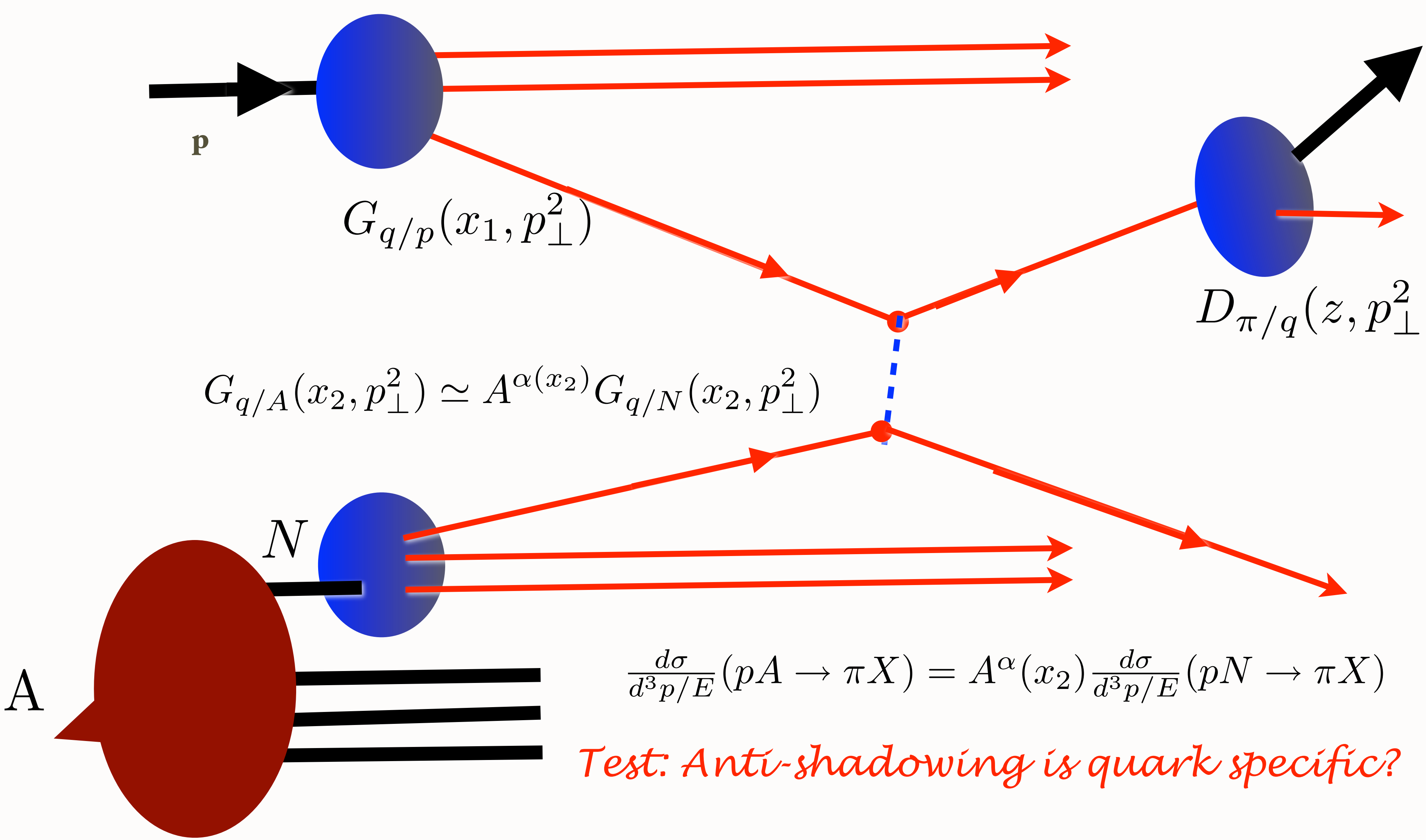
*Nuclear Antishadowing not universal !*

$Q^2 = 5\ \mathrm{GeV}^2$



# LHC p-A Collisions

## Leading-Twist Contribution to Hadron Production on Nuclei




$$\frac{d\sigma}{d^3p/E}(pA \to \pi X) = A^{\alpha}(x_2)\frac{d\sigma}{d^3p/E}(pN \to \pi X)$$

Test: Anti-shadowing is quark specific?

| Static | Dynamic |
|---|---|
| • Square of Target LFWFs | Modified by Rescattering: ISI & FSI |
| • No Wilson Line | Contains Wilson Line, Phases |
| • Probability Distributions | No Probabilistic Interpretation |
| • Process-Independent | Process-Dependent - From Collision |
| • T-even Observables | T-Odd (Sivers, Boer-Mulders, etc.) |
| • No Shadowing, Anti-Shadowing | Shadowing, Anti-Shadowing, Saturation |
| • Sum Rules: Momentum and $J^z$ | Sum Rules Not Proven |
| • DGLAP Evolution; mod. at large x | DGLAP Evolution |
| • No Diffractive DIS | Hard Pomeron and Odderon Diffractive DIS |

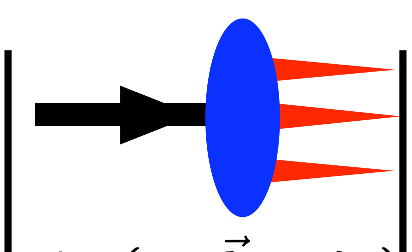
**Hwang, Schmidt, sjb,**

**Mulders, Boer**

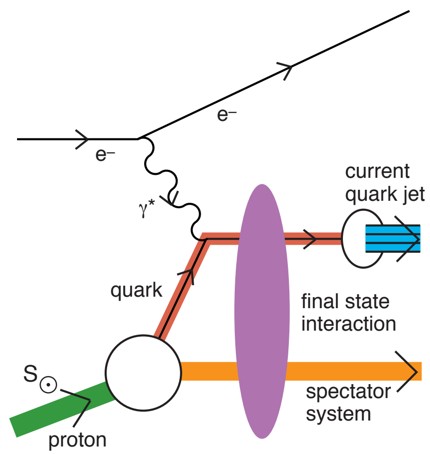
**Qiu, Sterman**

**Collins, Qiu**

**Pasquini, Xiao, Yuan, sjb**



$$\left| \Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i) \right|^2$$



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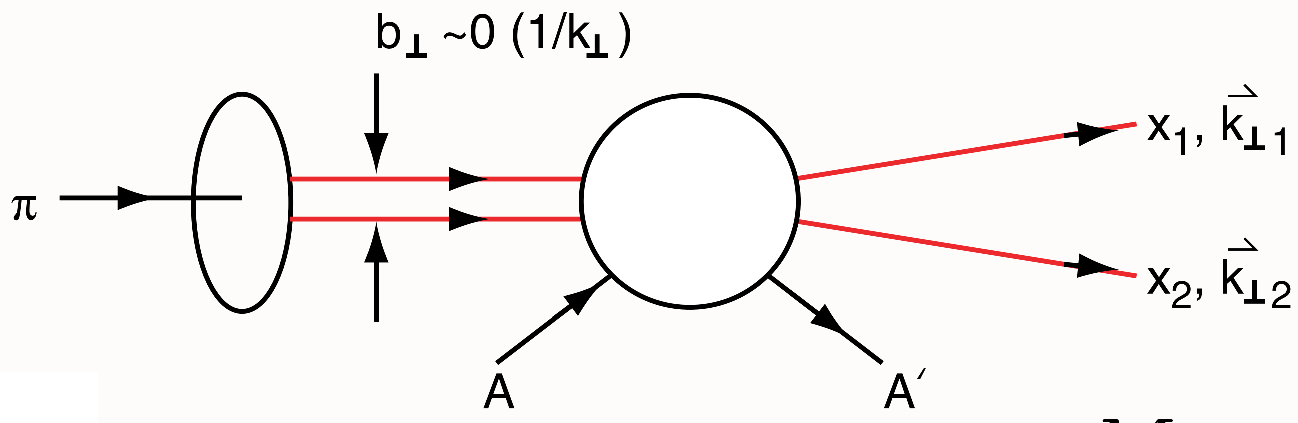
- Novel Effects: Color Transparency, Color Opaqueness, Intrinsic Charm, Odderon

# Diffractive Dissociation of Pion into Quark Jets

E791 Ashery et al.



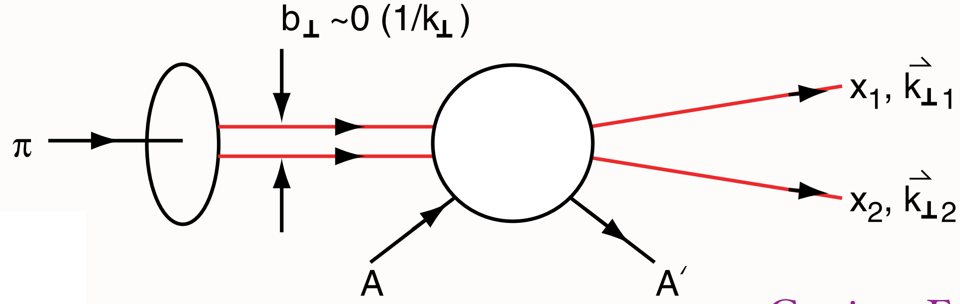

$$M \propto \frac{\partial^2}{\partial^2 k_\perp} \psi_\pi(x, k_\perp)$$

Measure Light-Front Wavefunction of Pion

Minimal momentum transfer to nucleus

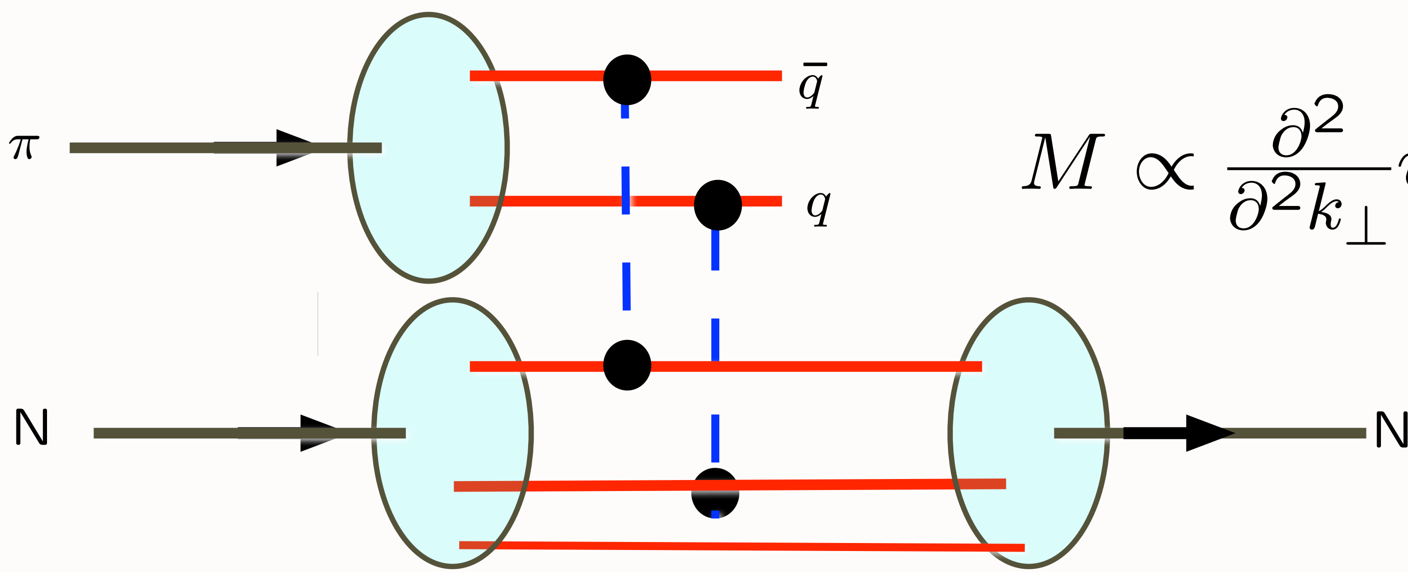
Nucleus left Intact!

# E791 FNAL Diffractive DiJet



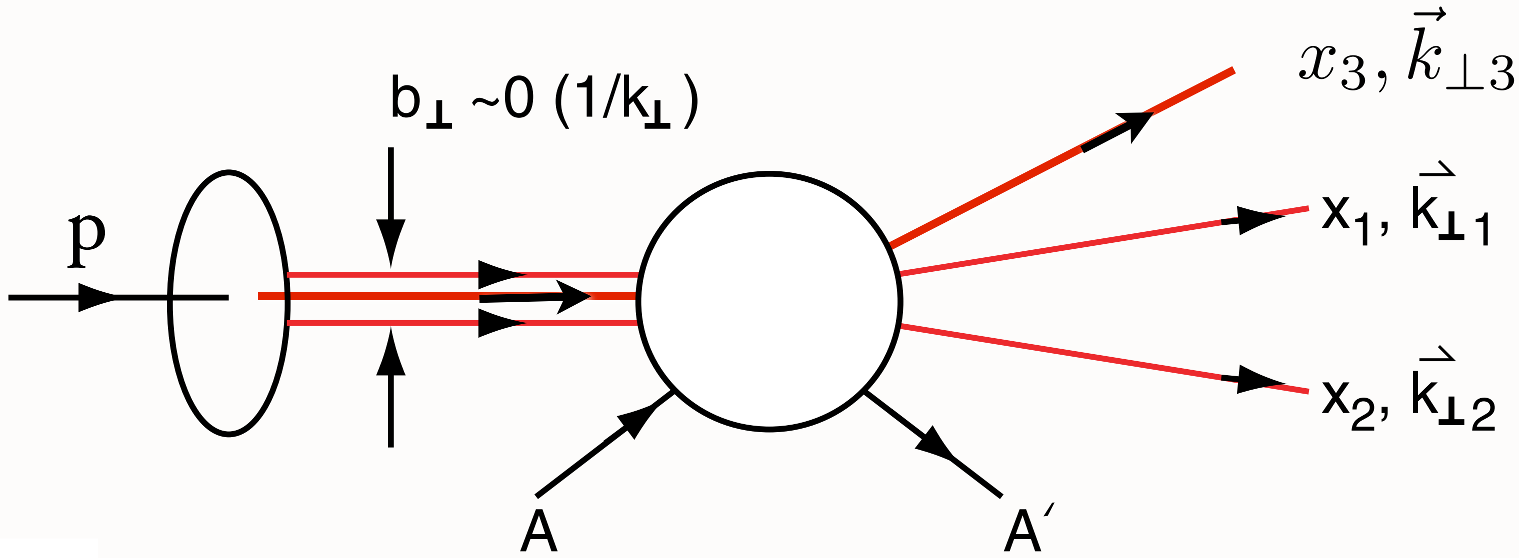

Gunion, Frankfurt, Mueller, Strikman, sjb
Frankfurt, Miller, Strikman

Two-gluon exchange measures the second derivative of the pion light-front wavefunction




$$M \propto \frac{\partial^2}{\partial^2 k_\perp} \psi_\pi(x, k_\perp)$$

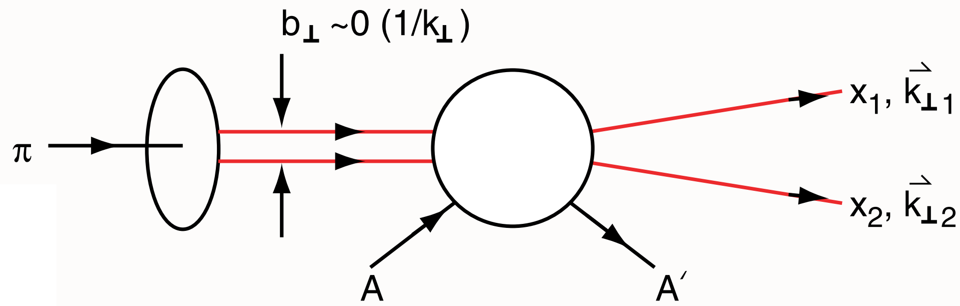
# Diffractive Dissociation of Proton into Three Quark Jets




Measure Light-Front Wavefunction of Proton

Minimal momentum transfer to nucleus
Nucleus left Intact!

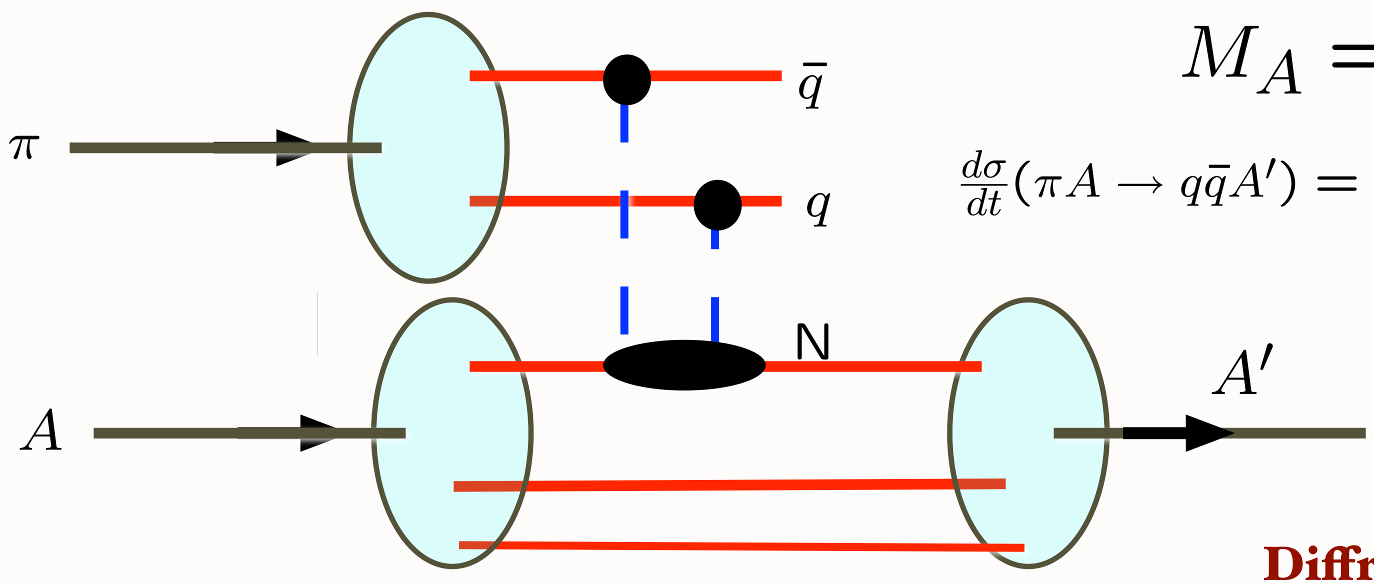
# Key Ingredients in E791 Experiment




Brodsky Mueller
Frankfurt Miller
Strikman

Small color-dipole moment pion not absorbed; interacts with each nucleon coherently

QCD COLOR Transparency



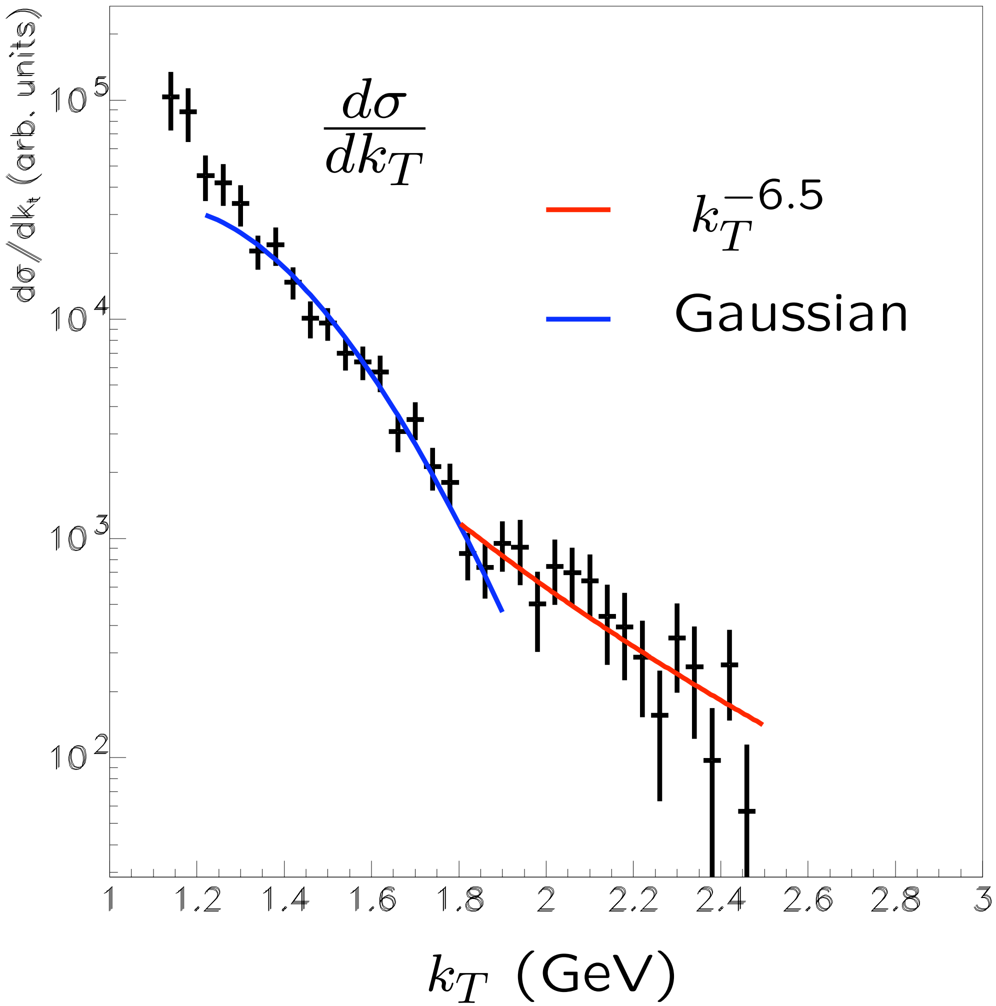

$$M_A = A\ M_N$$

$$\frac{d\sigma}{dt}(\pi A \to q\bar{q}A') = A^2\ \frac{d\sigma}{dt}(\pi N \to q\bar{q}N')\ F_A^2(t)$$

**Target left intact**

**Diffraction, Rapidity gap**

# E791 Diffractive Di-Jet transverse momentum distribution



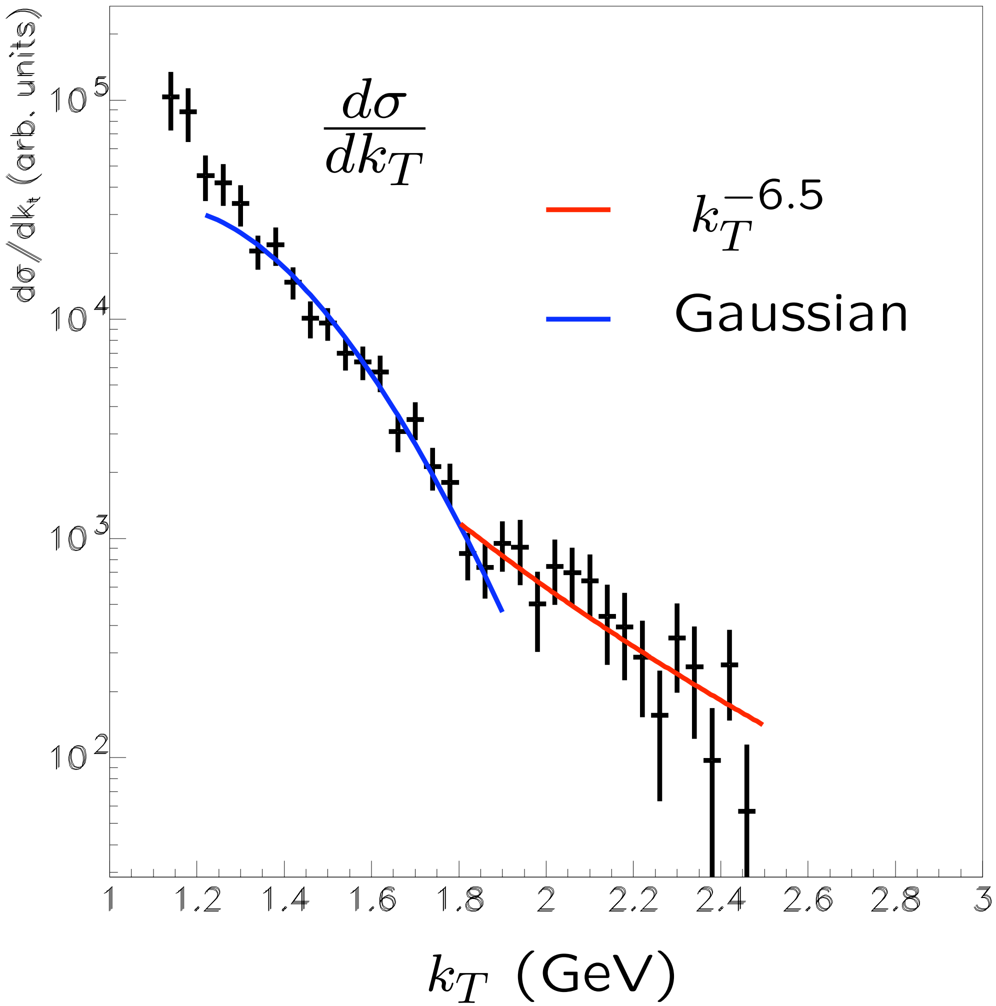

## Two Components

*High Transverse momentum dependence consistent with PQCD, ERBL Evolution*

$k_T^{-6.5}$

*Gaussian component similar to AdS/CFT HO LFWF*

# E791 Diffractive Di-Jet transverse momentum distribution




## Two Components

*High Transverse momentum dependence consistent with PQCD, ERBL Evolution* $k_T^{-6.5}$

*Gaussian component similar to AdS/CFT HO LFWF*

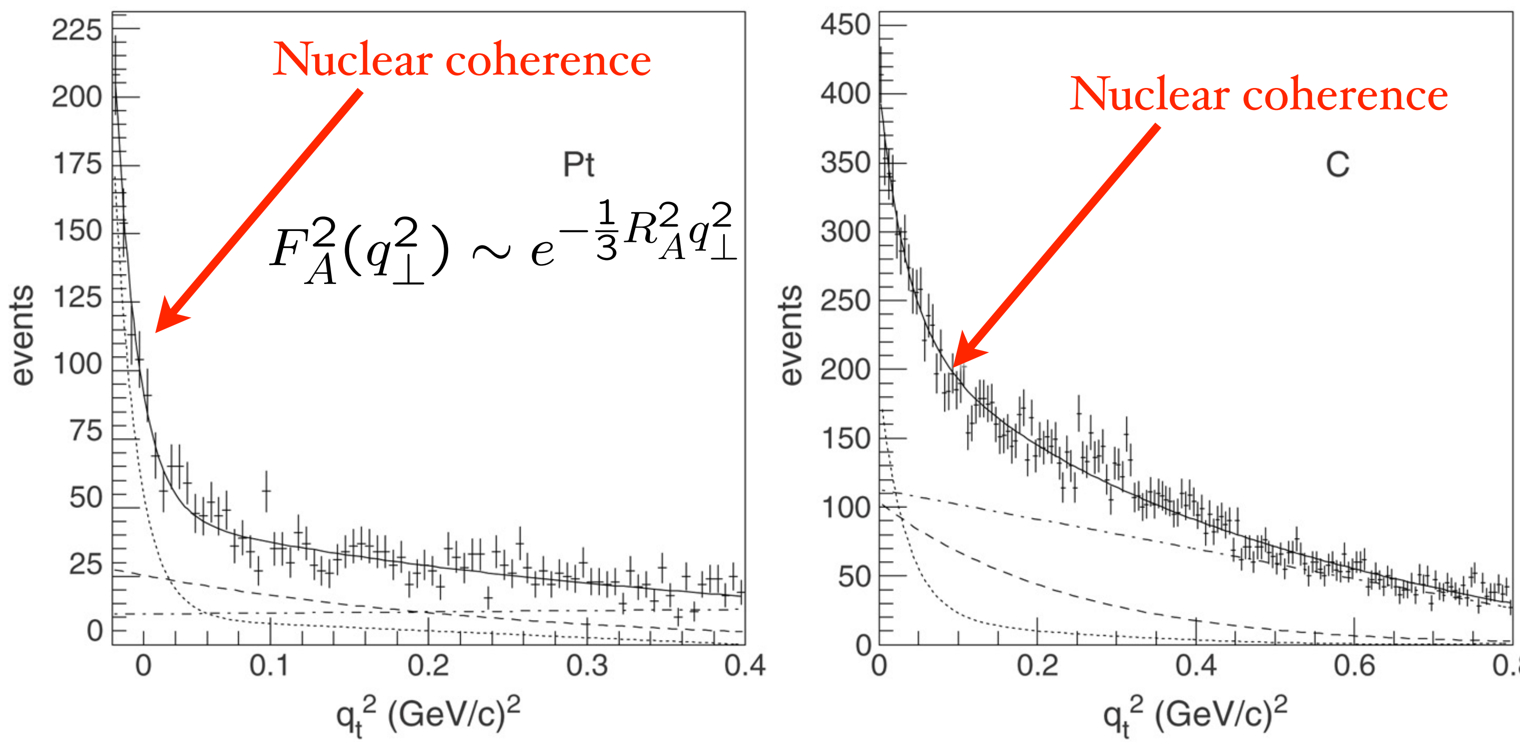
- Fully coherent interactions between pion and nucleons.

- Emerging Di-Jets do not interact with nucleus.

$$\mathcal{M}(\mathcal{A}) = \mathcal{A} \cdot \mathcal{M}(\mathcal{N})$$

$$\frac{d\sigma}{dq_t^2} \propto A^2 \quad q_t^2 \sim 0$$

$$\sigma \propto A^{4/3}$$



Mueller, sjb; Bertsch et al;
Frankfurt, Miller, Strikman

# *Measure pion LFWF in diffractive dijet production*
# *Confirmation of color transparency*

**A-Dependence results:** $\sigma \propto A^{\alpha}$

| $k_t$ range (GeV/c) | $\alpha$ | $\alpha$ (CT) |
|---|---|---|
| $1.25 < k_t < 1.5$ | $1.64 + 0.06 - 0.12$ | 1.25 |
| $1.5 < k_t < 2.0$ | $1.52 \pm 0.12$ | 1.45 |
| $2.0 < k_t < 2.5$ | $1.55 \pm 0.16$ | 1.60 |

Ashery E791

$\alpha$ (Incoh.) $= 0.70 \pm 0.1$

*Conventional Glauber Theory Ruled Out !*

**Factor of 7**

# Color Transparency

Bertsch, Gunion, Goldhaber, sjb

A. H. Mueller, sjb

- Fundamental test of gauge theory in hadron physics
- Small color dipole moments interact weakly in nuclei
- Complete coherence at high energies
- Clear Demonstration of CT from Diffractive Di-Jets

## $\pi^- N \to \mu^+\mu^- X$ at 80 GeV/c

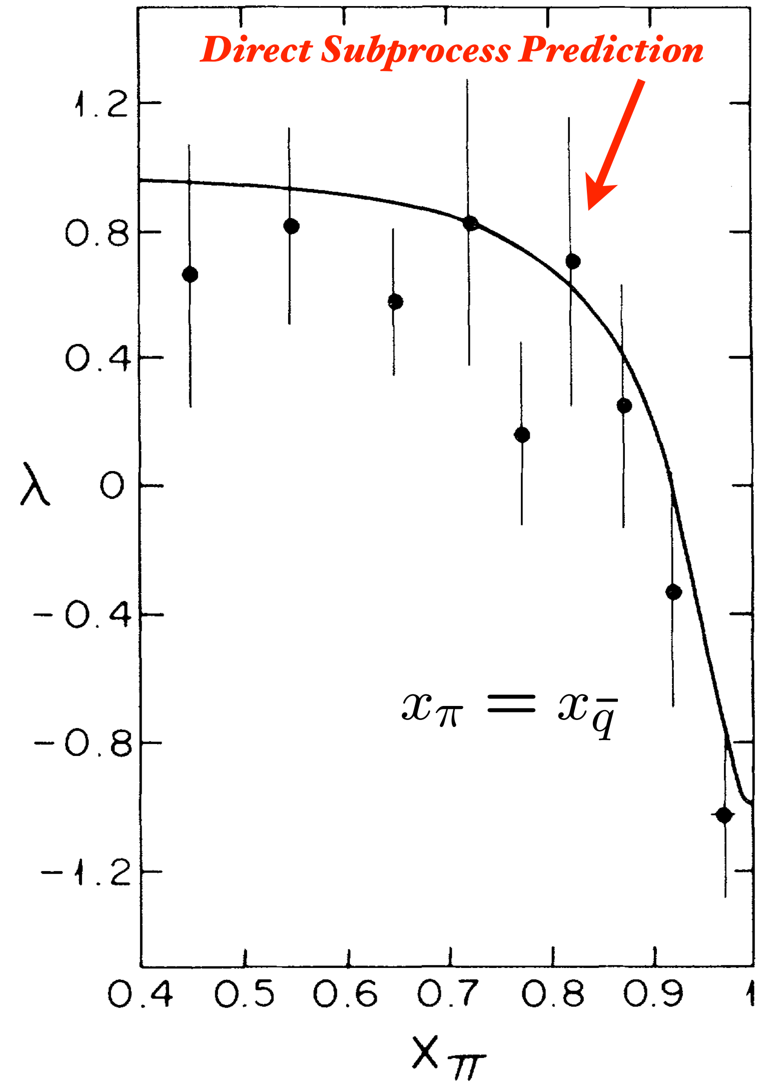
$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda\cos^2\theta + \rho\sin 2\theta\cos\phi + \omega\sin^2\theta\cos 2\phi.$$

$$\frac{d^2\sigma}{dx_\pi d\cos\theta} \propto x_\pi\left[(1-x_\pi)^2(1+\cos^2\theta) + \frac{4}{9}\frac{\langle k_T^2\rangle}{M^2}\sin^2\theta\right]$$

$$\langle k_T^2\rangle = 0.62 \pm 0.16 \ \mathrm{GeV}^2/c^2$$

$$Q^2 = M^2$$

*Dramatic change in angular distribution at large $x_F$*




Chicago-Princeton Collaboration

Phys.Rev.Lett.55:2649,1985

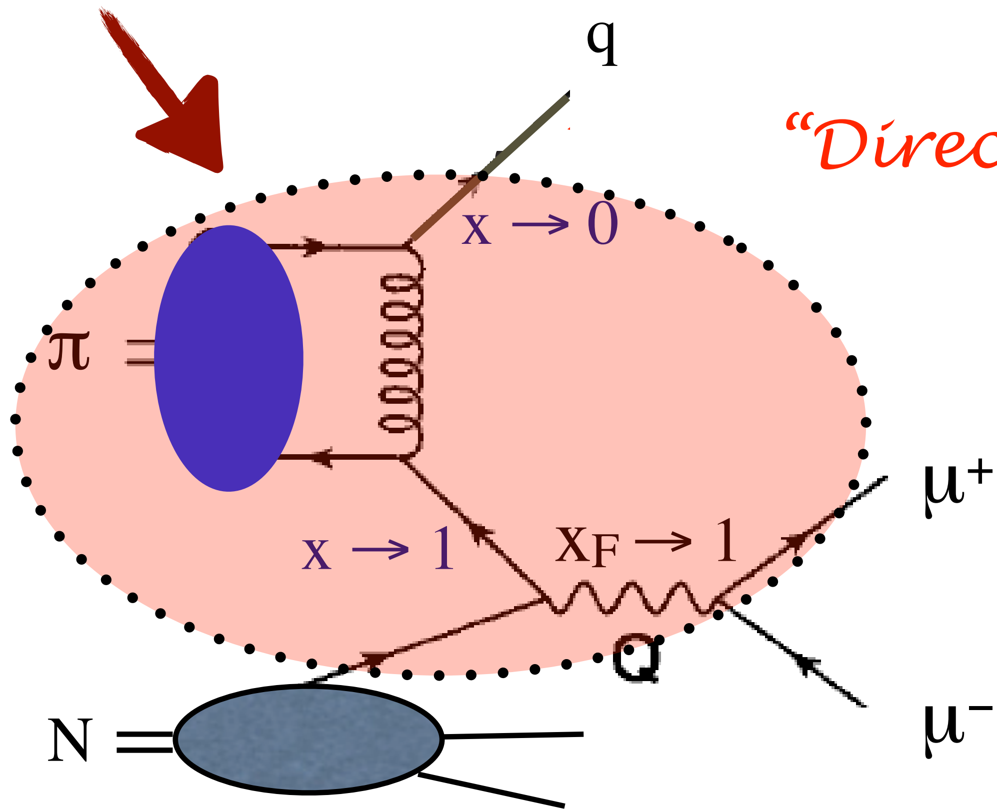
**Example of a higher-twist direct subprocess**

*Many Tests at AFTER*

# $\pi N \rightarrow \mu^+ \mu^- X$ at high $x_F$

In the limit where $(1-x_F)Q^2$ is fixed as $Q^2 \rightarrow \infty$

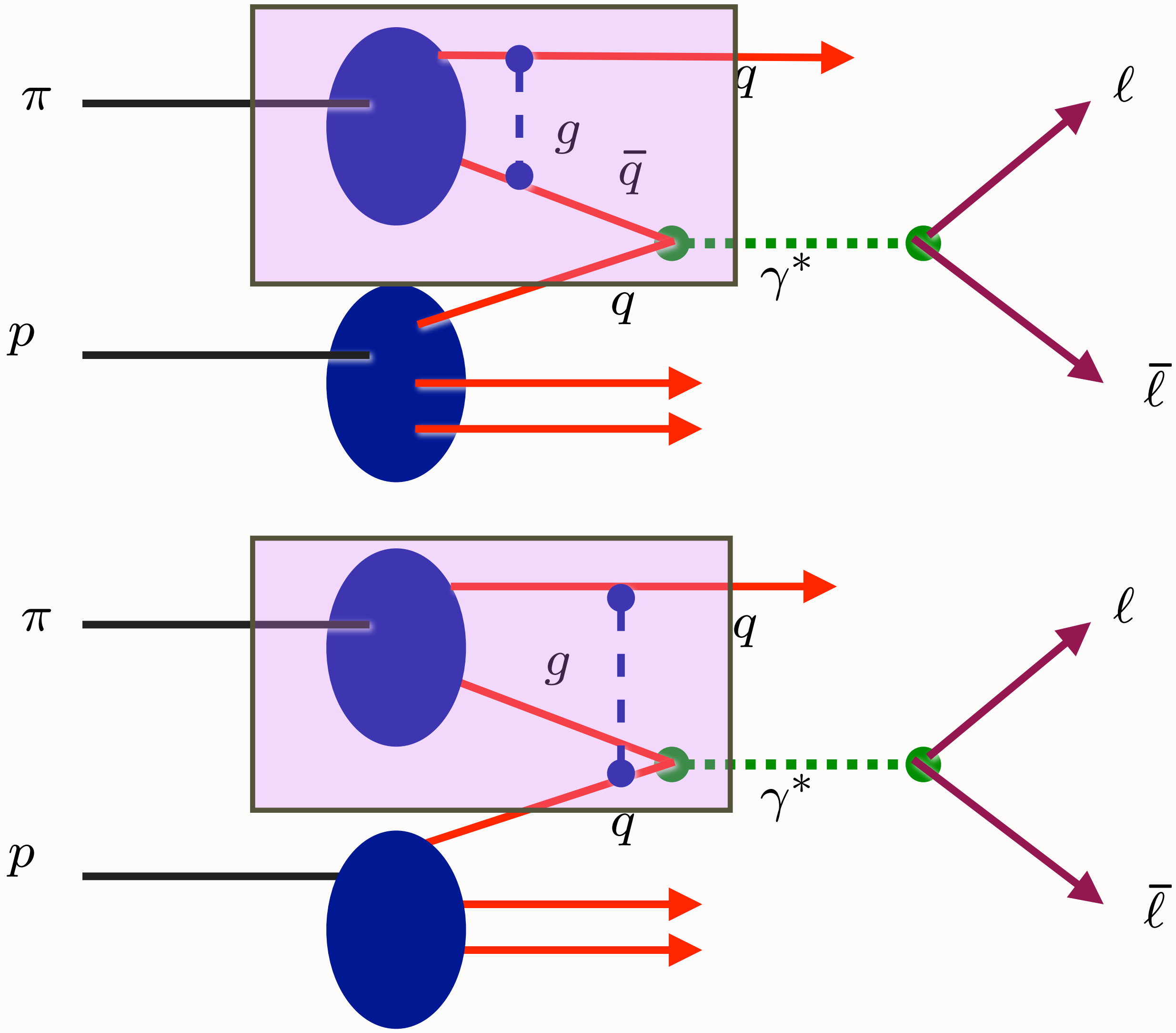
*Distribution amplitude from AdS/CFT*




***Similar higher twist terms in jet hadronization at large z***


**Berger, sjb**
**Khoze, Brandenburg, Muller, sjb**
**Hoyer Vanttinen**

Berger, Lepage, sjb




$$\pi q \to \gamma^* q$$

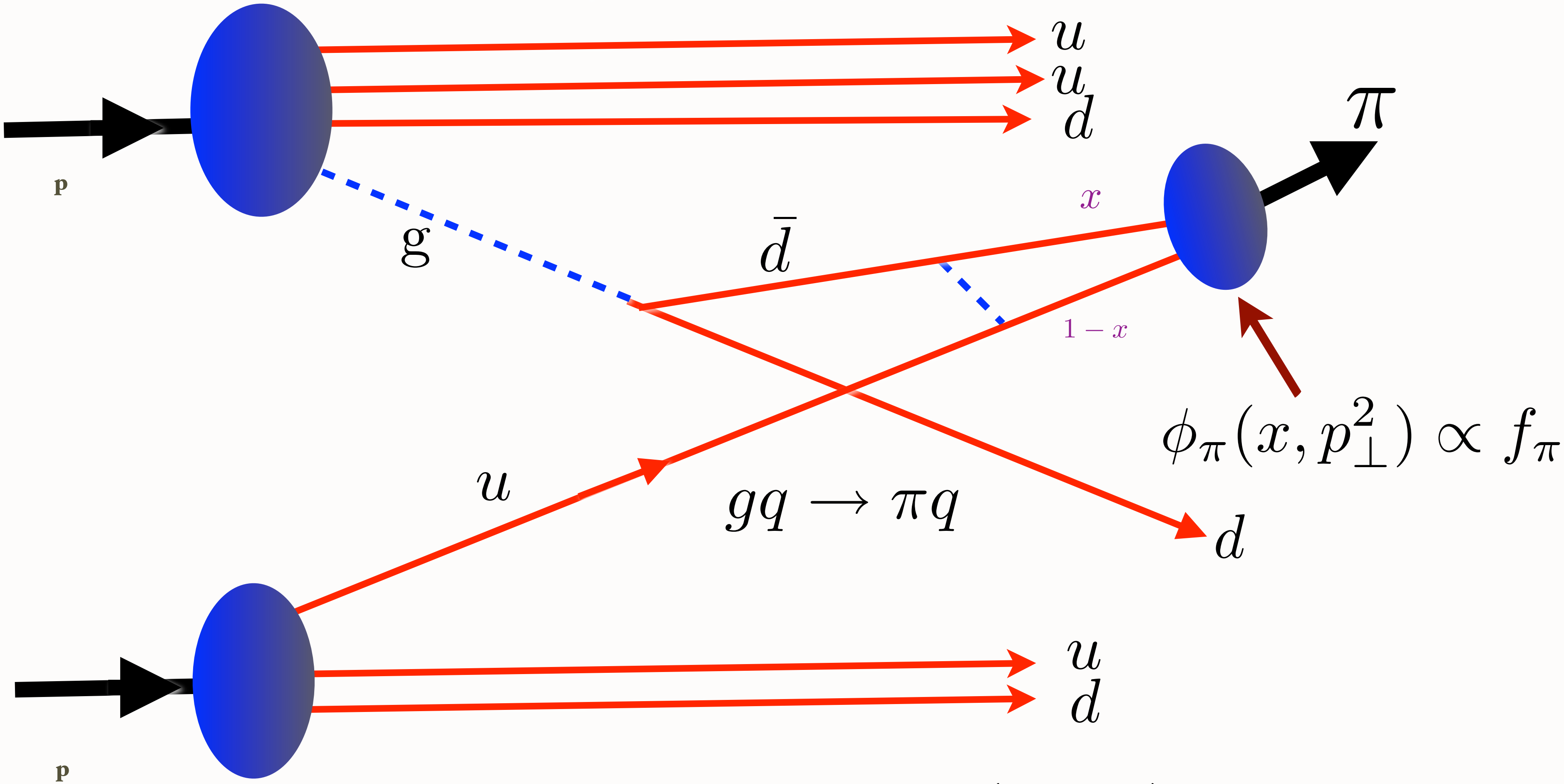
**Initial State Interaction**

***Pion appears directly in subprocess at large $x_F$***

*All of the pion's momentum is transferred to the lepton pair*

*Lepton Pair is produced longitudinally polarized*

# Direct Higher-Twist Contribution to Hadron Production




$$\frac{d\sigma}{d^3p/E} = \alpha_s^3 f_\pi^2 \frac{F(x_\perp, y)}{p_\perp^6}$$

No Fragmentation Function

Bjorken, Kogut, Soper; Blankenbecler, Gunion, sjb; Blankenbecler, Schmidt

## Crucial Test of Leading -Twist QCD: Scaling at fixed $x_T$

$$E \frac{d\sigma}{d^3p}(pp \to HX) = \frac{F(x_T, \theta_{cm})}{p_T^{n_{\rm eff}}}$$

$$x_T = \frac{2p_T}{\sqrt{s}}$$

**Parton model: $n_{eff} = 4$**

**As fundamental as Bjorken scaling in DIS**

**scaling law: $n_{eff} = 2\, n_{active} - 4$**

# Dimensional analysis

Scattering amplitude $1\ 2 \cdots \to \ldots n$ has dimension

$$\mathcal{M} \sim [\text{length}]^{n-4}$$

## Consequence

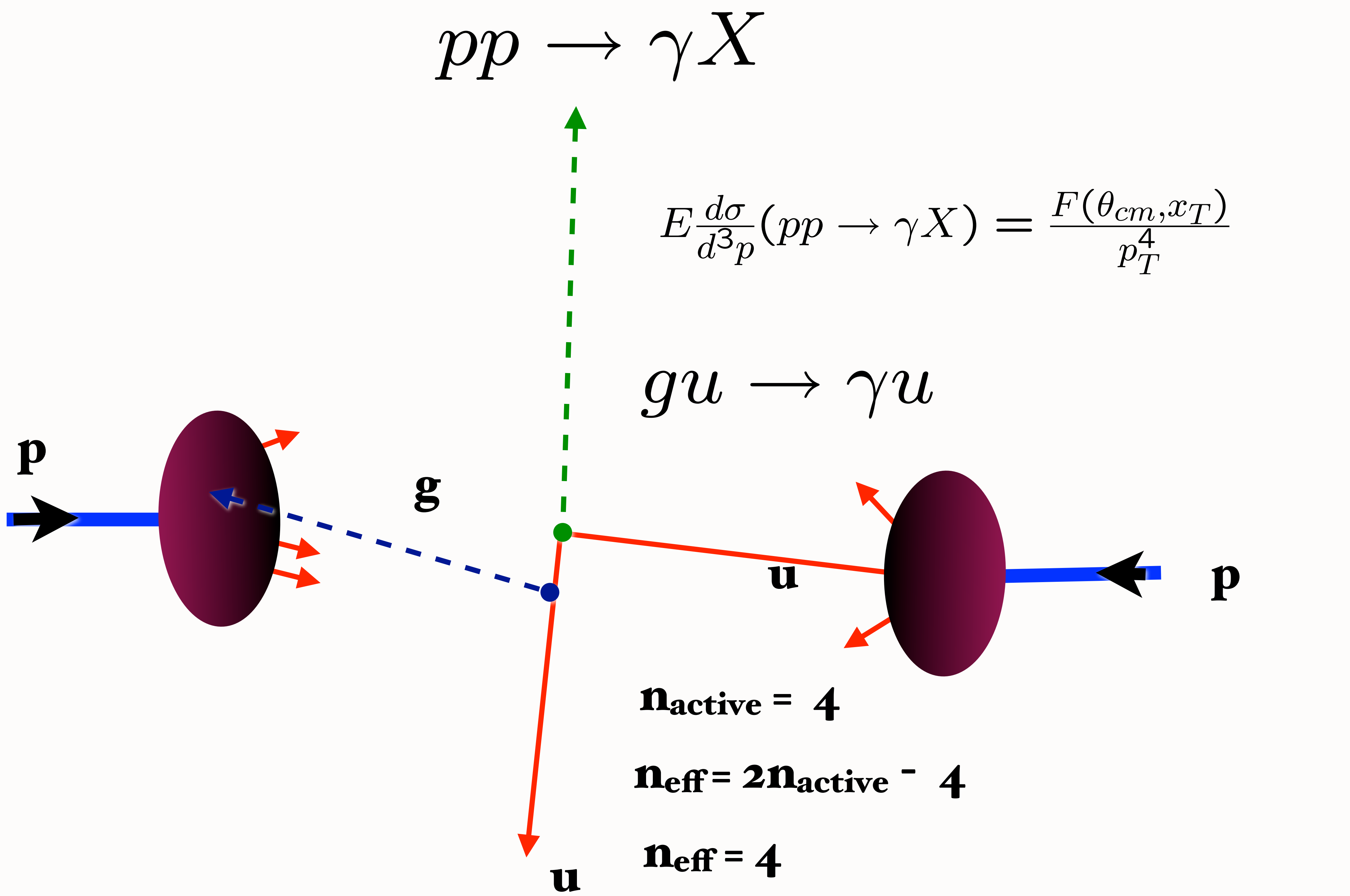
In a conformal theory (no intrinsic scale), scaling of inclusive particle production

$$E\,\frac{d\sigma}{d^3p}(A\ B\ \to C\ X) \sim \frac{|\mathcal{M}|^2}{s^2} = \frac{F(x_\perp, \vartheta^{\text{cm}})}{p_\perp^{2n_{\text{active}}-4}}$$

where $n_{\text{active}}$ is the number of fields participating to the hard process

$x_\perp = 2p_\perp/\sqrt{s}$ and $\vartheta^{\text{cm}}$: ratios of invariants

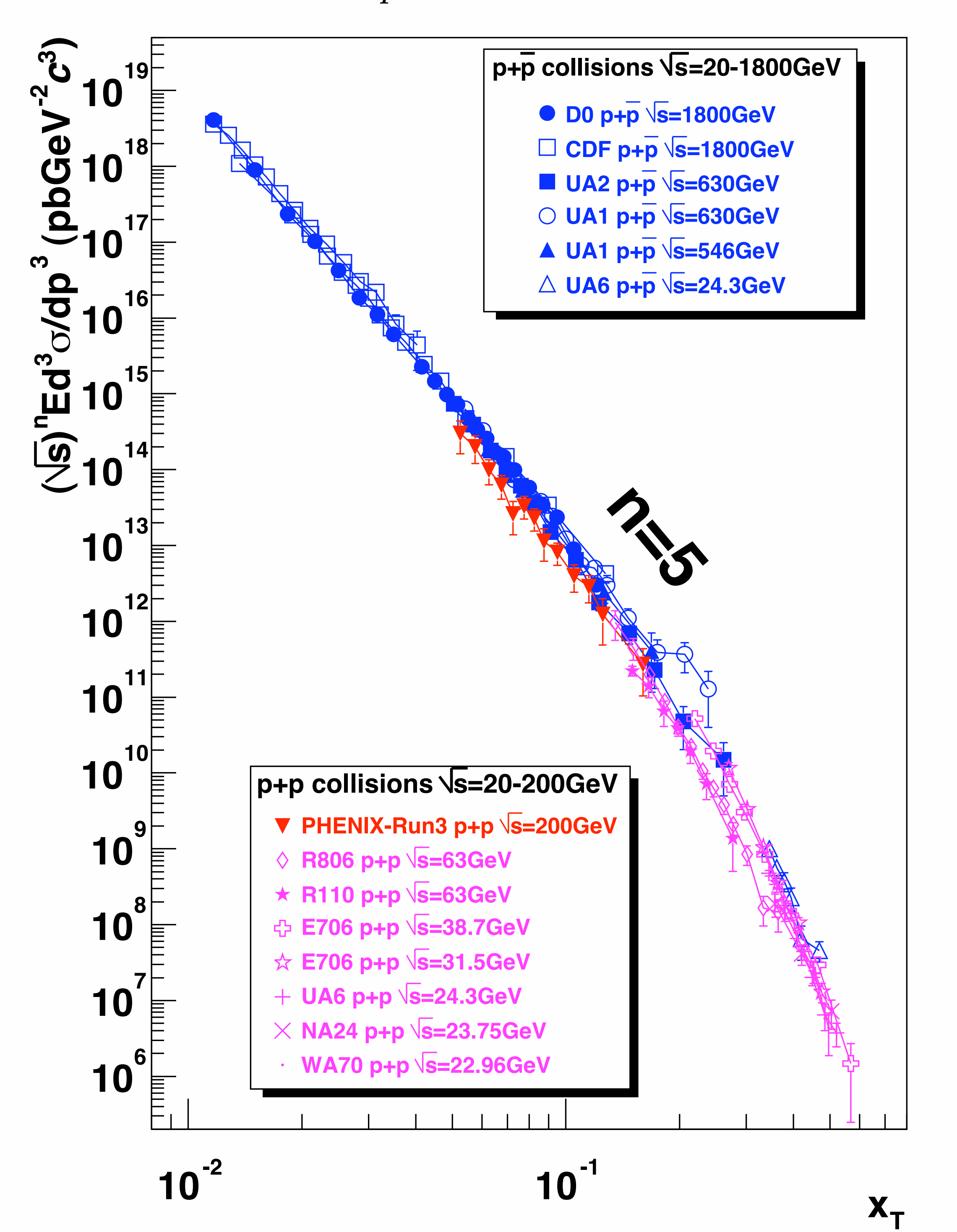
$$n_{active} = 4 \to n_{eff} = 4$$



$pp \to \gamma X$
$E\frac{d\sigma}{d^3p}(pp \to \gamma X) = \frac{F(\theta_{cm}, x_T)}{p_T^4}$
$gu \to \gamma u$
p
g
u
p
u
$n_{active} = 4$
$n_{eff} = 2n_{active} - 4$
$n_{eff} = 4$

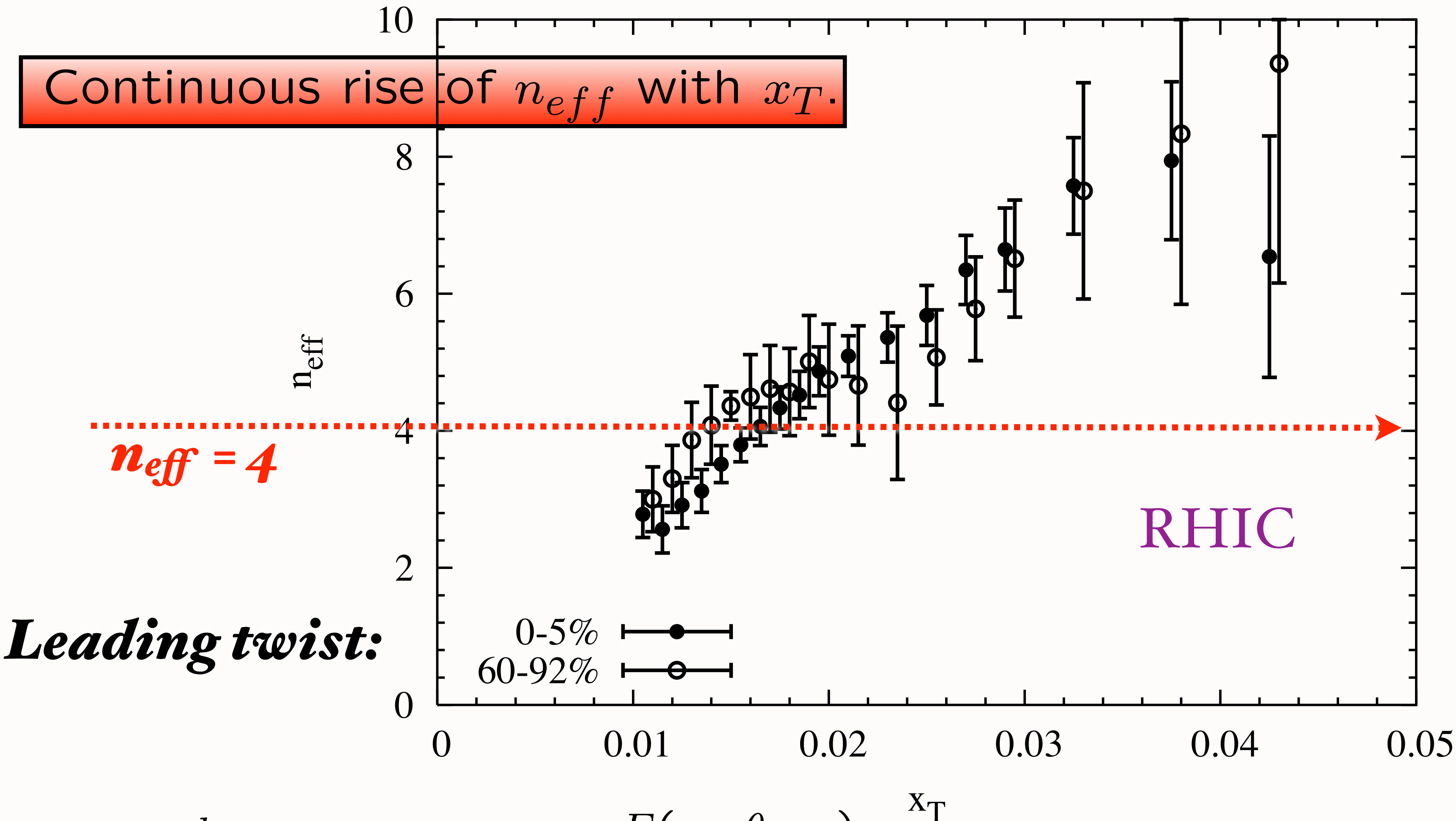
$\sqrt{s}^n E \frac{d\sigma}{d^3p}(pp \to \gamma X)$ at fixed $x_T$

Tannenbaum




**$x_T$-scaling of direct photon production: consistent with PQCD**

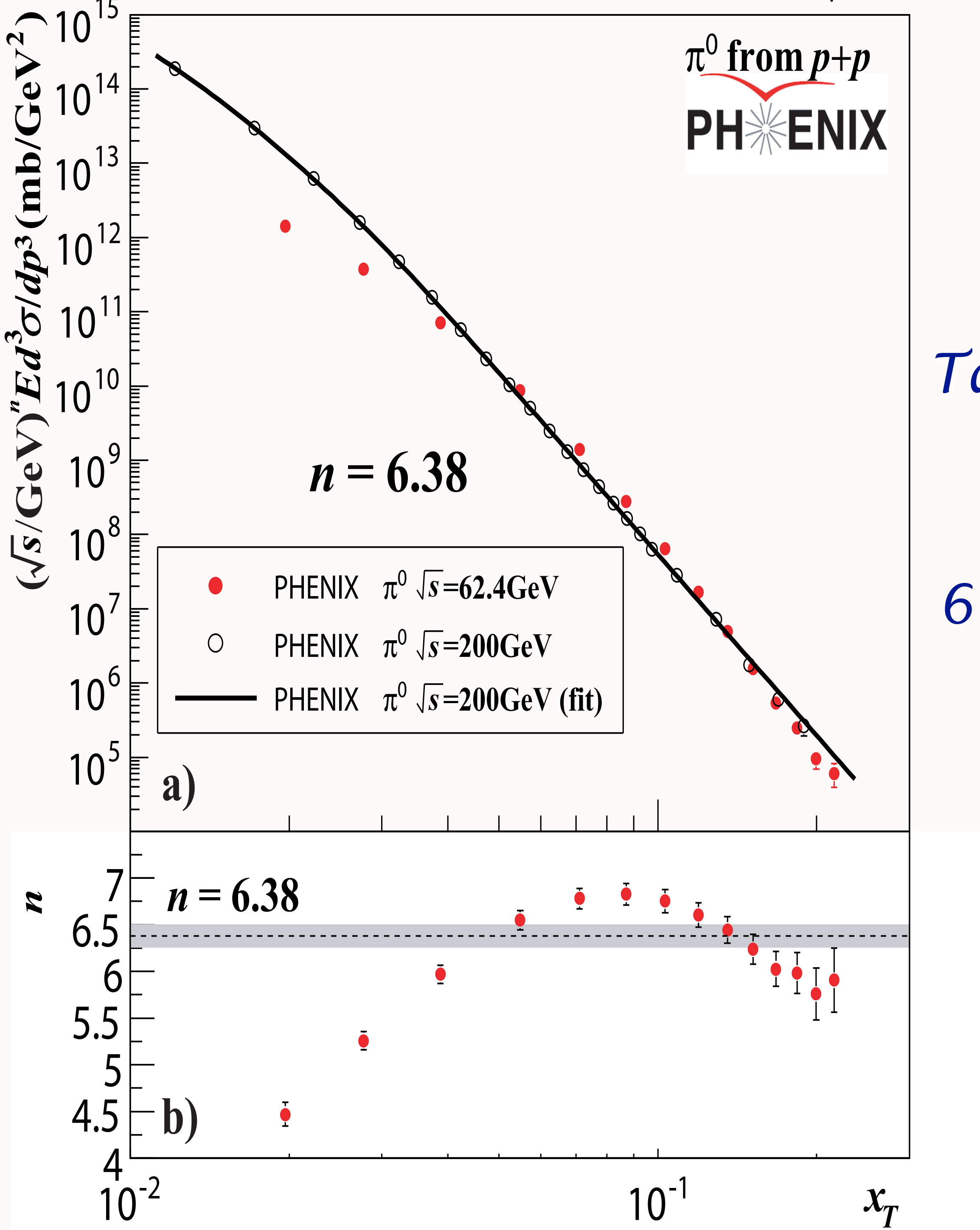
*Protons produced in AuAu collisions at RHIC do not exhibit clear scaling properties in the available $p_T$ range. Shown are data for central $(0-5\%)$ and for peripheral $(60-90\%)$ collisions.*




***Leading twist:***

$$E\frac{d\sigma}{d^3p}(pN \to pX) = \frac{F(x_T,\theta_{CM})}{p_T^{n_{eff}}}$$

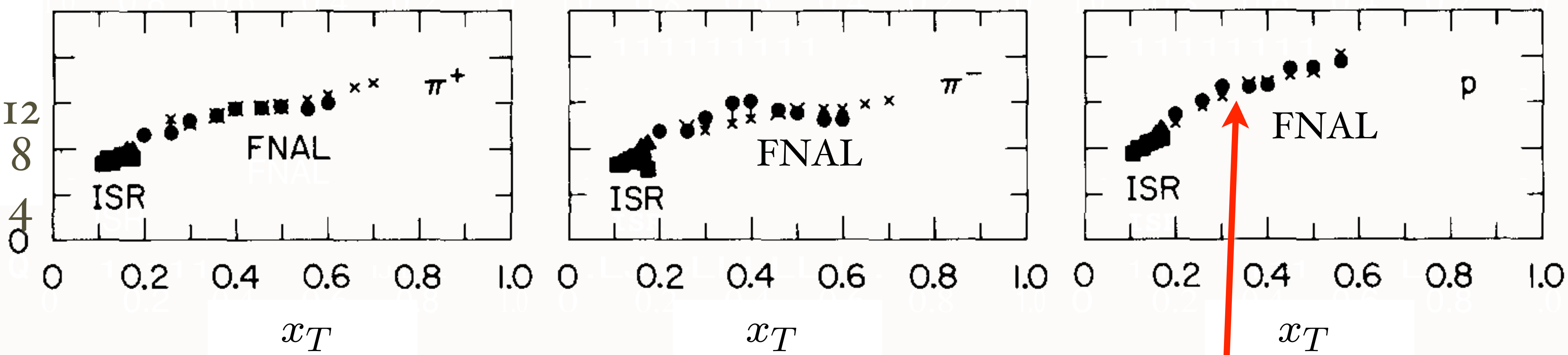
$$\sqrt{s}^{n} E \frac{d\sigma}{d^3p}(pp \rightarrow \pi^0 X) \text{ at fixed } x_T = \frac{2p_T}{\sqrt{s}}$$

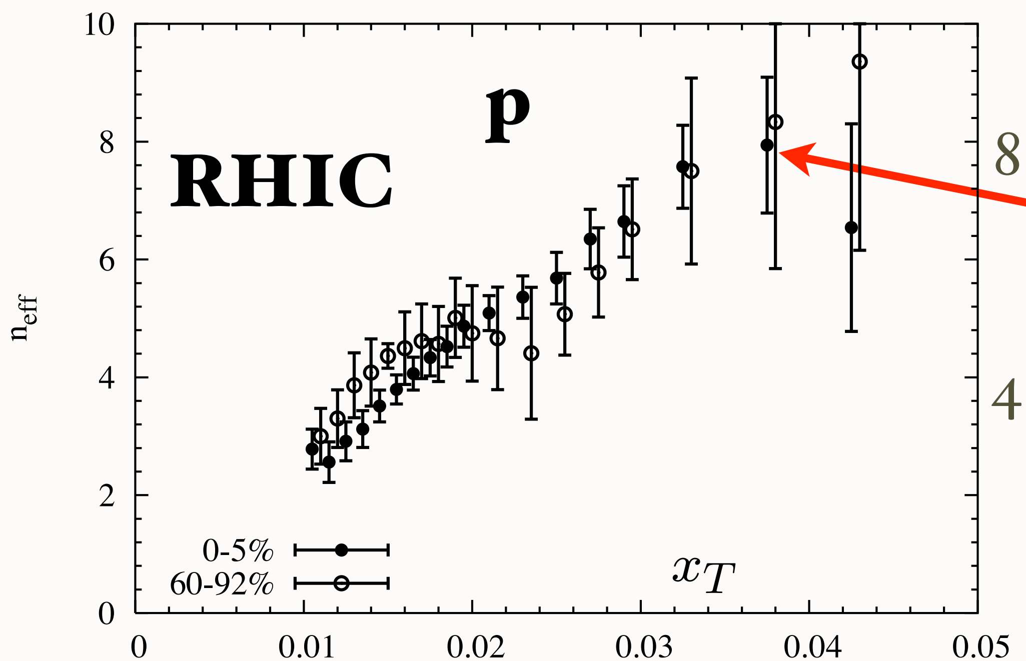



M. J. Tannenbaum

PHENIX 62.4 and 200 GeV data

$$E\frac{d\sigma}{d^3p}(pp \to HX) = \frac{F(x_T,\theta_{CM})}{p_T^{n_{eff}}}$$



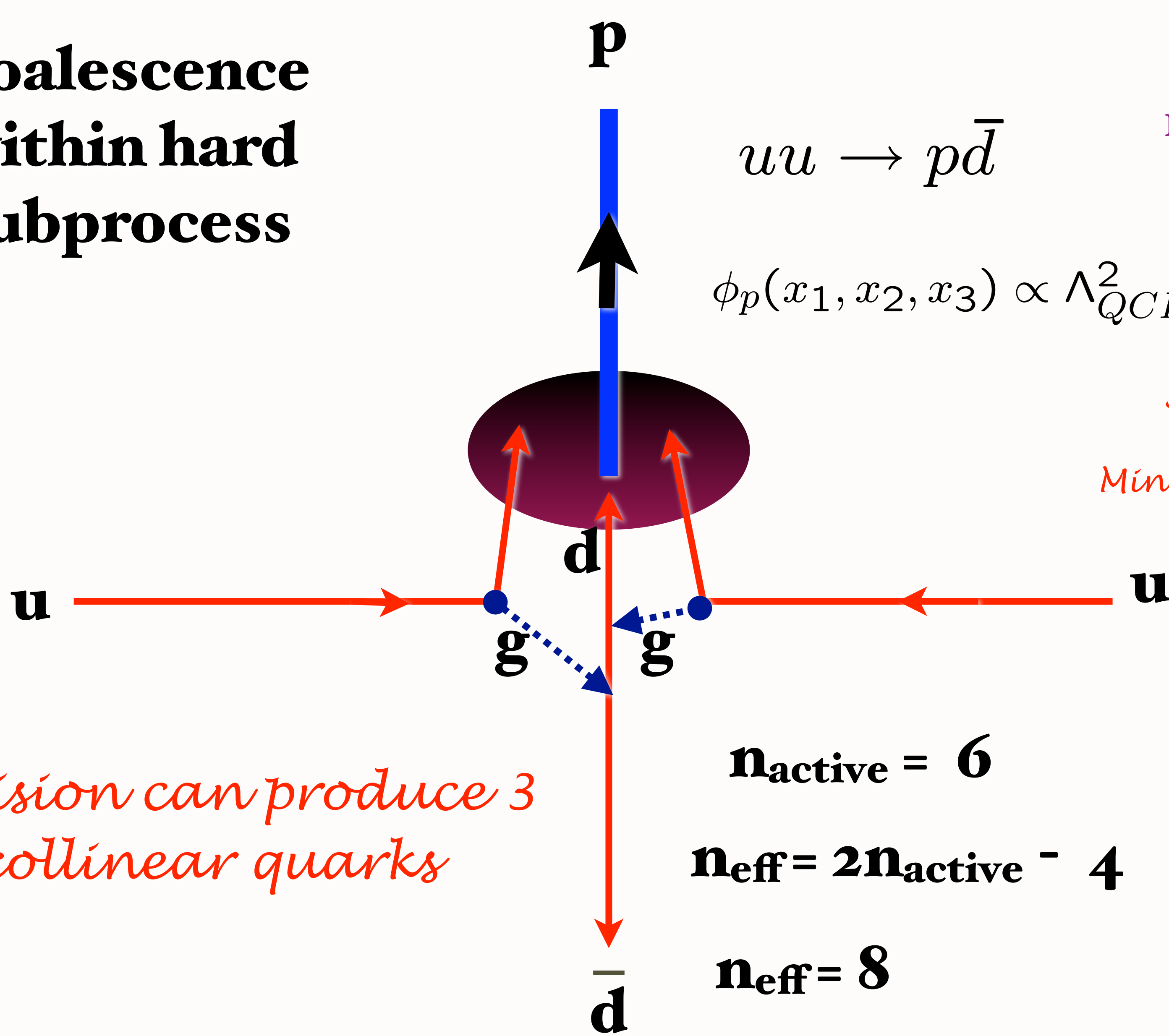

$$E\frac{d\sigma}{d^3p}(pp \to pX) = \frac{F(x_T,\theta_{CM})}{p_T^{12}}$$

$$E\frac{d\sigma}{d^3p}(pp \to pX) = \frac{F(x_T,\theta_{CM})}{p_T^{8}}$$

Trend consistent with RHIC at small $x_T$

# *Baryon can be made directly within hard subprocess*

**Coalescence within hard subprocess**




$uu \to p\bar{d}$

$\phi_p(x_1, x_2, x_3) \propto \Lambda^2_{QCD}$

**Bjorken**
**Blankenbecler, Gunion, sjb**
**Berger, sjb**
**Hoyer, et al: Semi-Exclusive**

**Sickles; sjb**

*Small color-singlet*
*Color Transparent*
*Minimal same-side energy*

*Collision can produce 3 collinear quarks*

$n_{active} = 6$

$n_{eff} = 2n_{active} - 4$

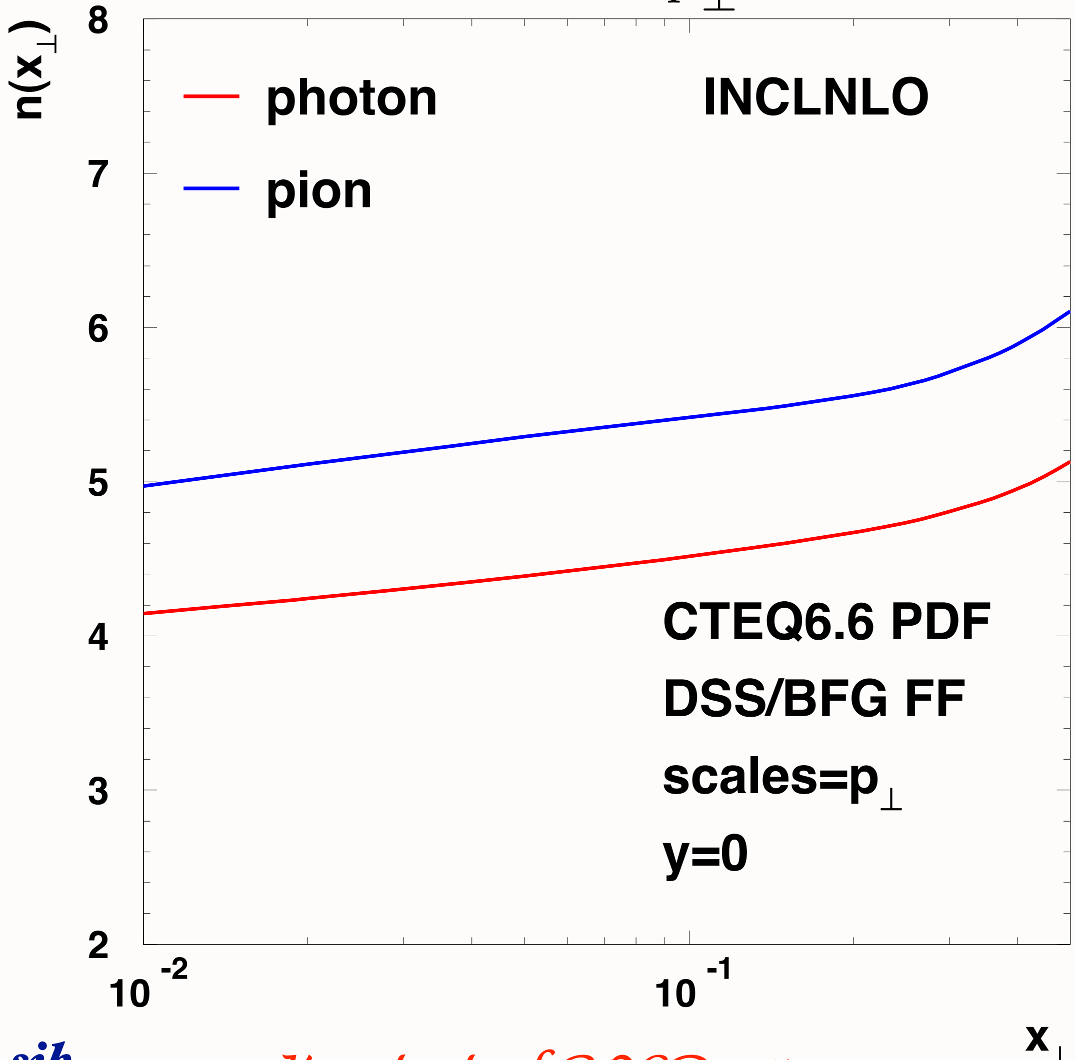
$n_{eff} = 8$

*Explains Baryon anomaly*

$qq \to B\bar{q}$

# QCD prediction: Modification of power fall-off due to DGLAP evolution and the Running Coupling

$$\frac{d\sigma}{d^3p/E} = \frac{F(x_\perp, y)}{p_\perp^{n(x_\perp)}}$$




$$pp \to \pi X$$

$$pp \to \gamma X$$

$$5 < p_\perp < 20\ GeV$$

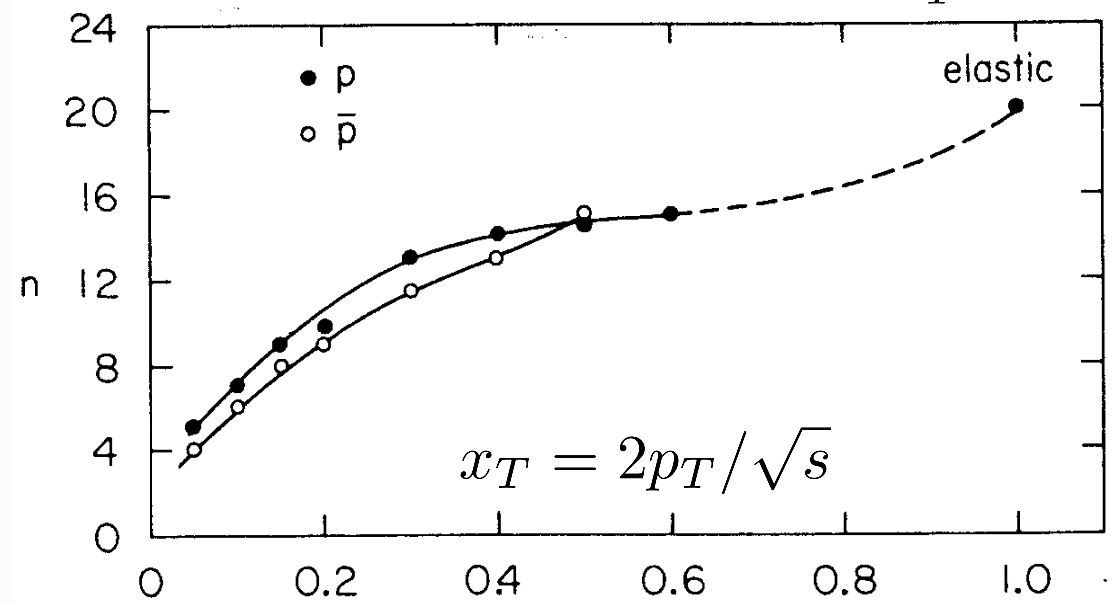
$$70\ GeV < \sqrt{s} < 4\ TeV$$

***Arleo, Hwang, Sickles, sjb***

***Pirner, Raufeisen, sjb***

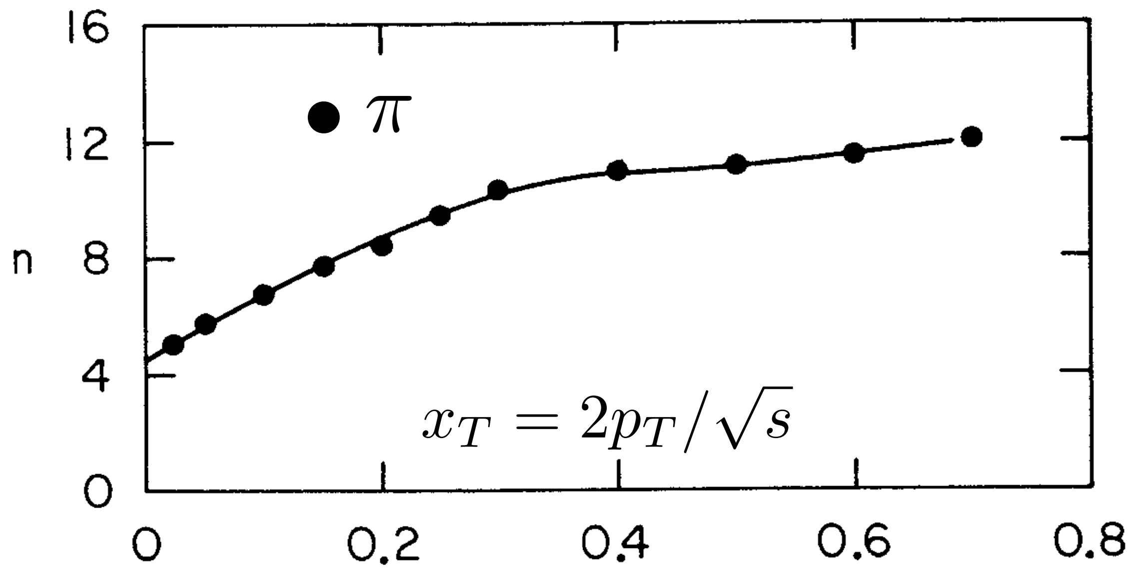
Key test of PQCD: power-law fall-off at fixed $x_T$

$$E\frac{d\sigma}{d^3p}(pp \rightarrow HX) = \frac{F(x_T, \theta_{cm} = \pi/2)}{p_T^n}$$

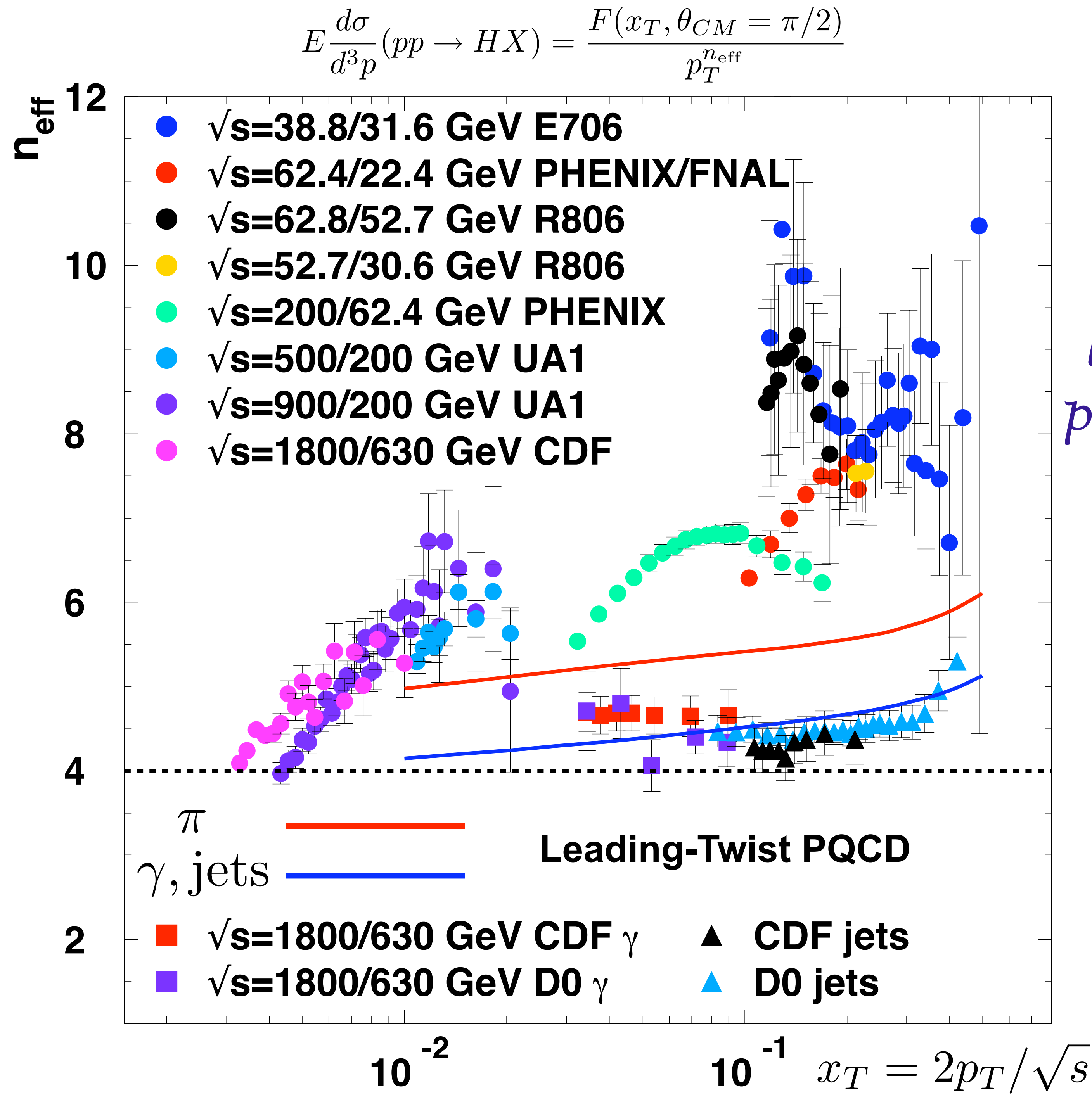



*Clear evidence for higher-twist contributions*

**J. W. Cronin, SSI 1974**




**Chicago-Princeton FNAL**

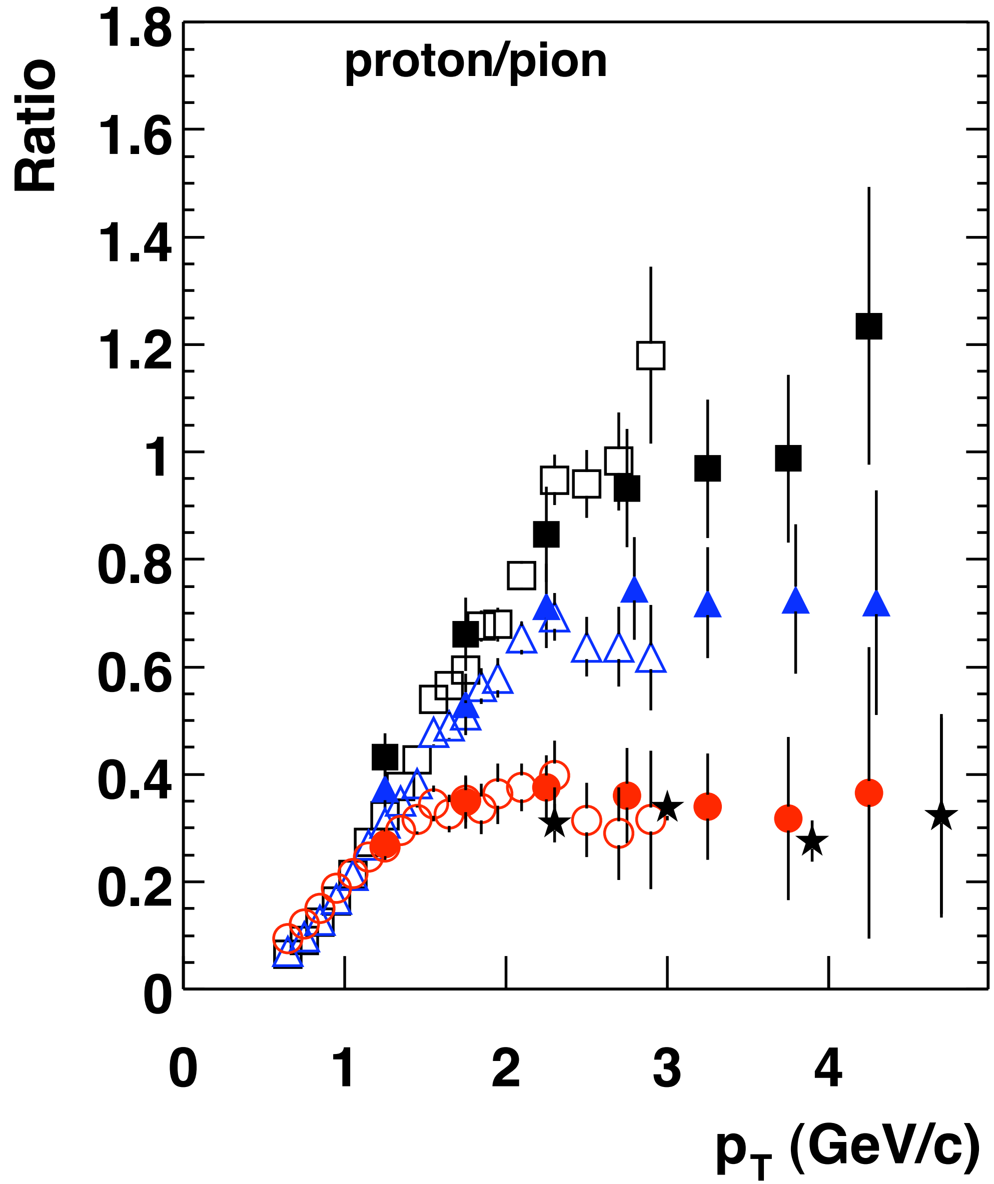



*Leading-twist prediction fails at ISR, FNAL, RHIC, CDF!*

***Arleo, Hwang, Sickles, sjb***

S. S. Adler *et al*. PHENIX Collaboration *Phys. Rev. Lett.* **91**, 172301 (2003).

*Particle ratio changes with centrality!*




***Protons less absorbed in nuclear collisions than pions because of dominant color transparent higher twist process***

**← Central**

**← Peripheral**

*Tannenbaum:*
*Baryon Anomaly:*

# Scale dependence

Pion scaling exponent extracted vs. $p_\perp$ at fixed $x_\perp$

2-component toy-model

$$\sigma^{\mathrm{model}}(pp \to \pi\ \mathrm{X}) \propto \frac{A(x_\perp)}{p_\perp^4} + \frac{B(x_\perp)}{p_\perp^6}$$

Define effective exponent

$$\begin{aligned} n_{\mathrm{eff}}(x_\perp, p_\perp, B/A) &\equiv -\frac{\partial \ln \sigma^{\mathrm{model}}}{\partial \ln p_\perp} + n^{\mathrm{NLO}}(x_\perp, p_\perp) - 4 \\ &= \frac{2B/A}{p_\perp^2 + B/A} + n^{\mathrm{NLO}}(x_\perp, p_\perp) \end{aligned}$$

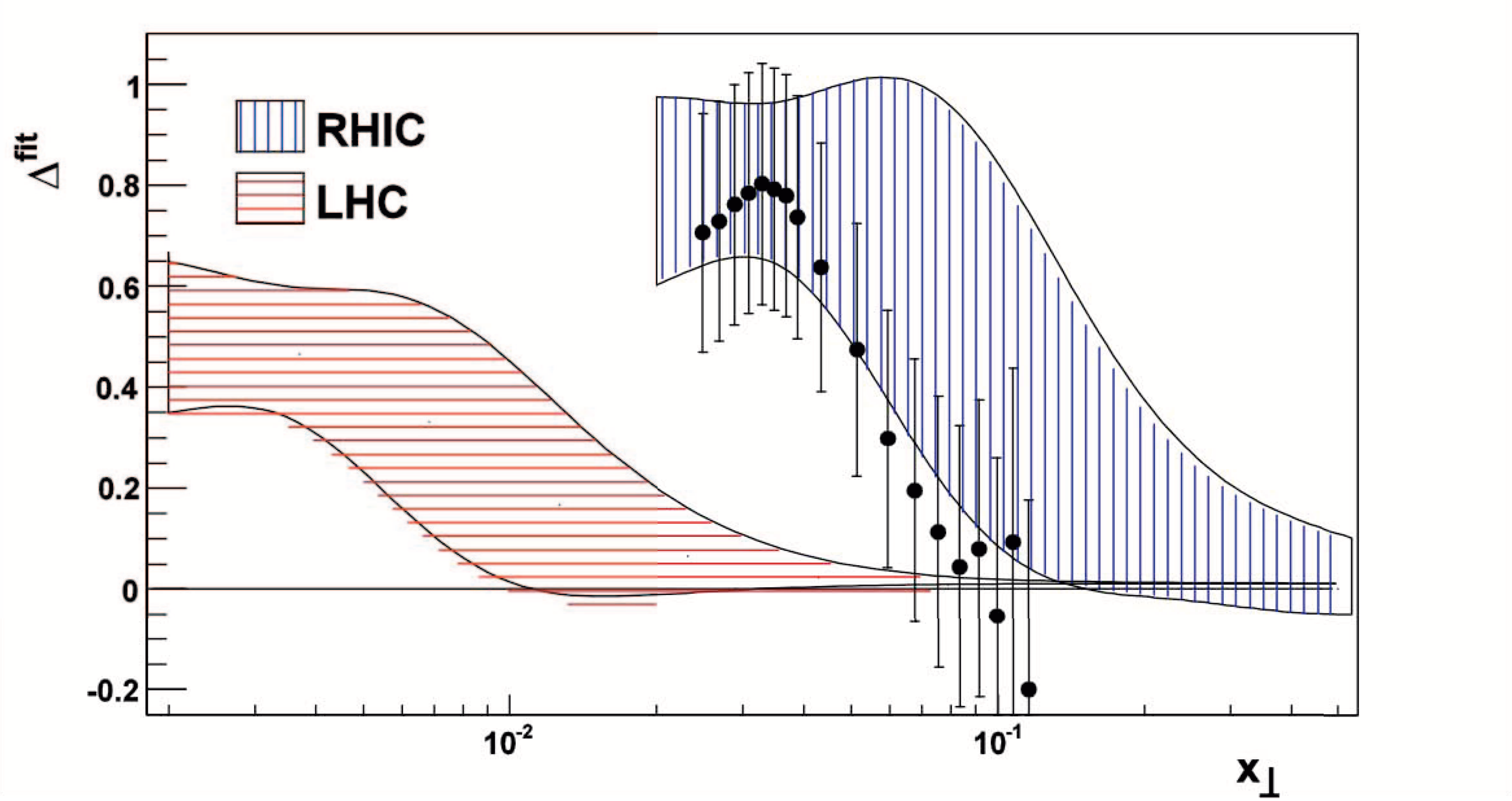
***Arleo, Hwang, Sickles, sjb***

# RHIC/LHC predictions

## PHENIX results

Scaling exponents from $\sqrt{s} = 500$ GeV preliminary data

[ A. Bezilevsky, APS Meeting ]




- Magnitude of $\Delta$ and its $x_{\perp}$-dependence consistent with predictions

*Arleo,Hwang, Sickles, sjb*

# Direct Subprocesses

- Explains Drell Yan polarization at high $x_F$
- Hadrons produced directly without jet hadronization
- Explains power-laws at fixed $x_T$
- Energy efficient; minimal $x_1$,$x_2$; large rate
- Color Transparent; Explains Baryon-Anomaly in Heavy-Ion collisions; change of power with centrality; depletion of same-side yield

# Higher Twist at the LHC

- **Fixed $x_T$: powerful analysis of PQCD**
- **Insensitive to modeling**
- **Higher twist terms energy efficient since no wasted fragmentation energy**
- **Evaluate at minimal $x_1$ and $x_2$ where structure functions are maximal**
- **Higher Twist competitive despite faster fall-off in $p_T$**
- **Direct processes can confuse new physics searches**
- **Related to Quarkonium Processes -- Jian-wei Qiu**
- **Bound-state production: Light-Front Wavefunctions, Distribution amplitudes, ERBL evolution.**

$$|p, S_z> = \sum_{n=3} \Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i) |n; \vec{k}_{\perp_i}, \lambda_i>$$

*sum over states with n=3, 4, ...constituents*

The Light Front Fock State Wavefunctions

$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

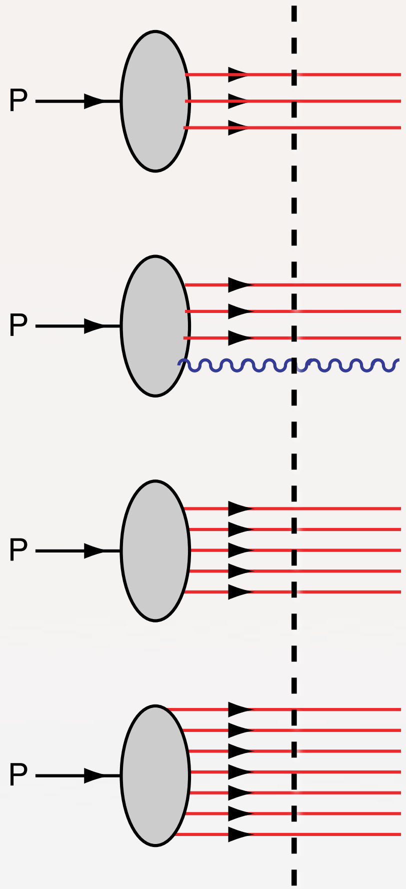
are boost invariant; they are independent of the hadron's energy and momentum $P^\mu$.

The light-cone momentum fraction

$$x_i = \frac{k_i^+}{p^+} = \frac{k_i^0 + k_i^z}{P^0 + P^z}$$

are boost invariant.

$$\sum_i^n k_i^+ = P^+, \ \sum_i^n x_i = 1, \ \sum_i^n \vec{k}_i^\perp = \vec{0}^\perp.$$




*Fixed LF time*

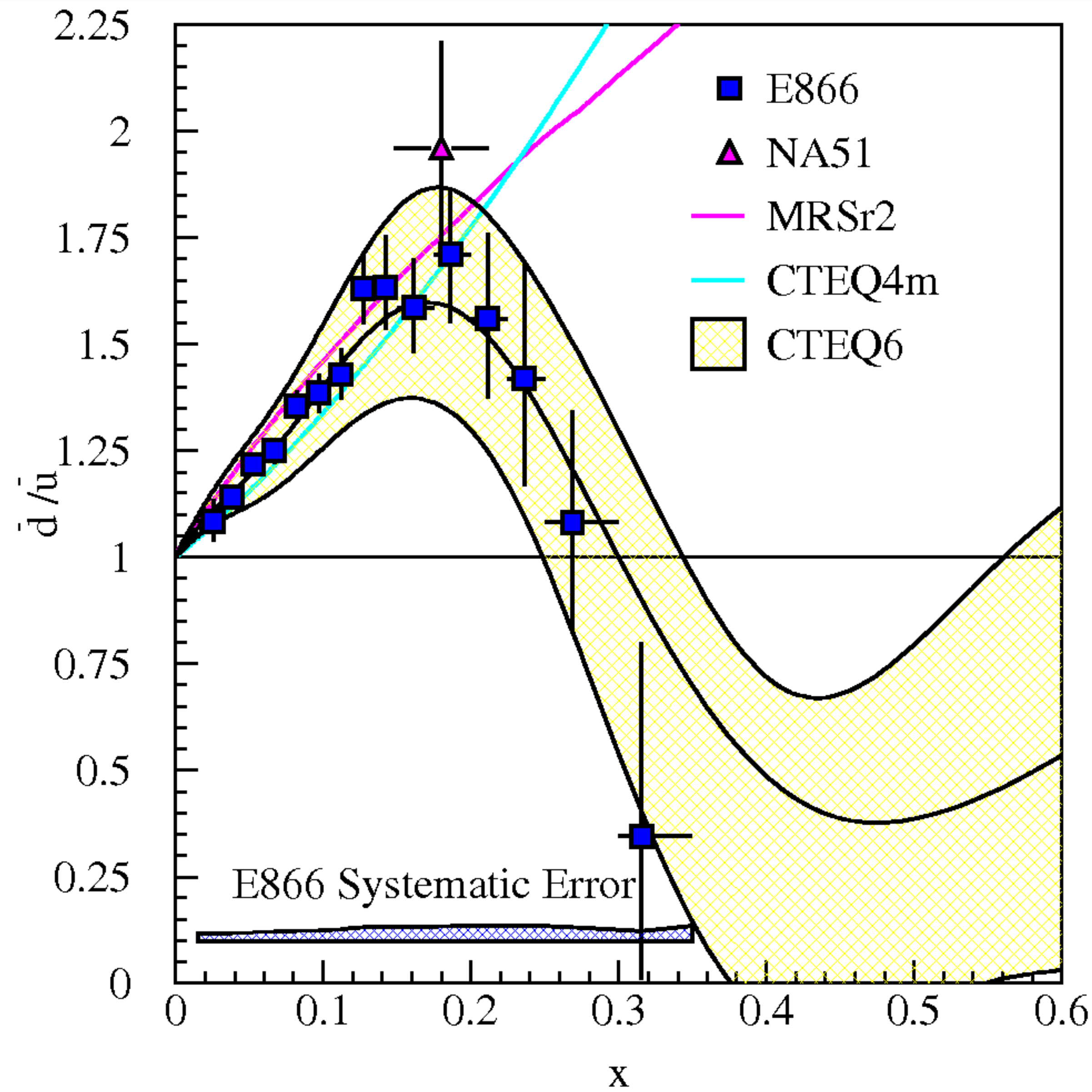
*Intrinsic heavy quarks*
***c(x), b(x) at high x !***

$\bar{s}(x) \neq s(x)$
$\bar{u}(x) \neq \bar{d}(x)$

**Mueller: gluon Fock states BFKL**

*Hidden Color*

$\bar{d}(x)/\bar{u}(x)$ for $0.015 \leq x \leq 0.35$



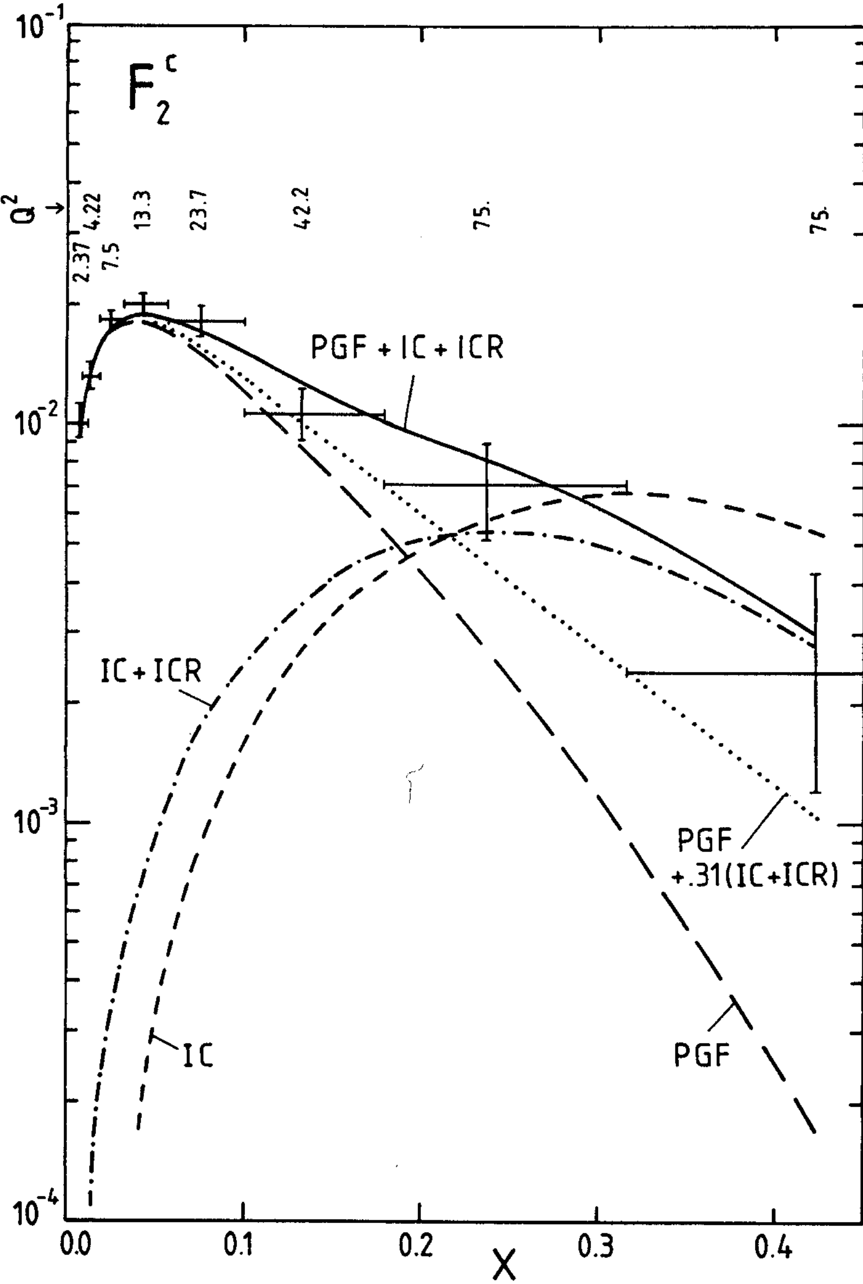

- E866/NuSea (Drell-Yan)

$$\bar{d}(x) \neq \bar{u}(x)$$

$$s(x) \neq \bar{s}(x)$$

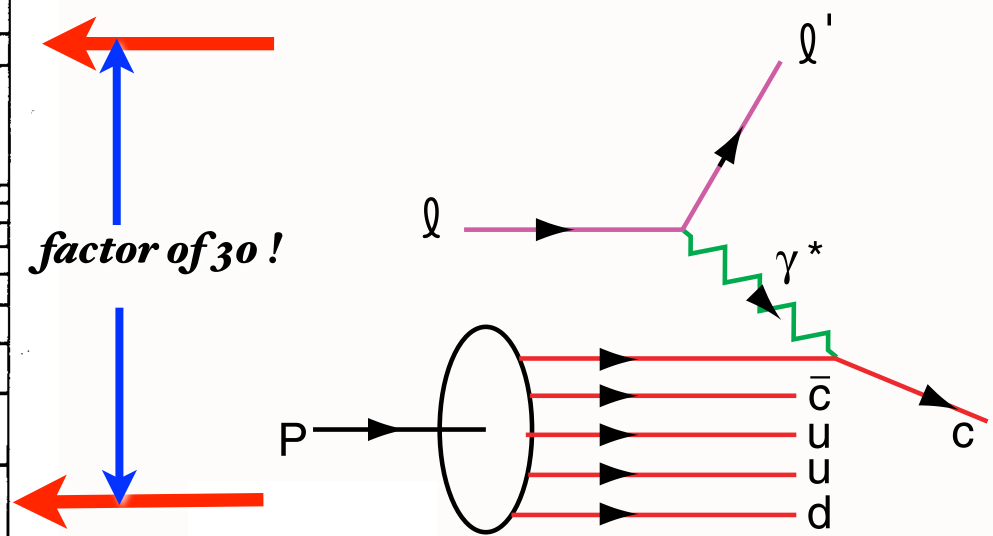
*Intrinsic glue, sea, heavy quarks*

# Measurement of Charm Structure Function



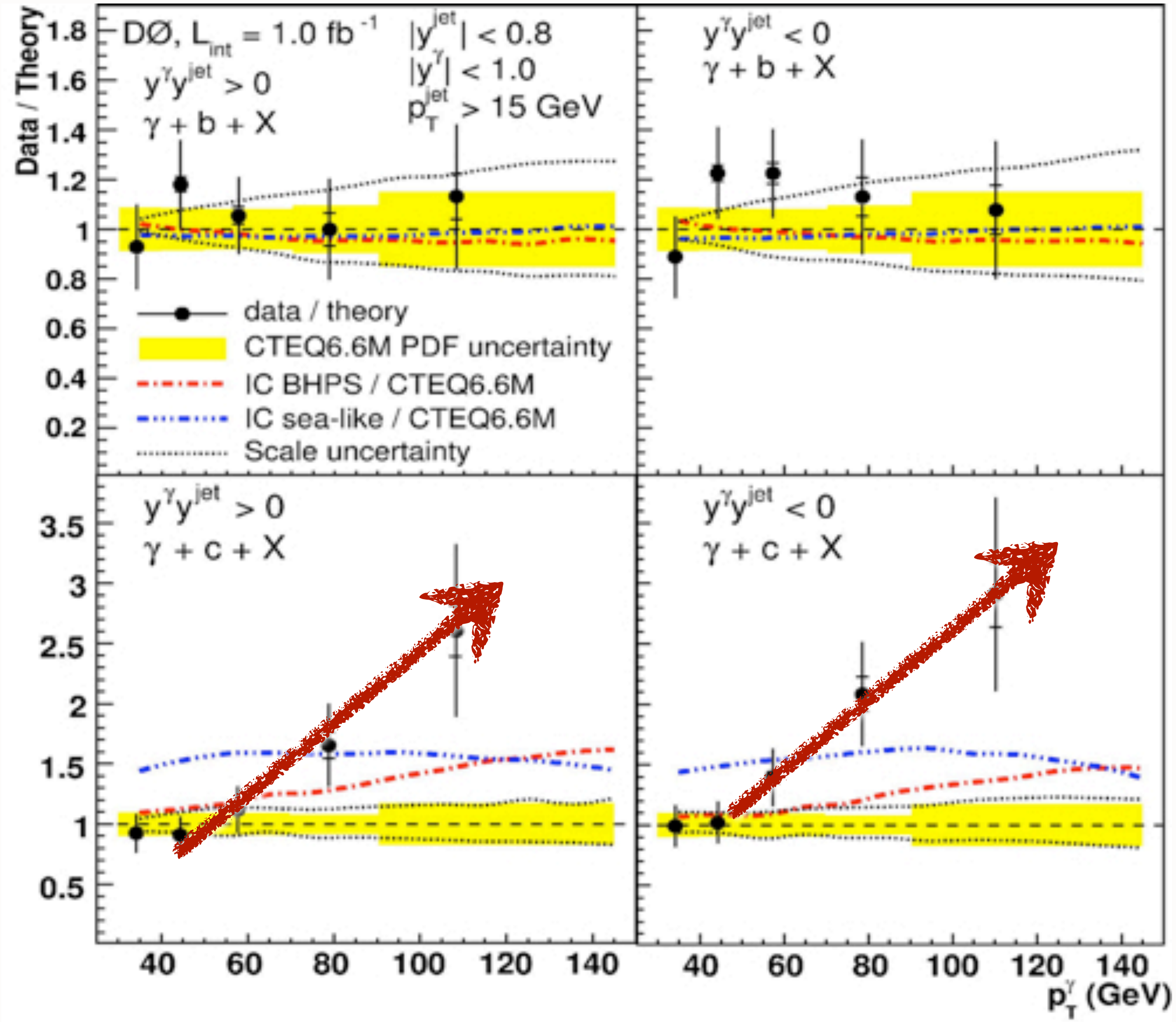

J. J. Aubert et al. [European Muon Collaboration], "Production Of Charmed Particles In 250-Gev Mu+ - Iron Interactions," Nucl. Phys. B 213, 31 (1983).

## First Evidence for Intrinsic Charm




***DGLAP / Photon-Gluon Fusion: factor of 30 too small***

**Measurement of $\gamma + b + X$ and $\gamma + c + X$ Production Cross Sections in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV**

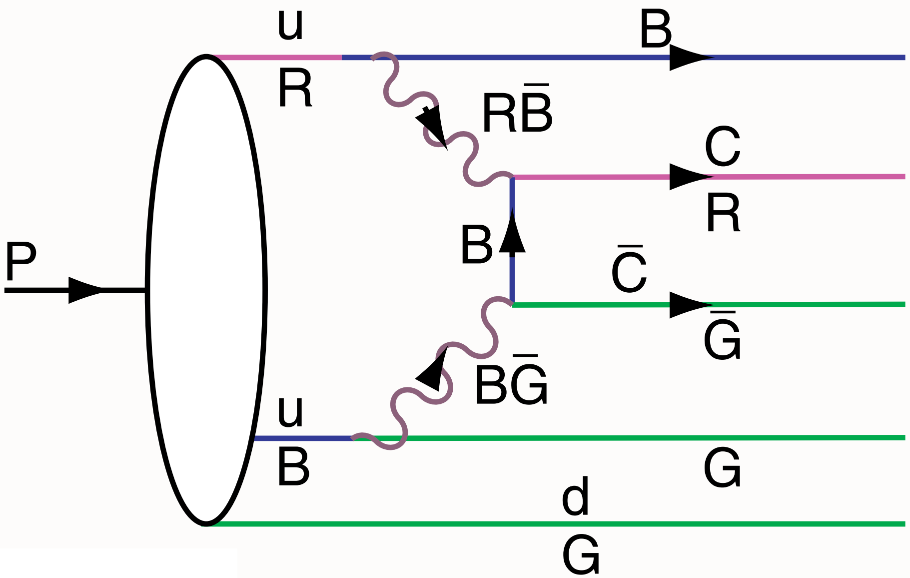



$$\frac{\Delta\sigma(\bar{p}p \to \gamma c X)}{\Delta\sigma(\bar{p}p \to \gamma b X)}$$

**Ratio insensitive to gluon PDF, scales**

**Signal for significant IC at x > 0.1 ?**

Hoyer, Peterson, Sakai, sjb




$|uudcc>$ Fluctuation in Proton

QCD: Probability $\frac{\sim\Lambda^2_{QCD}}{M^2_Q}$

$|e^+e^-\ell^+\ell^->$ Fluctuation in Positronium

QED: Probability $\frac{\sim(m_e\alpha)^4}{M^4_\ell}$

OPE derivation - M.Polyakov et al.

$$< p|\frac{G^3_{\mu\nu}}{m^2_Q}|p > \text{ vs. } < p|\frac{F^4_{\mu\nu}}{m^4_\ell}|p >$$

$cc$ in Color Octet

Distribution peaks at equal rapidity (velocity)
Therefore heavy particles carry the largest momentum fractions

$$\hat{x}_i = \frac{m_{\perp i}}{\sum_j^n m_{\perp j}}$$

*High x charm!* *Charm at Threshold*

**Action Principle: Minimum KE, maximal potential**

- EMC data: $c(x, Q^2) > 30 \times$ DGLAP
  $Q^2 = 75$ GeV$^2$, $x = 0.42$

- High $x_F$ $pp \to J/\psi X$

- High $x_F$ $pp \to J/\psi J/\psi X$

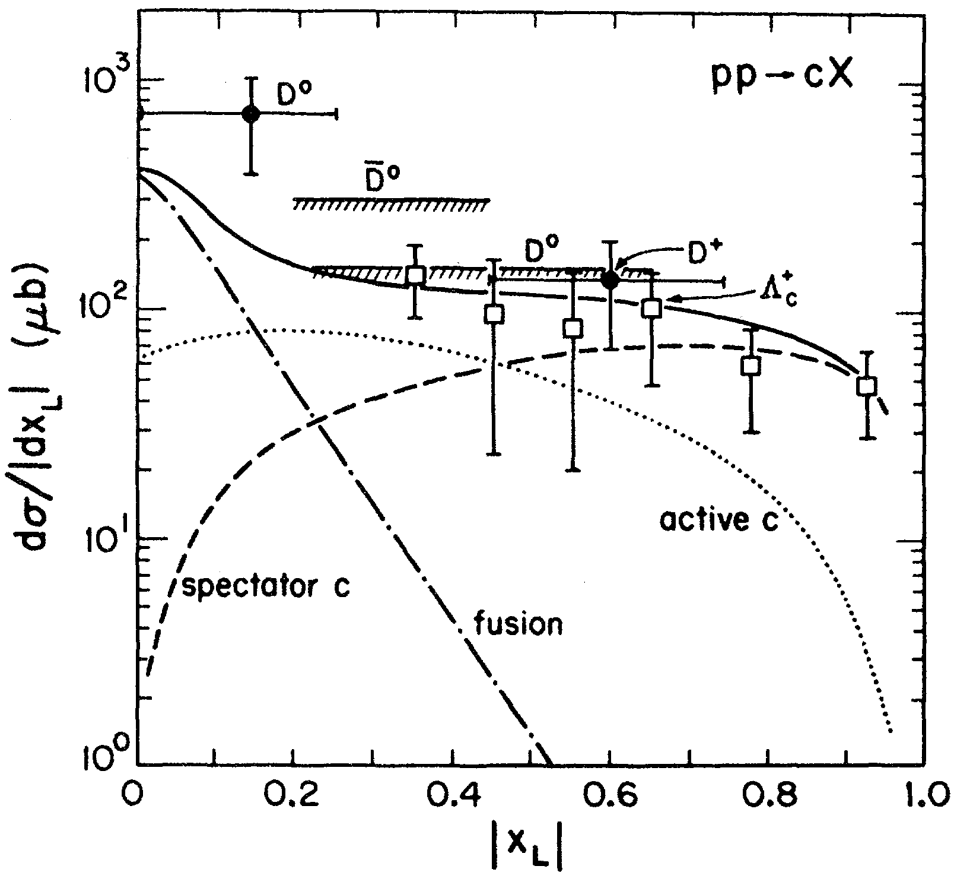
- High $x_F$ $pp \to \Lambda_c X$

- High $x_F$ $pp \to \Lambda_b X$

- High $x_F$ $pp \to \Xi(ccd)X$ (SELEX)

**IC Structure Function: Critical Measurement for EIC**

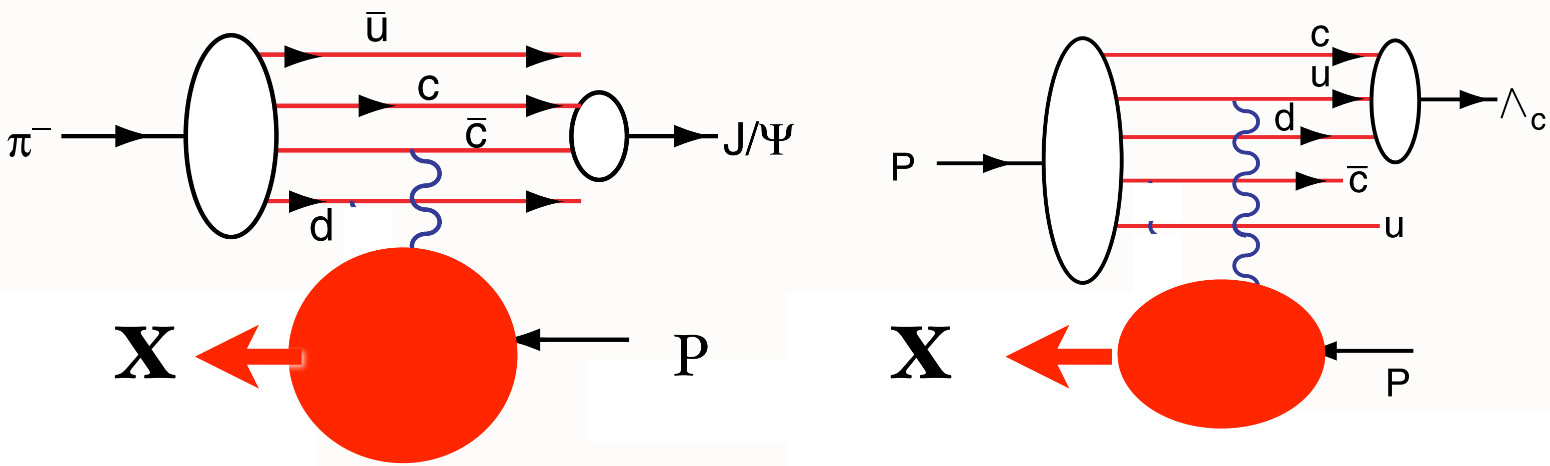
**Many interesting spin, charge asymmetry, spectator effects**




*Model similar to Intrinsic Charm*

V. D. Barger, F. Halzen and W. Y. Keung,
"The Central And Diffractive Components Of Charm Production,"
Phys. Rev. D 25, 112 (1982).

# Leading Hadron Production from Intrinsic Charm




Coalescence of Comoving Charm and Valence Quarks Produce $J/\psi$, $\Lambda_c$ and other Charm Hadrons at High $x_F$

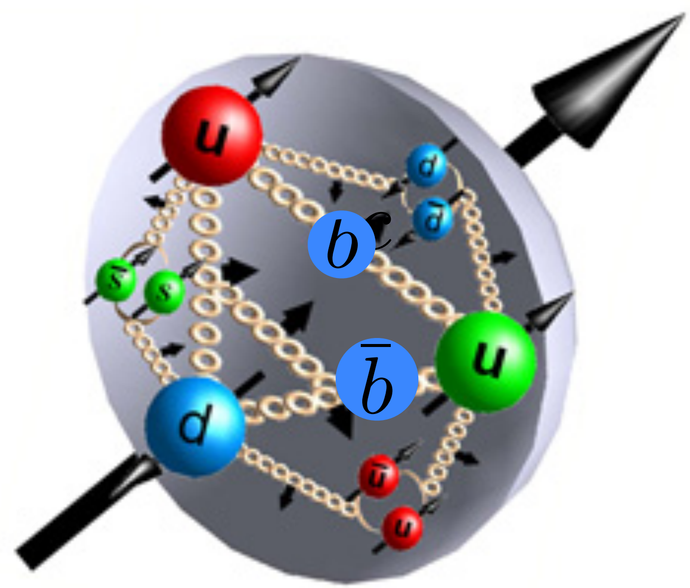
CM-P00063074

27 May 1991

# THE $\Lambda_b^o$ BEAUTY BARYON PRODUCTION IN PROTON-PROTON INTERACTIONS AT $\sqrt{s}$=62 GeV: A SECOND OBSERVATION

G. Bari, M. Basile, G. Bruni, G. Cara Romeo, R. Casaccia, L. Cifarelli, F. Cindolo, A. Contin, G. D'Alì, C. Del Papa, S. De Pasquale, P. Giusti, G. Iacobucci, G. Maccarrone, T. Massam, R. Nania, F. Palmonari, G. Sartorelli, G. Susinno, L. Votano and A. Zichichi

CERN, Geneva, Switzerland
Dipartimento di Fisica dell'Università, Bologna, Italy
Dipartimento di Fisica dell'Università, Cosenza, Italy
Istituto di Fisica dell'Università, Palermo, Italy
Istituto Nazionale di Fisica Nucleare, Bologna, Italy
Istituto Nazionale di Fisica Nucleare, LNF, Frascati, Italy



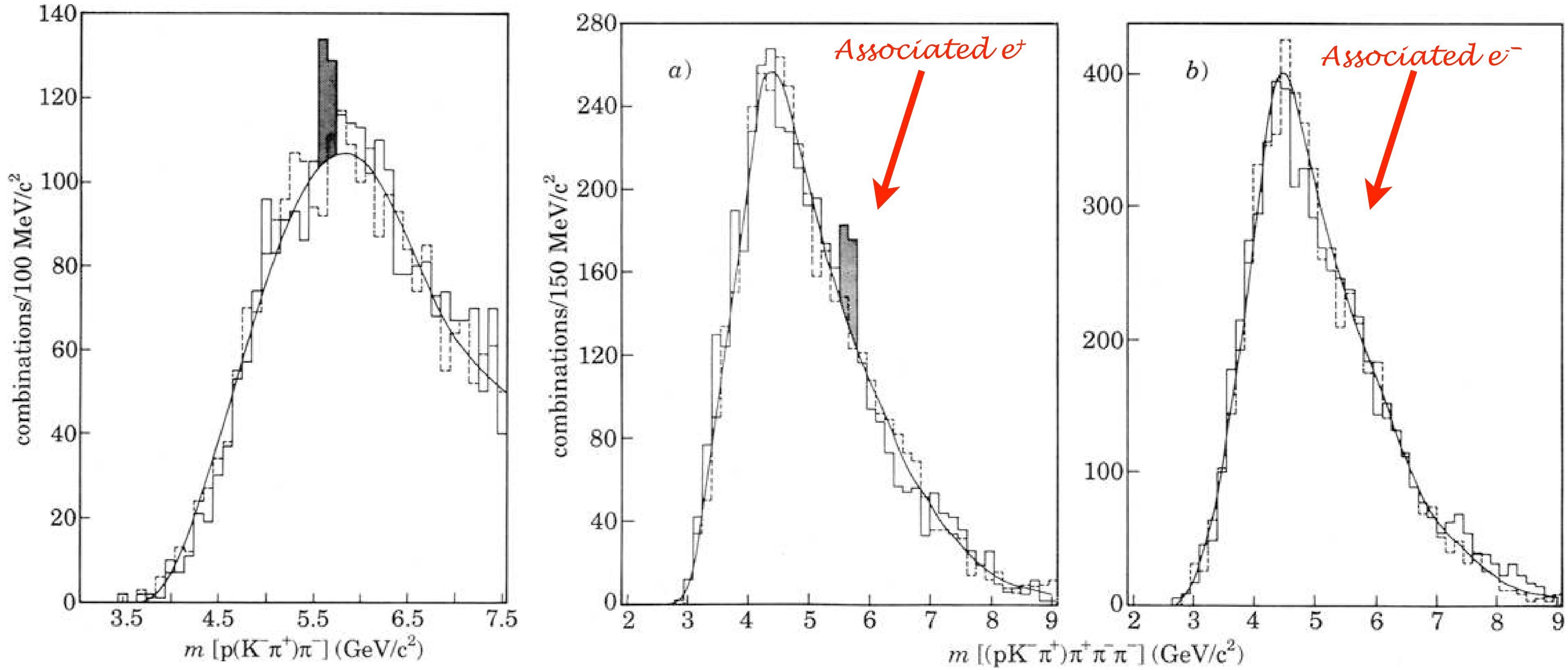

## Abstract

Another decay mode of the $\Lambda_b^o$ (open-beauty baryon) state has been observed: $\Lambda_b^o \rightarrow \Lambda_c^+\pi^+\pi^-\pi^-$. In addition, new results on the previously observed decay channel, $\Lambda_b^o \rightarrow pD^o\pi^-$, are reported. These results confirm our previous findings on $\Lambda_b^o$ production at the ISR. The mass value (5.6 GeV/$c^2$) is found to be in good agreement with theoretical predictions. The production mechanism is found to be "leading".

*First Evidence for Intrinsic Bottom!*

# $pp \to \Lambda_b(bud)B(\bar{b}q)X$ at large $x_F$

## CERN-ISR R422 (Split Field Magnet), 1988/1991




$\Lambda_b^0 \to pD^0\pi^-$ $\qquad$ $\Lambda_b^0 \to \Lambda_c^+\pi^+\pi^-\pi^-$

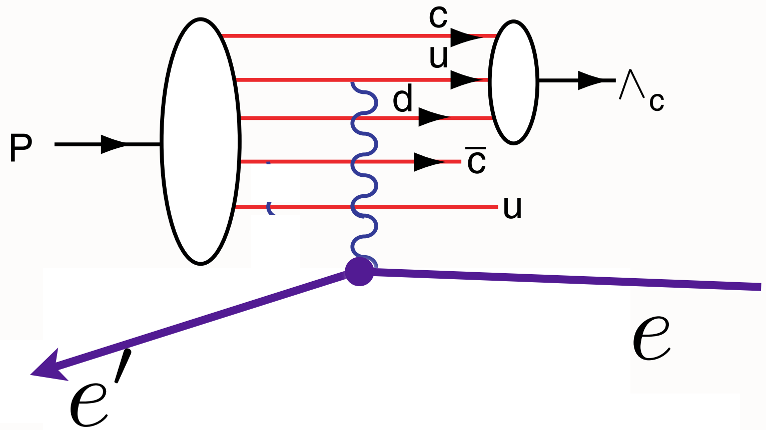
Il Nuovo Cimento 104, 1787

*First Evidence for Intrinsic Bottom!*

# Leading charm production in proton fragmentation region at the EIC

Intrinsic charm and bottom quarks have same rapidity as valence quarks

Produce $\Xi(ccd), B(\bar{b}u), \Lambda(cbu), \Xi(bbu)$



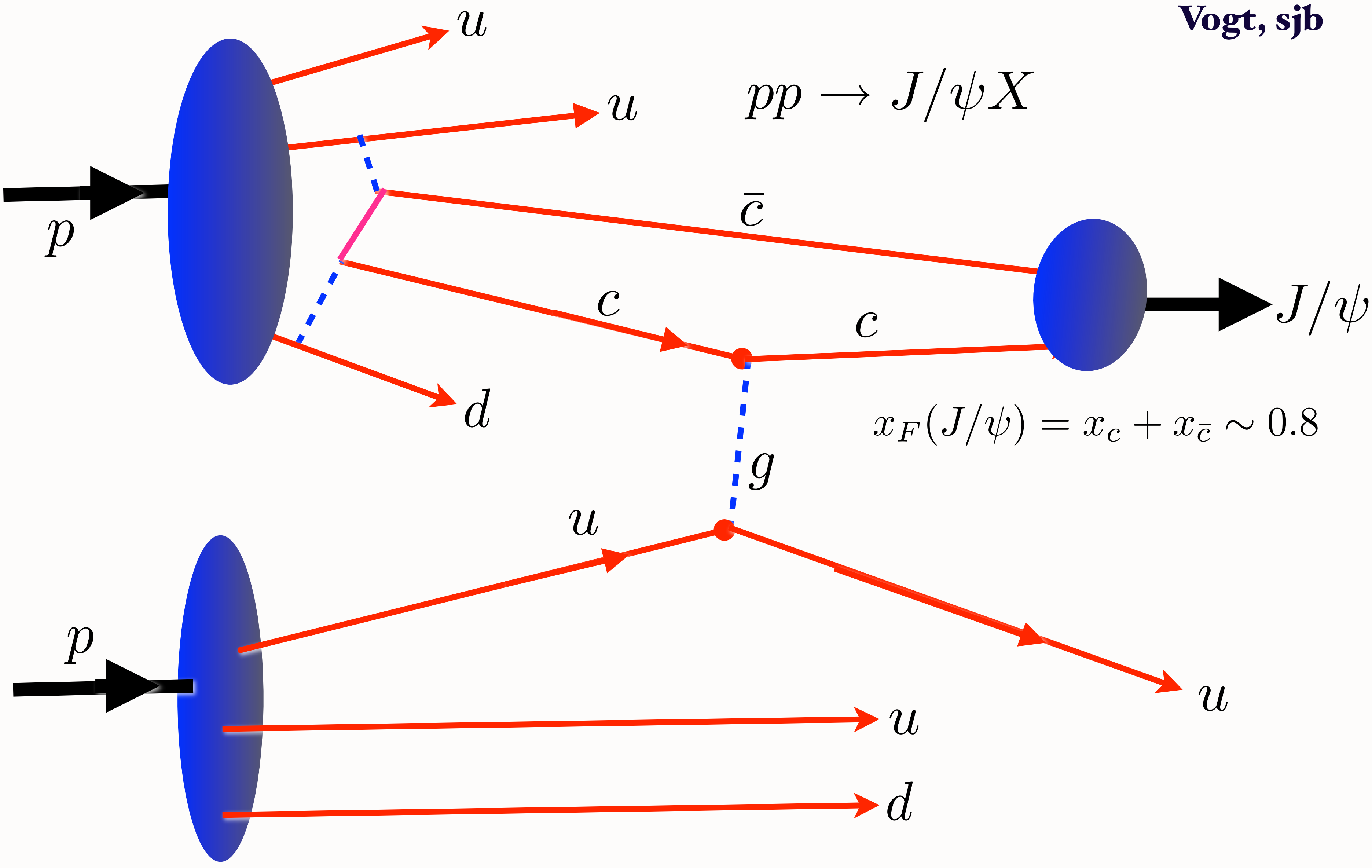

Coalescence of Comoving Charm and Valence Quarks
Produce $J/\psi, \Lambda_c$ and other Charm Hadrons at High $x_F$

# Intrinsic Heavy Quark Contribution to Quarkonium Hadroproduction at High $x_F$

Lansberg, sjb

Vogt, sjb

$pp \to J/\psi X$

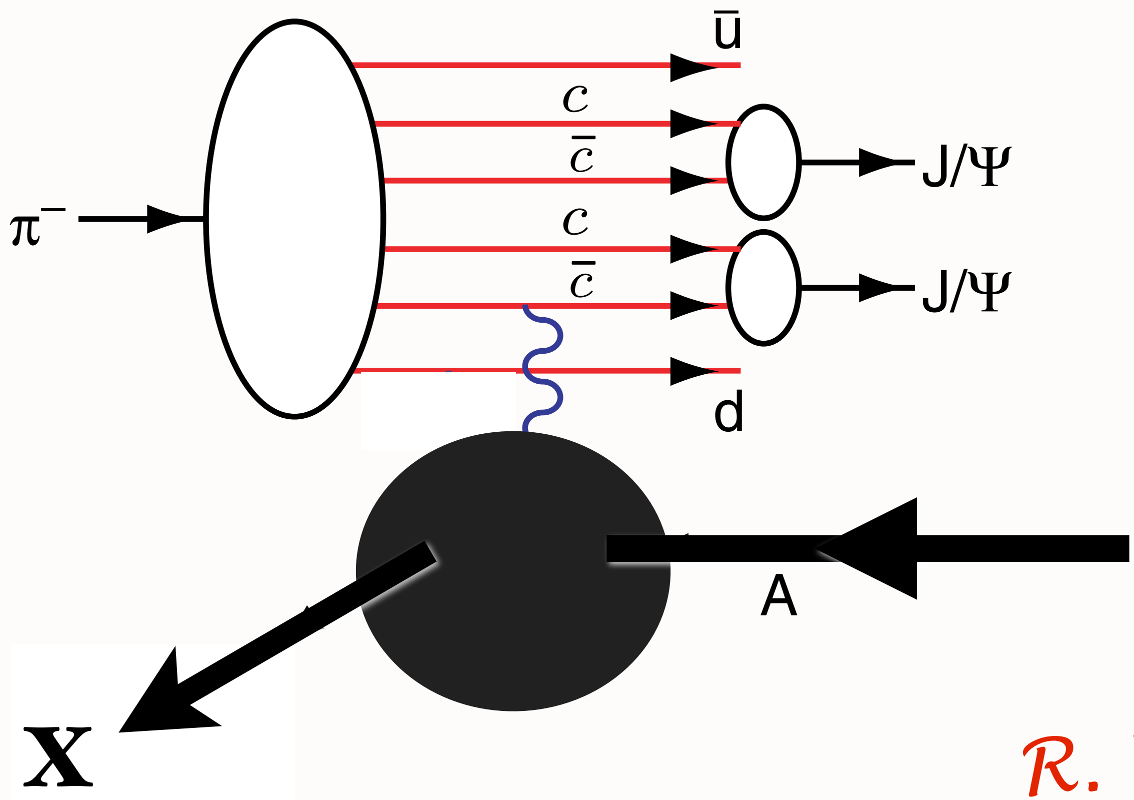



$x_F(J/\psi) = x_c + x_{\bar{c}} \sim 0.8$

Maximal Wavefunction Strength at Minimal Invariant Mass : Equal Rapidity

$$x_i \propto \frac{m_{\perp i}}{\sum_j m_{\perp j}}$$

# Production of Two Quarkonia at High $x_F$




R. Vogt, sjb

All events have $x^F_{\psi\psi} > 0.4$ !

# Excludes `color drag' model

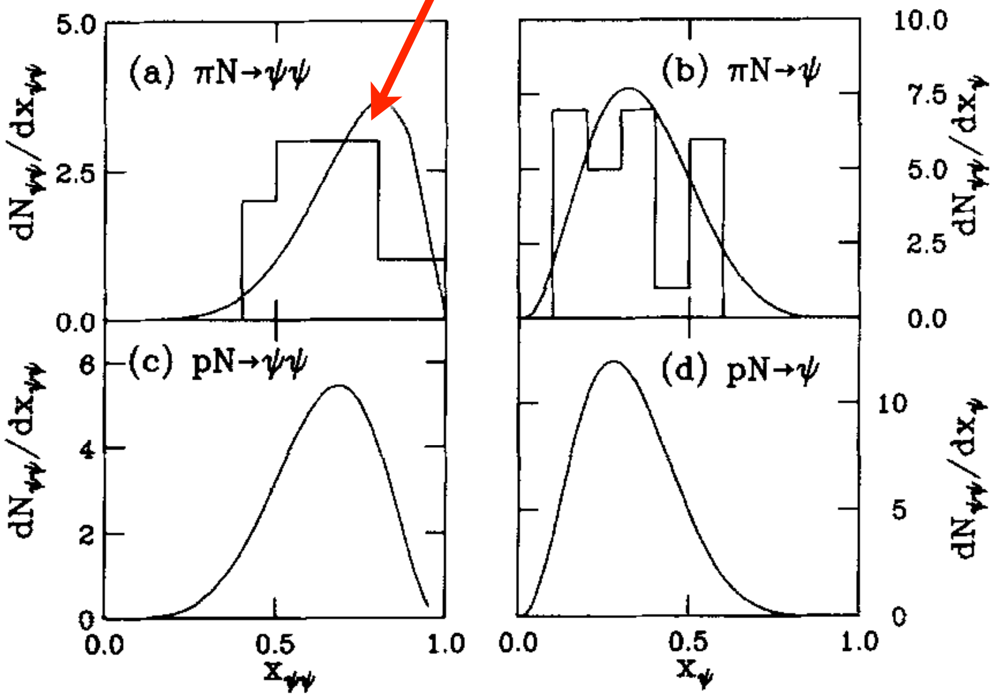



Fig. 3. The $\psi\psi$ pair distributions are shown in (a) and (c) for the pion and proton projectiles. Similarly, the distributions of $J/\psi$'s from the pairs are shown in (b) and (d). Our calculations are compared with the $\pi^- N$ data at 150 and 280 GeV/$c$ [1]. The $x_{\psi\psi}$ distributions are normalized to the number of pairs from both pion beams (a) and the number of pairs from the 400 GeV proton measurement (c). The number of single $J/\psi$'s is twice the number of pairs.

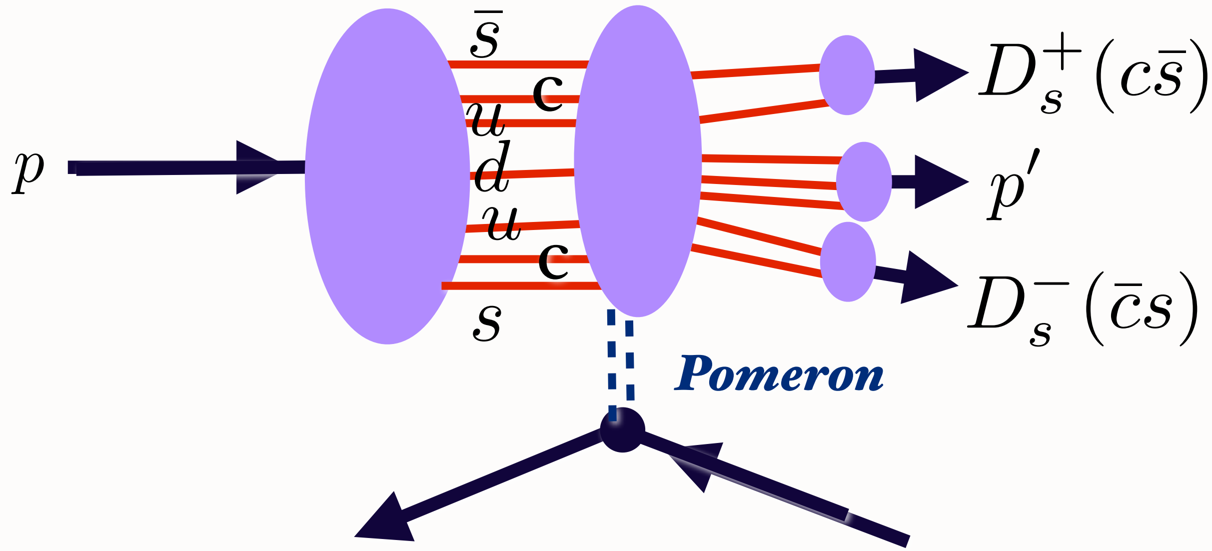
**NA3 Data**

$\pi A \rightarrow J/\psi J/\psi X$

R. Vogt, sjb

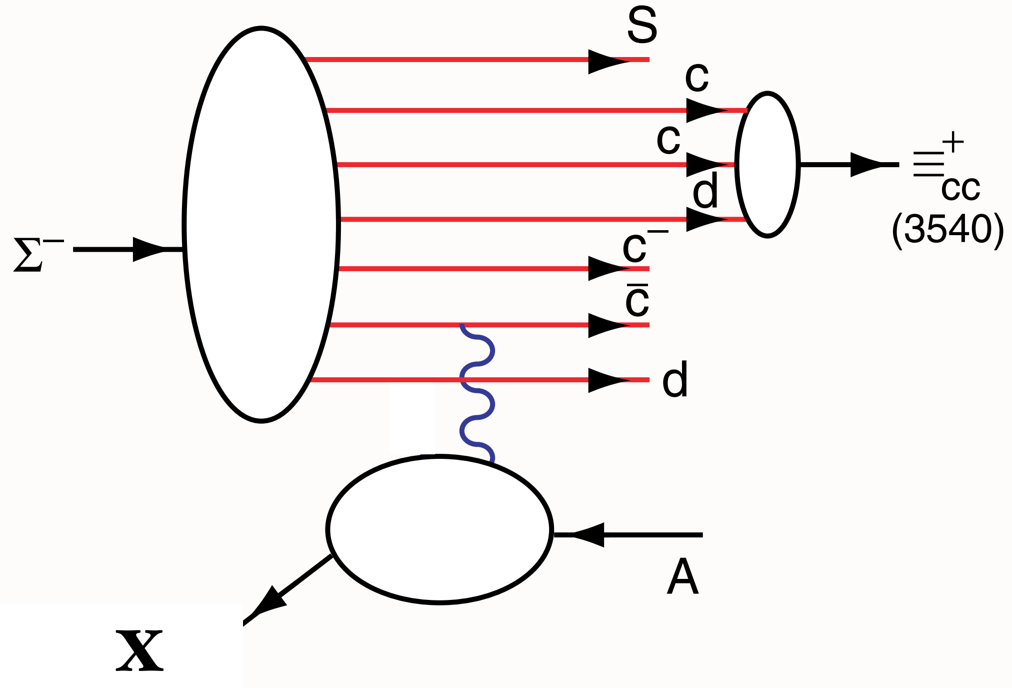
The probability distribution for a general $n$-particle intrinsic $c\bar{c}$ Fock state as a function of $x$ and $\boldsymbol{k}_T$ is written as

$$\frac{dP_{\rm ic}}{\prod_{i=1}^{n} dx_i d^2k_{T,i}} = N_n \alpha_s^4(M_{c\bar{c}}) \frac{\delta(\sum_{i=1}^{n} \boldsymbol{k}_{T,i})\delta(1 - \sum_{i=1}^{n} x_i)}{(m_h^2 - \sum_{i=1}^{n}(m_{T,i}^2/x_i))^2},$$




Look for $D_s^-(\bar{c}s)$ vs. $D_s^+(c\bar{s})$ asymmetry

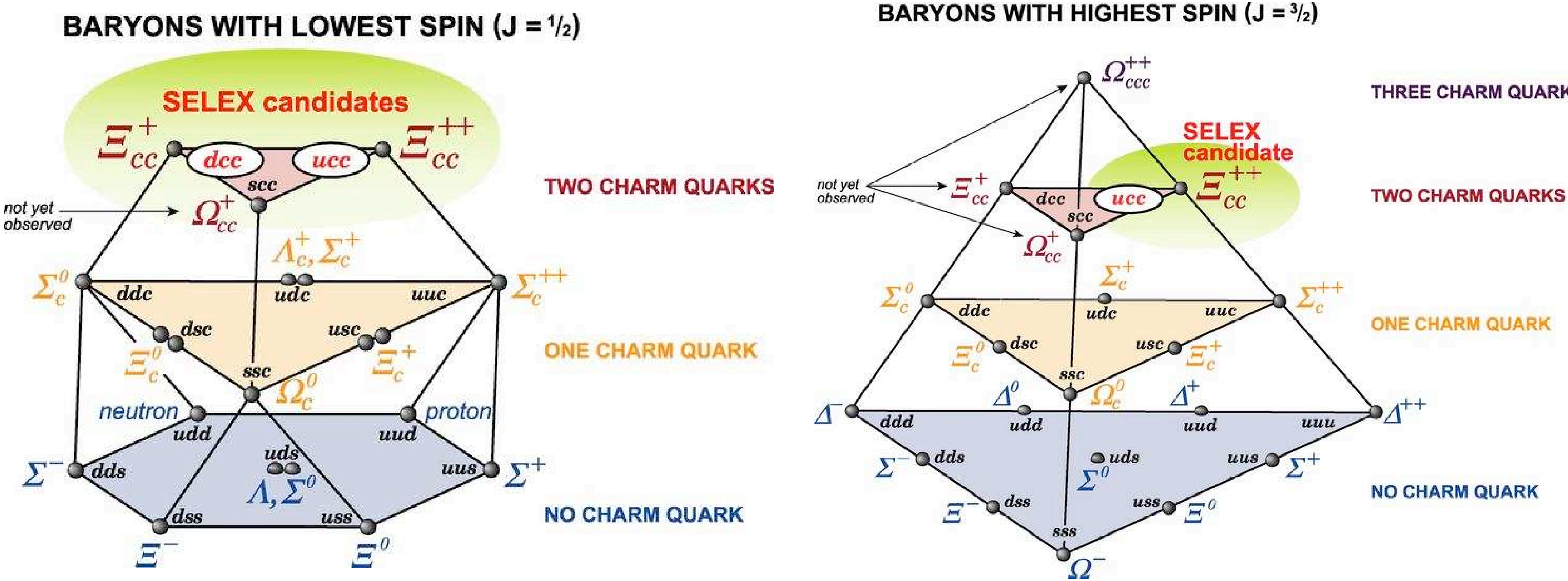
Reflects $s$ vs. $\bar{s}$ asymmetry in proton $|uudc\bar{c}s\bar{s}>$ Fock LF state.




# *Production of a Double-Charm Baryon*

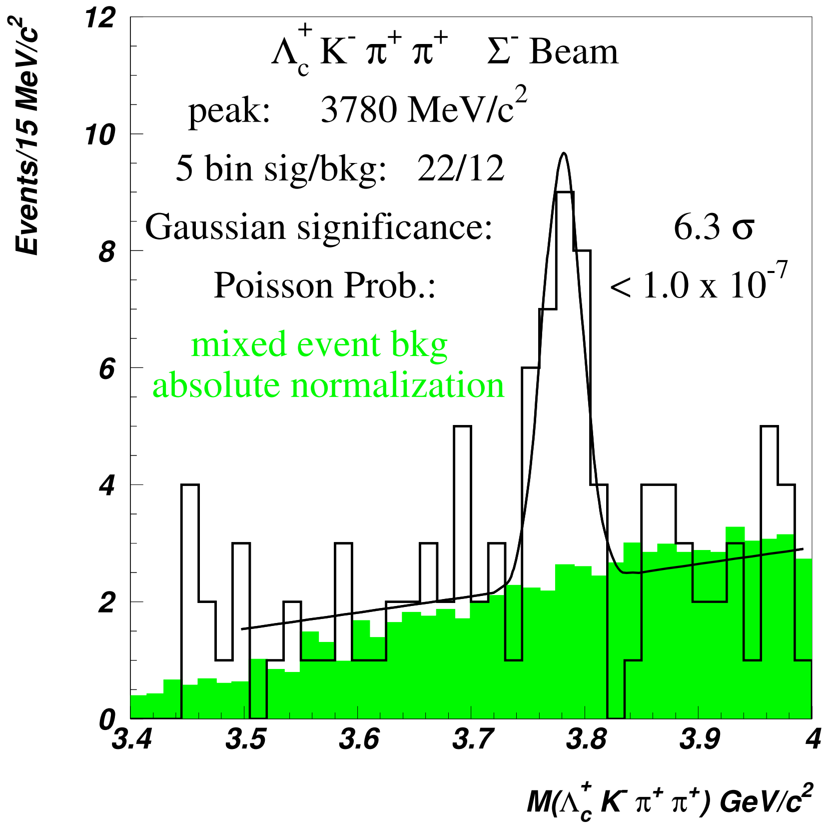
**SELEX high $x_F$** $< x_F >= 0.33$

# Doubly Charmed Baryons



# $\Xi_{cc}(3780)^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$

- Re-Analyzed Data
- Restrict to $\Sigma^-$–Beam
- Peak wider than Resolution
- Half decay to $\Xi_{cc}^+(3520)$
- Still working on Details

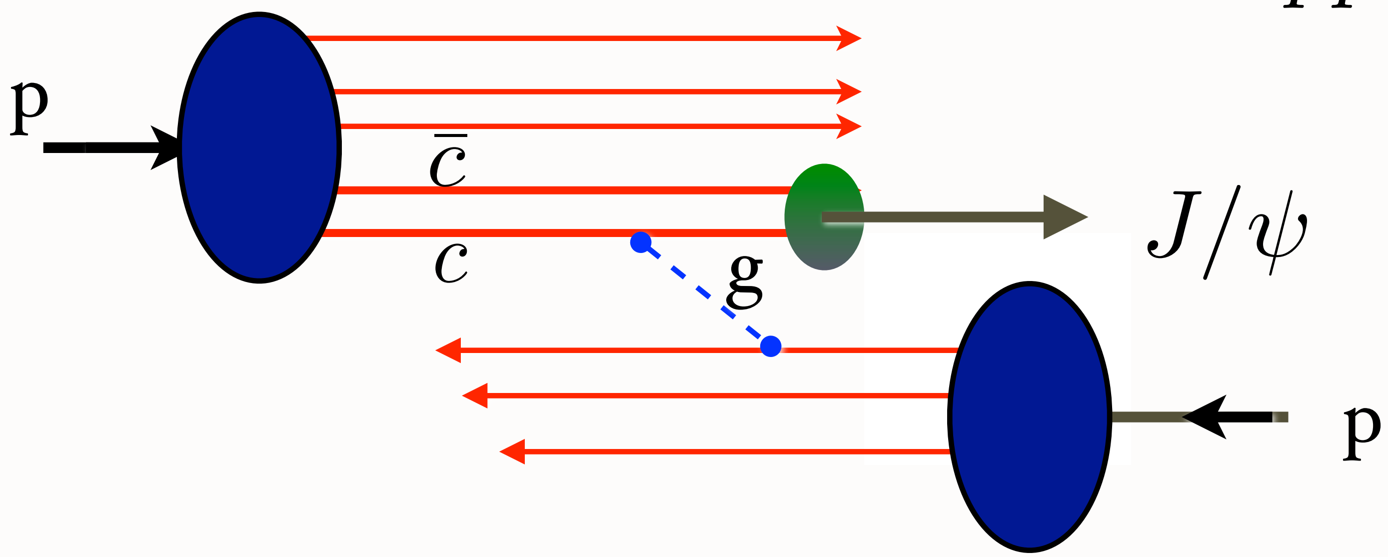


Produce entire set of Heavy Baryons up to bbb

AFTER @ LHC

# Intrinsic Charm Mechanism for Inclusive High-$X_F$ Quarkonium Production

$$pp \rightarrow J/\psi X$$



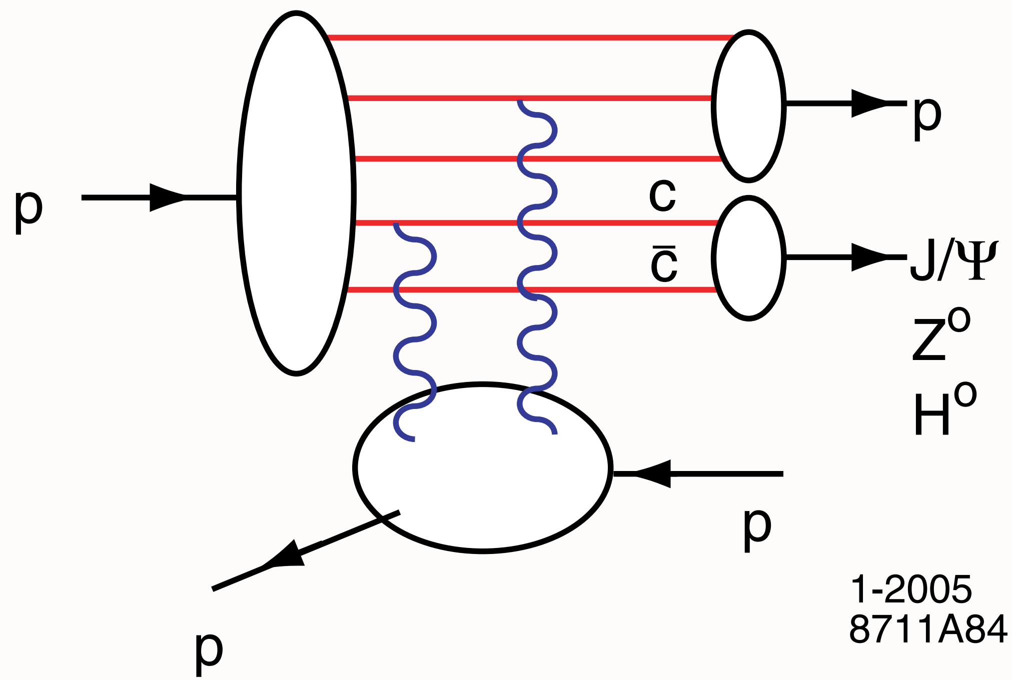

Goldhaber, Kopeliovich, Soffer, Schmidt, sjb

**Quarkonia can have 80% of Proton Momentum!**

*Color-octet IC interacts at front surface of nucleus*

**IC can explains large excess of quarkonia at large $x_F$, A-dependence**

# Intrinsic Charm Mechanism for Exclusive Diffraction Production




$$p\,p \to J/\psi\ p\ p$$

$$x_{J/\psi} = x_c + x_c$$

**Exclusive Diffractive High-$X_F$ Higgs Production**

**Kopeliovitch, Schmidt, Soffer, sjb**

Intrinsic *cc* pair formed in color octet $8_C$ in proton wavefunction     Large Color Dipole

Collision produces color-singlet $J/\psi$ through color exchange

RHIC Experiment

# *Heavy Quark Anomalies*

Nuclear dependence of $J/\psi$ hadroproduction

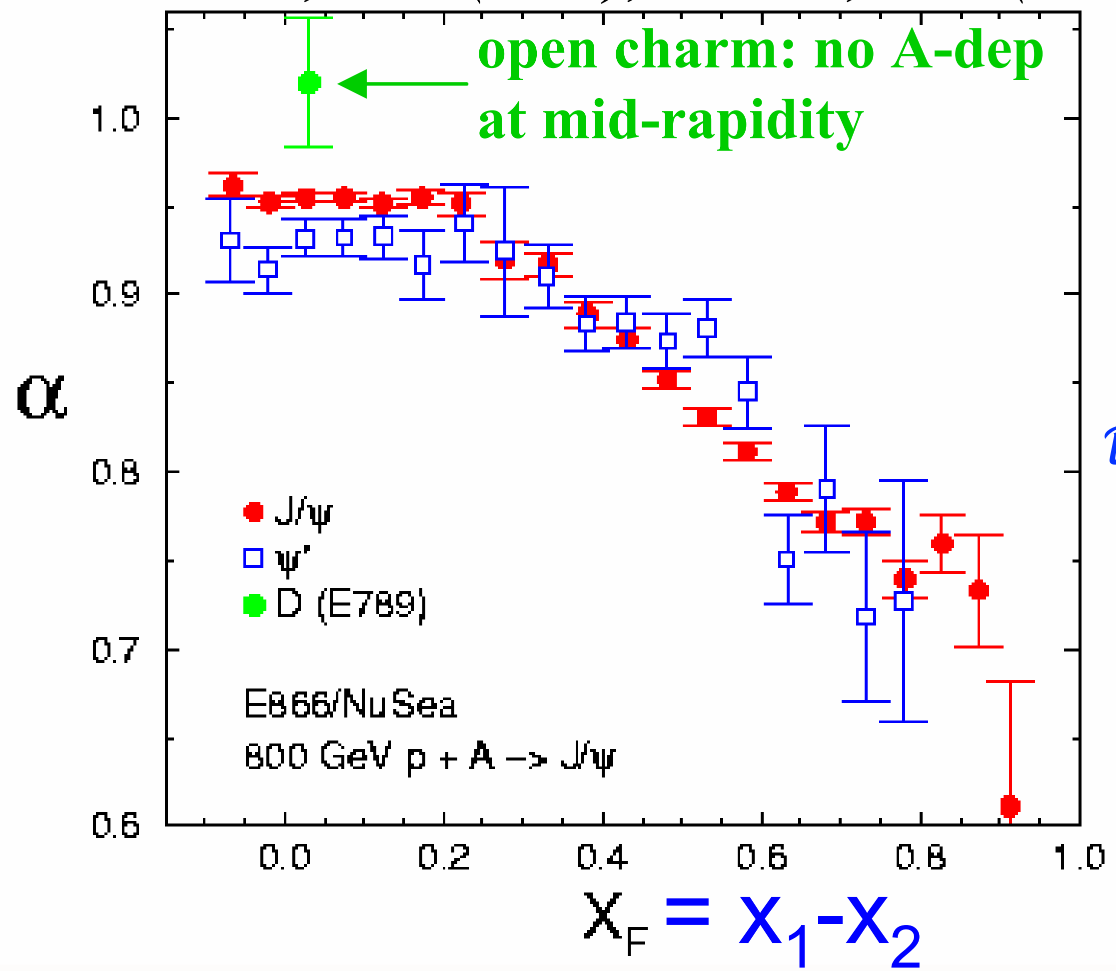
Violates PQCD Factorization: $A^{\alpha}(x_F)$ not $A^{\alpha}(x_2)$

Huge $A^{2/3}$ effect at large $x_F$

800 GeV p-A (FNAL) $\sigma_A = \sigma_p * A^\alpha$

*PRL 84, 3256 (2000); PRL 72, 2542 (1994)*

M. Leitch




$$\frac{d\sigma}{dx_F}(pA \to J/\psi X)$$

*Remarkably Strong Nuclear Dependence for Fast Charmonium*

*Violation of PQCD Factorization*

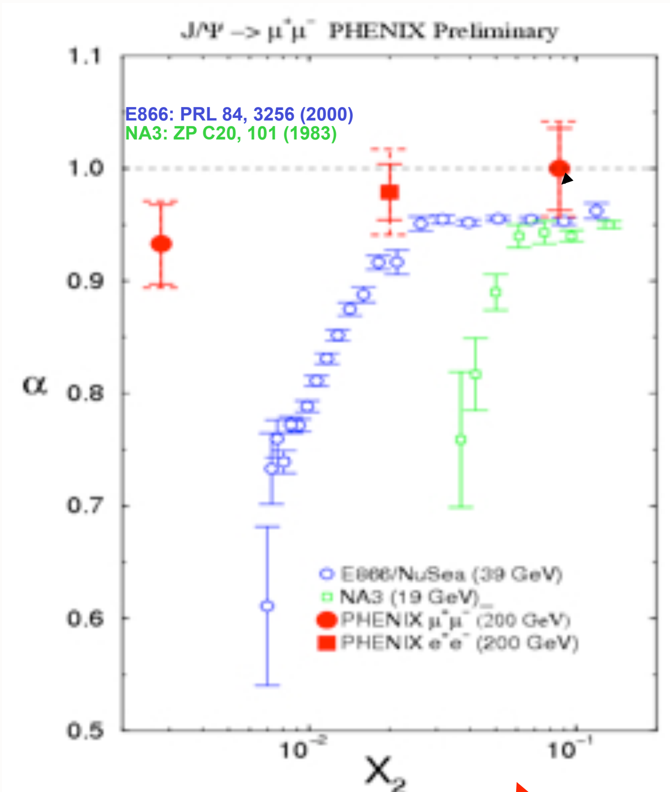
Violation of factorization in charm hadroproduction.
P. Hoyer, M. Vanttinen (Helsinki U.) , U. Sukhatme (Illinois U., Chicago) . HU-TFT-90-14, May 1990. 7pp.
Published in Phys.Lett.B246:217-220,1990

**IC Explains large excess of quarkonia at large $x_F$, A-dependence**

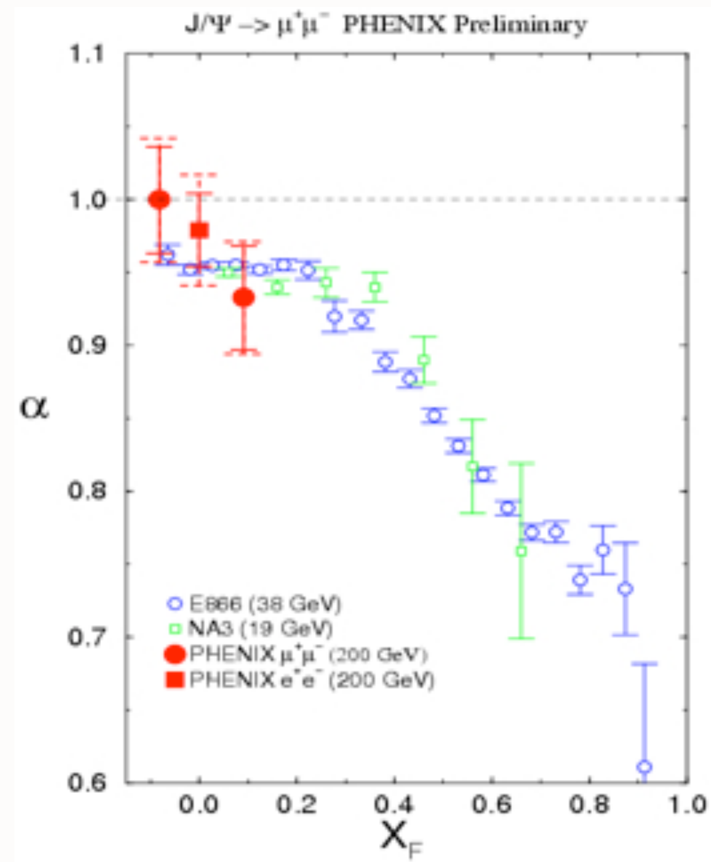
# J/ψ nuclear dependence vrs rapidity, $x_{Au}$, $x_F$

M.Leitch

PHENIX compared to lower energy measurements




Klein,Vogt, PRL 91:142301,2003
Kopeliovich, NP A696:669,2001




*Huge "absorption" effect*

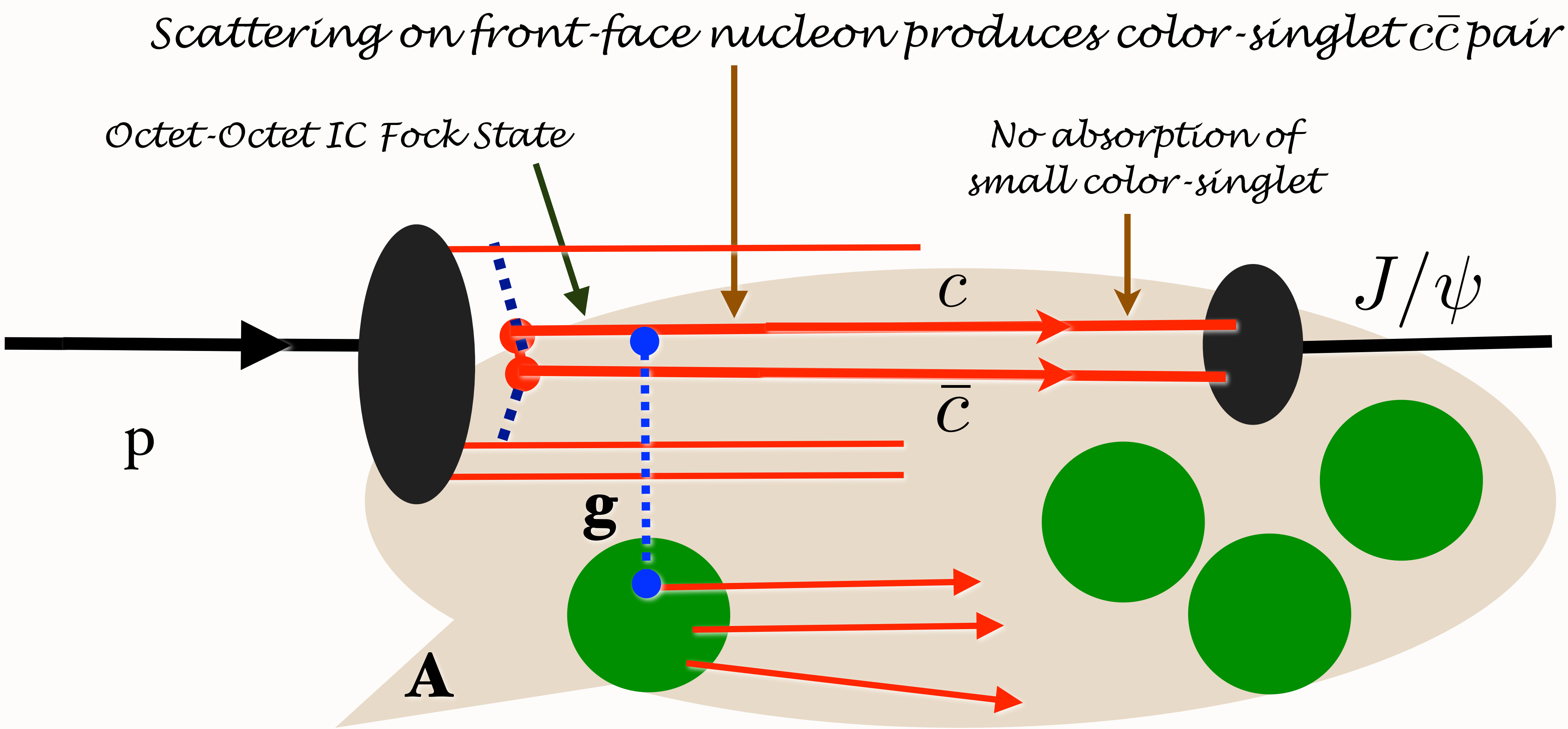
*Violates PQCD factorization!*

$$\frac{d\sigma}{dx_F}(pA \to J/\psi X)$$

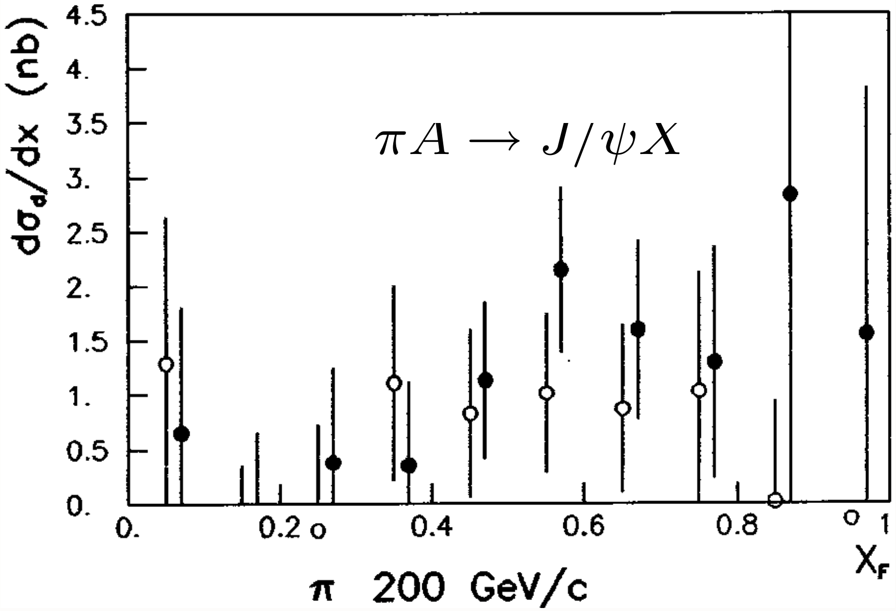
Hoyer, Sukhatme, Vanttinen

# Color-Opaque IC Fock state interacts on nuclear front surface

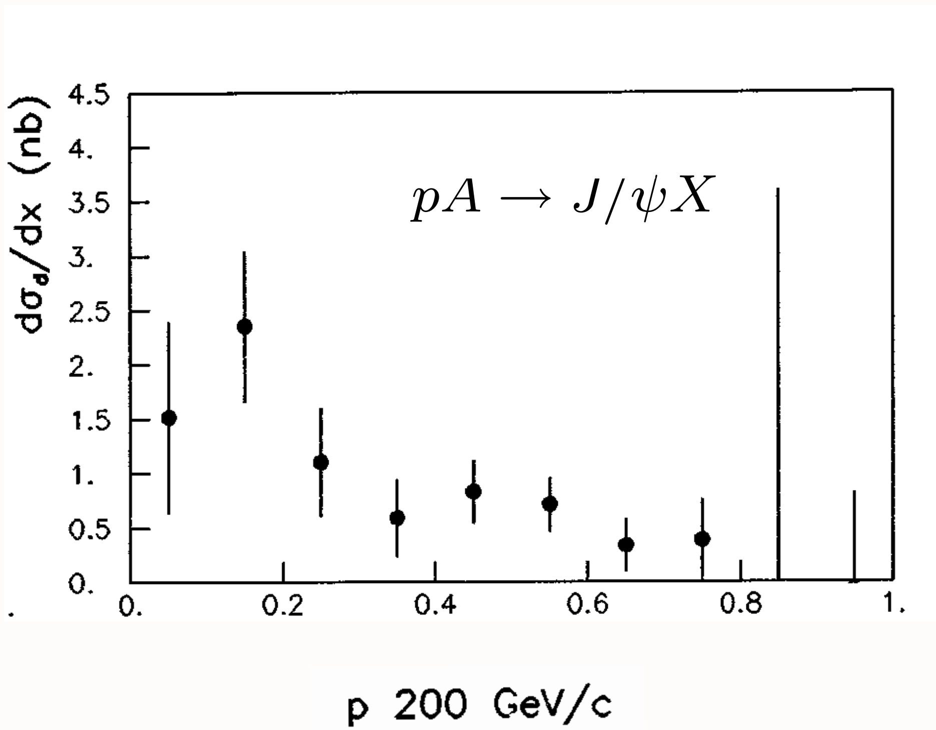
Kopeliovich, Schmidt, Soffer, sjb




$$\frac{d\sigma}{dx_F}(pA \to J/\psi X) = A^{2/3} \times \frac{d\sigma}{dx_F}(pN \to J/\psi X)$$




$$\frac{d\sigma}{dx_F}(pA \to J/\psi X) = A^1 \frac{d\sigma_1}{dx_F} + A^{2/3}\frac{d\sigma_{2/3}}{dx_F}$$




$A^{2/3}$ component

**J. Badier et al, NA3**

**Excess beyond conventional PQCD subprocesses**

- IC Explains Anomalous $\alpha(x_F)$ not $\alpha(x_2)$ dependence of $pA \to J/\psi X$ (Mueller, Gunion, Tang, SJB)

- Color Octet IC Explains $A^{2/3}$ behavior at high $x_F$ (NA3, Fermilab) (Kopeliovitch, Schmidt, Soffer, SJB)

*Color Opaqueness*

- IC Explains $J/\psi \to \rho\pi$ puzzle (Karliner, SJB)

- IC leads to new effects in $B$ decay (Gardner, SJB)

**Higgs production at $x_F$ = 0.8**

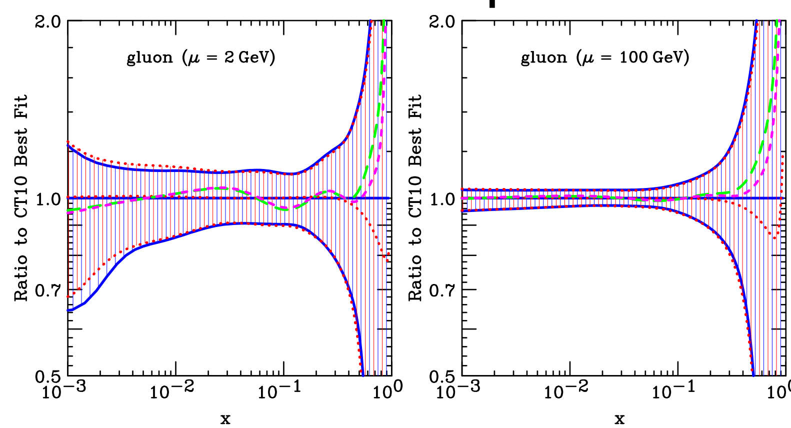
# Need for a quarkonium observatory

- To put an end to production controversies (since 1995 !), we need
  - a study of direct $J/\psi$ yield ( $\chi_c$ only measured in *pp* by CDF and PHENIX)
  - a study of direct $\Upsilon(nS)$ ( $\chi_b$ only measured in *pp* by CDF (1 point))
  - a study of the polarisation of direct yields
    (at least in 2 frames or 2D distrib.)
  - + probably associated production
- $\chi_{c,b}$ production is badly known, even worse for the $\eta_c$
- The latter are **potentially better probes** of glue in *pp*
- LO processes are $gg \to \begin{cases} \chi_{c,b,2} \\ \eta_{c,b} \end{cases}$
- For that, we need
  - high stats
    $\to$ wide acceptance (also help not to bias 1D polarisation analyses)
  - a vertex detector
  - state-of-the-art calorimetry for $\gamma$ ($\chi_Q \to {}^3S_1 + \gamma$, $\eta_c \to \gamma\gamma$)
  - adapted triggers (Big issue for CMS and ATLAS)

# A Fixed Target ExpeRiment: A quarkonium observatory

- Interpolating the world data set:
- Rates expected at RHIC in 2011:
  $J/\psi$: $10^6$ in *pp*, $\Upsilon$: $10^4$ in *pp*
- 2-3 orders of magnitude higher here
  (RHIC yields are much lower in dAu compared to p*A* here)
- Numbers are for only one unit of *y* about 0
- Unique access in the backward region
- Probe of the (very) large *x* in the target
- AIM/HOPE: Extract $g(x, Q^2)$ with $Q^2$ as low as 10 GeV$^2$
  from $x = 10^{-3}$ up to $\simeq$ one

| Target | $N_{J/\Psi}$ ($y^{-1}$) $N_{J/\Psi} = A\mathcal{L}\sigma_{\Psi}$ | $N_{\Upsilon}$ ($y^{-1}$) $N_{\Upsilon} = A\mathcal{L}\sigma_{\Upsilon}$ |
|---|---|---|
| | (with branching and per unit of rapidity) | |
| Liq. H² ( 1m) | 0.6 $10^9$ | $10^6$ |
| Liq. D² | 1.5 $10^9$ | 23 $10^5$ |
| Be | 0.2 $10^9$ | 2.7 $10^5$ |
| Cu | 0.8 $10^9$ | 13 $10^5$ |
| W | 1.7 $10^9$ | 27 $10^5$ |
| Pb | 1. $10^9$ | 16 $10^5$ |



# A quarkonium observatory in *pA* collisions

| Target | $N_{J/\Psi}$ ($y^{-1}$) $N_{J/\Psi} = A\mathcal{L}\sigma_{\Psi}$ | $N_{\Upsilon}$ ($y^{-1}$) $N_{\Upsilon} = A\mathcal{L}\sigma_{\Upsilon}$ |
|---|---|---|
| | (with branching and per unit of rapidity) | |
| Liq. H² (1m) | 0.6 $10^9$ | $10^6$ |
| Liq. D² | 1.5 $10^9$ | 23 $10^5$ |
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| Cu | 0.8 $10^9$ | 13 $10^5$ |
| W | 1.7 $10^9$ | 27 $10^5$ |
| Pb | 1. $10^9$ | 16 $10^5$ |

- Reminder:
- Total yield measured by PHENIX during *d*Au Run08: $9 \times 10^5$ $J/\psi$ (inclusive yield in nearly 3 units of *y*!)
- Future plan for *d*Au runs at RHIC ?
- In principle, one can get 1000 times more $J/\psi$ (in 1 unit of *y*), allowing for
  - $\chi_c$ measurement in *pA* via $J/\psi + \gamma$
  - Polarisation measurement as function of *A*, the centrality, *y* and $P_T$ :

    For $\alpha^{octet} \neq \alpha^{singlet}$, probe of different obsorption of octets & singlets ?
  - Ratio $\psi'$ over direct $J/\psi$ measurement in *pA*
  - not to mention ratio with open charm, Drell-Yan, etc ...

## A Fixed Target ExpeRiment: a quarkonium observatory in *PbA*

Observation of $J/\psi$ sequential suppression seems to be hindered by

- the Cold Nuclear Matter effects: non trivial and ... not well-known, after all
- the difficulty to observe directly the excited states which would melt before the ground states
  - $\chi_c$ never studied in *AA* collisions
  - $\psi(2S)$ not yet studied in *AA* collisions at RHIC and the LHC
- the possibilities for $c\bar{c}$ recombination
  - Open charm studies are difficult where recombination matters most i.e. at low $P_T$
  - Only indirect indications –from the $y$ and $P_T$ dependence of $R_{AA}$– that recombination may be at work
  - CNM effects may show a non-trivial $y$ and $P_T$ dependence too !
  - not clear what $v_2$ tells us

# A Fixed Target ExpeRiment: a quarkonium observatory in *PbA*

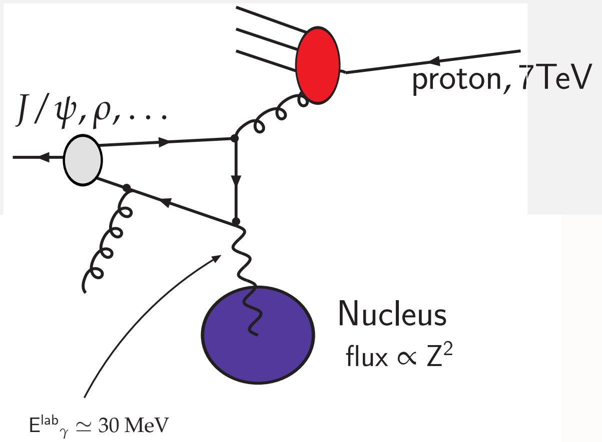
- The excellent capabilities in *pA* should help
  - to reduce the CNM uncertainties
  - to measure their dependence in $y$ and $P_T$
- Even though recombination may not be large at 72 GeV:
  - Open charm may be well measured, via displaced e/$\mu$ or $D \to K\pi$ a priori even at low $P_T$ thanks to the boost
- last but not least, excited states would be studied
  - $\psi(2S)$ thanks to the statistics and the resolution
  - $\chi_c$ thanks the excellent colorimetry in high-multiplicity environment cf. the CALICE detector using particle flow techniques
  - and maybe ... for the very first time the $\eta_c$
- As STAR people suggested, why not to look for gluon quenching in $J/\psi$+hadron correlations vs. centrality (I suspect that we need a good *pA* baseline)

Rough estimation of the yield: $2 \times 10^7 J/\psi$, $10^4 \Upsilon$ per year ($10^6$ sec)

# A Fixed Target ExpeRiment

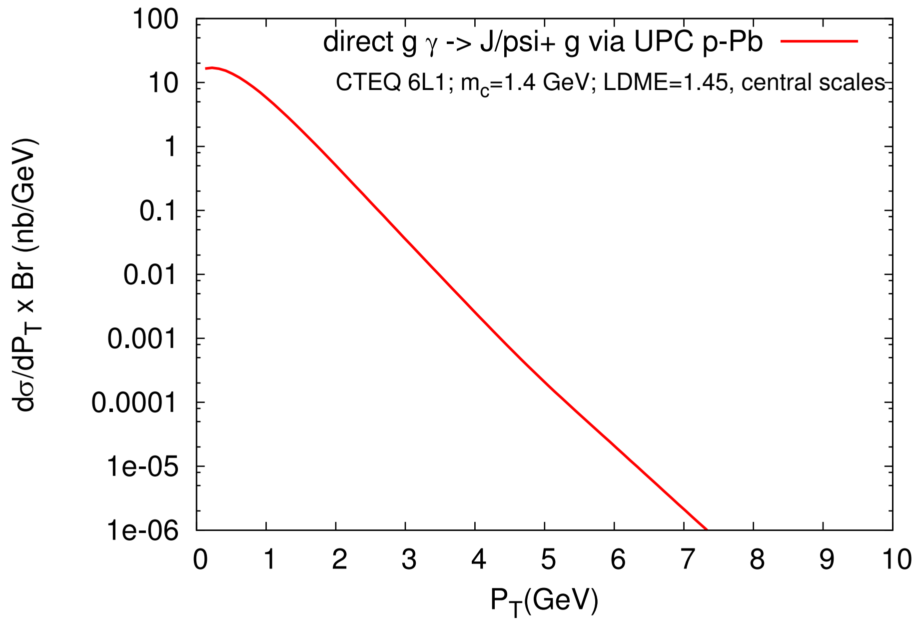
One exotic illustration of the potentialities:

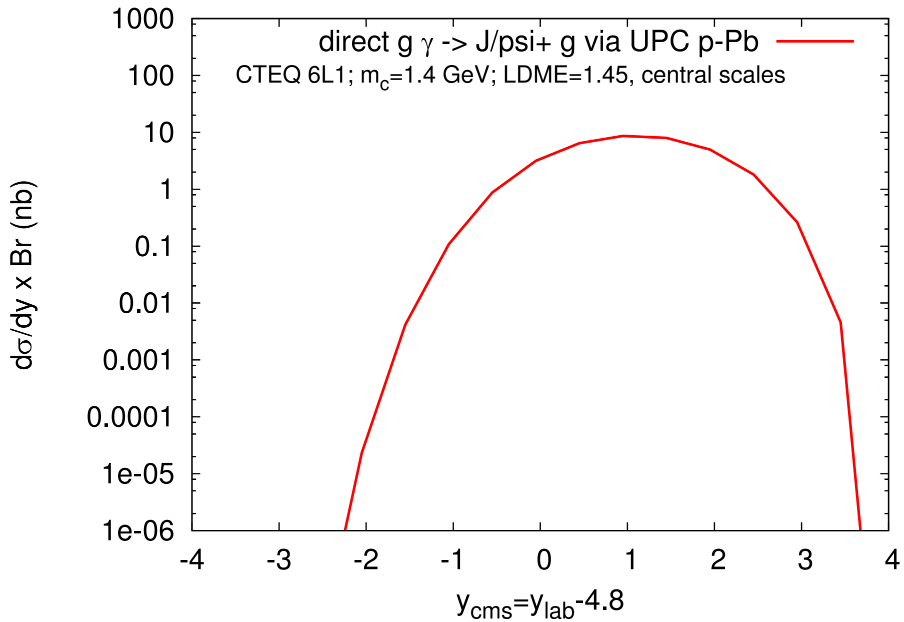
Ultra-peripheral collisions




## Inelastic photoproduction of $J/\psi$ via UPC*

Thanks to the boost: $W^{max}_{\gamma+p}$ for a coherent photon emission ($Z^2$ fact.) can be as high as 25 GeV !




**Disclaimer:** these numbers suppose a dedicated trigger and are preliminary

*(In the extraction mode, pile-up is drastically reduced)

# A Fixed Target ExpeRiment

## A dilepton observatory

➟ Region in $x$ probed by dilepton production as function of $M_{\ell\ell}$

→ Above $c\bar{c}$: $x \in [10^{-3}, 1]$

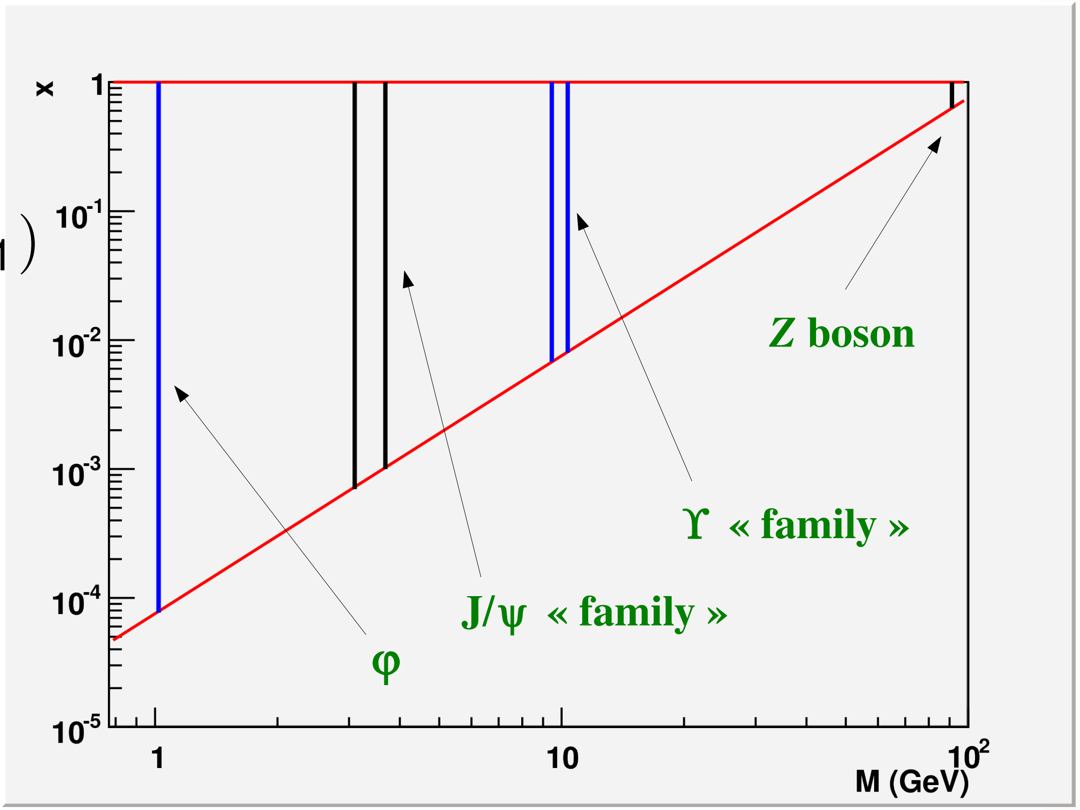
→ Above $b\bar{b}$: $x \in [9 \times 10^{-3}, 1]$

**Note:** $x_{target} (\equiv x_2) > x_{projectile} (\equiv x_1)$
"backward" region

→ sea-quark asymetries
via $p$ and $d$ studies

- at large(est) $x$: backward ("easy")

- at small(est) $x$: forward (need to stop the (extracted) beam)

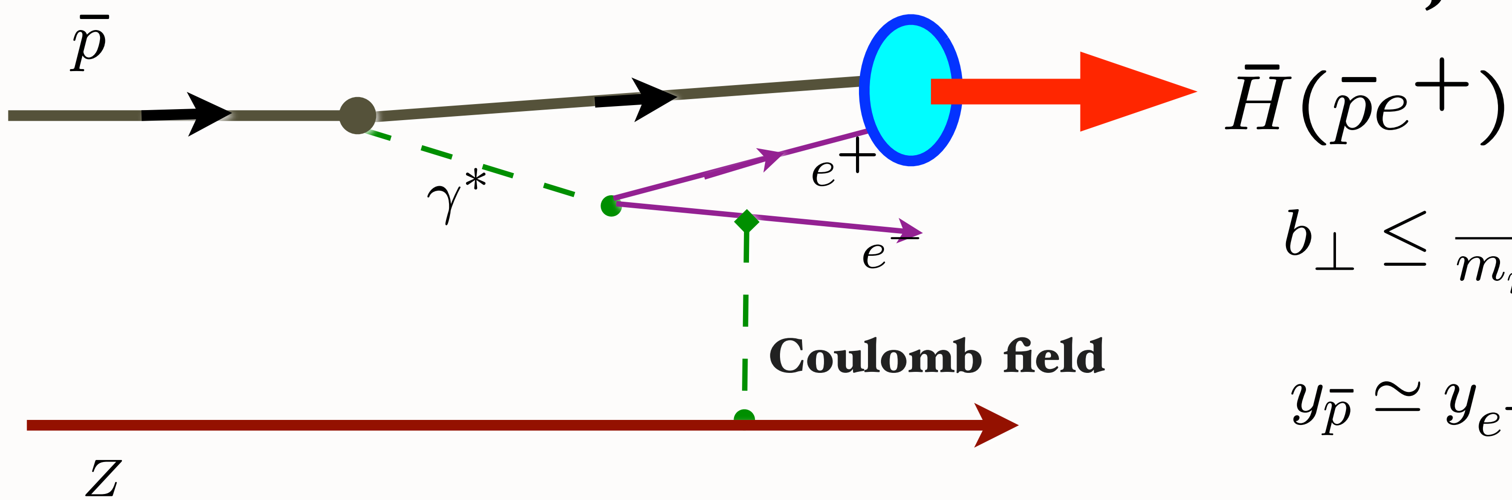



➟ To do: to look at the rates to see how competitive this will be

# Formation of Relativistic Anti-Hydrogen

**Measured at CERN-LEAR and FermiLab**

**Munger, Schmidt, sjb**




$$b_\perp \leq \frac{1}{m_{red}\alpha}$$

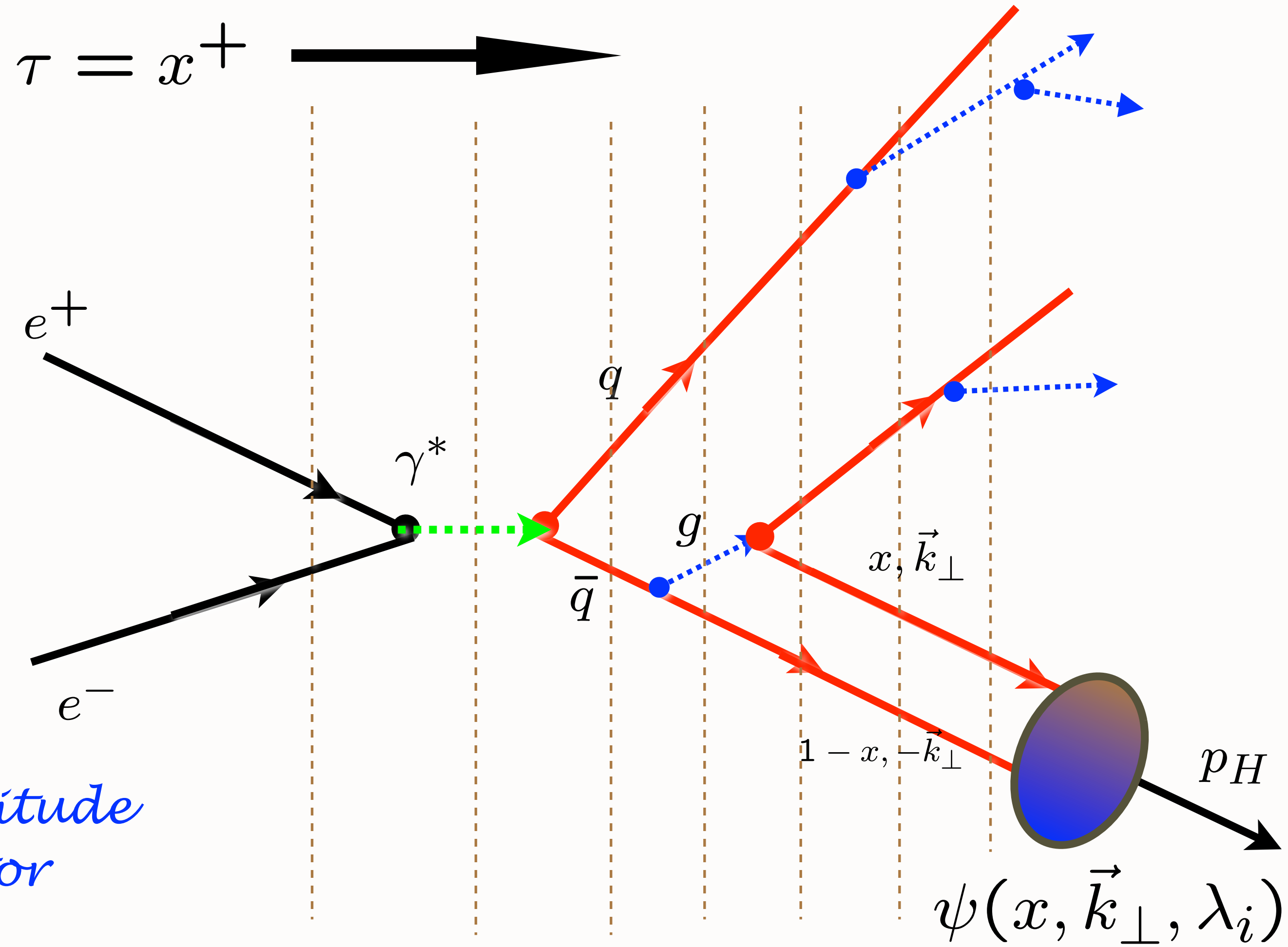
$$y_{\bar{p}} \simeq y_{e^+}$$

*Coalescence of* off-shell *co-moving positron and antiproton*

***Wavefunction maximal at small impact separation and equal rapidity***

"Hadronization" at the Amplitude Level

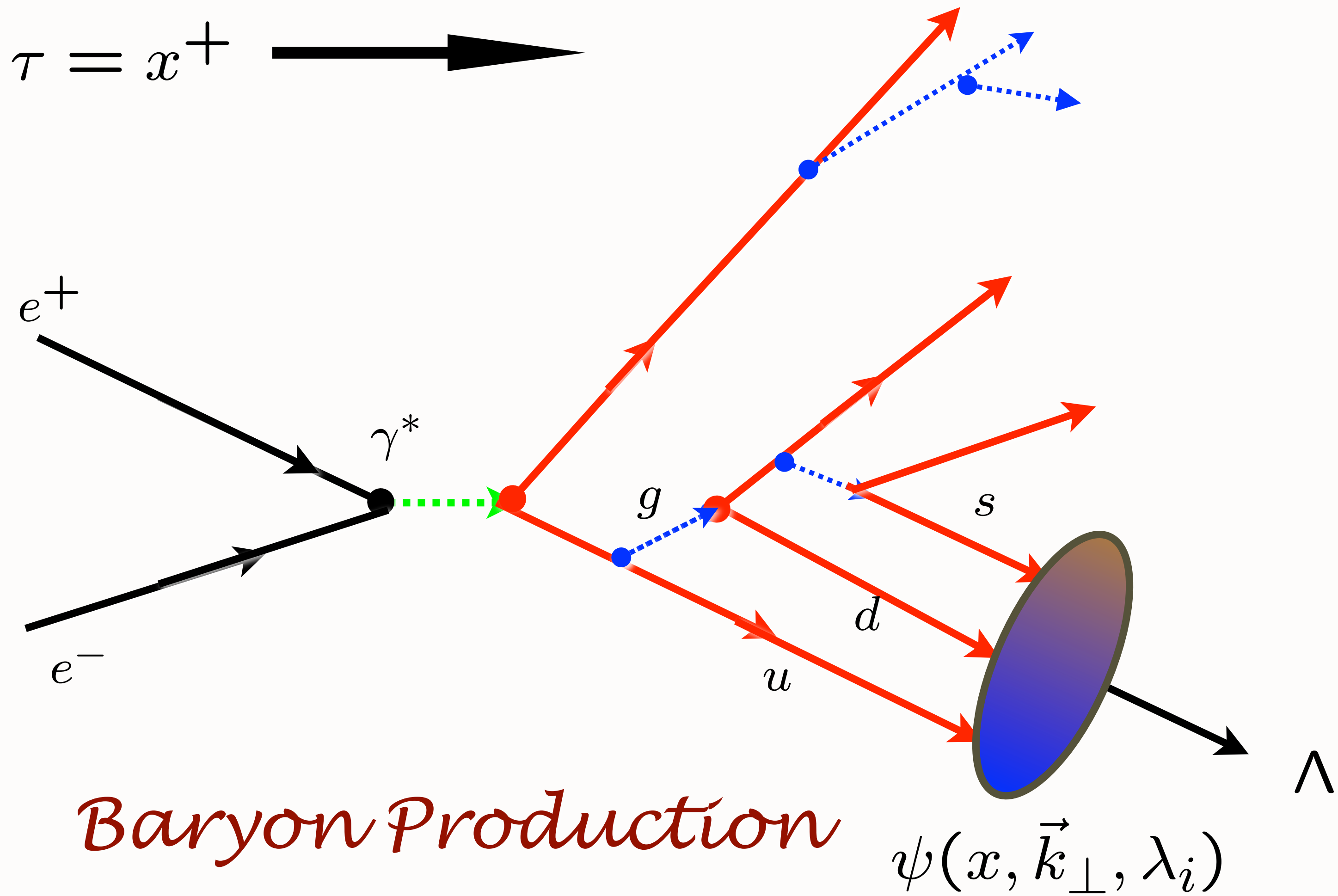
# Hadronization at the Amplitude Level




Event amplitude generator

**Construct helicity amplitude using Light-Front Perturbation theory; coalesce quarks via LFWFs**

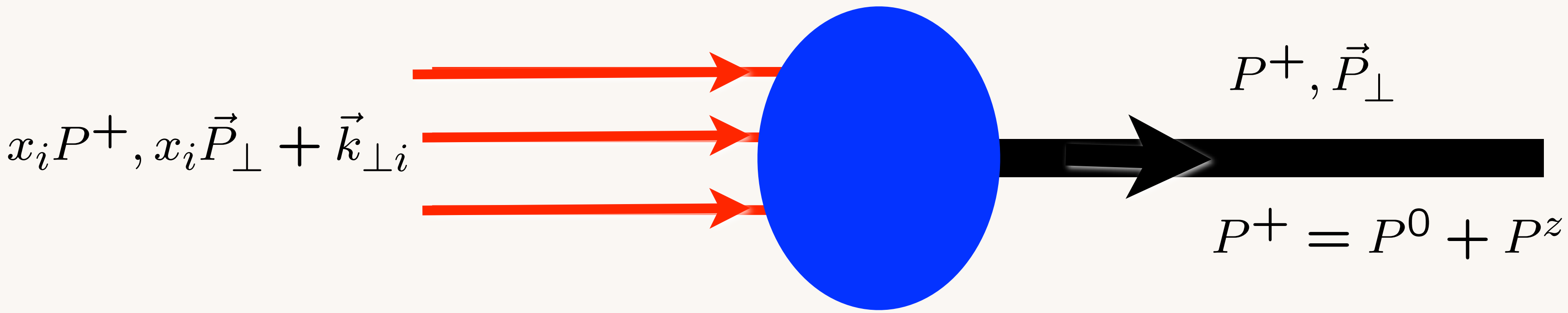
# Hadronization at the Amplitude Level



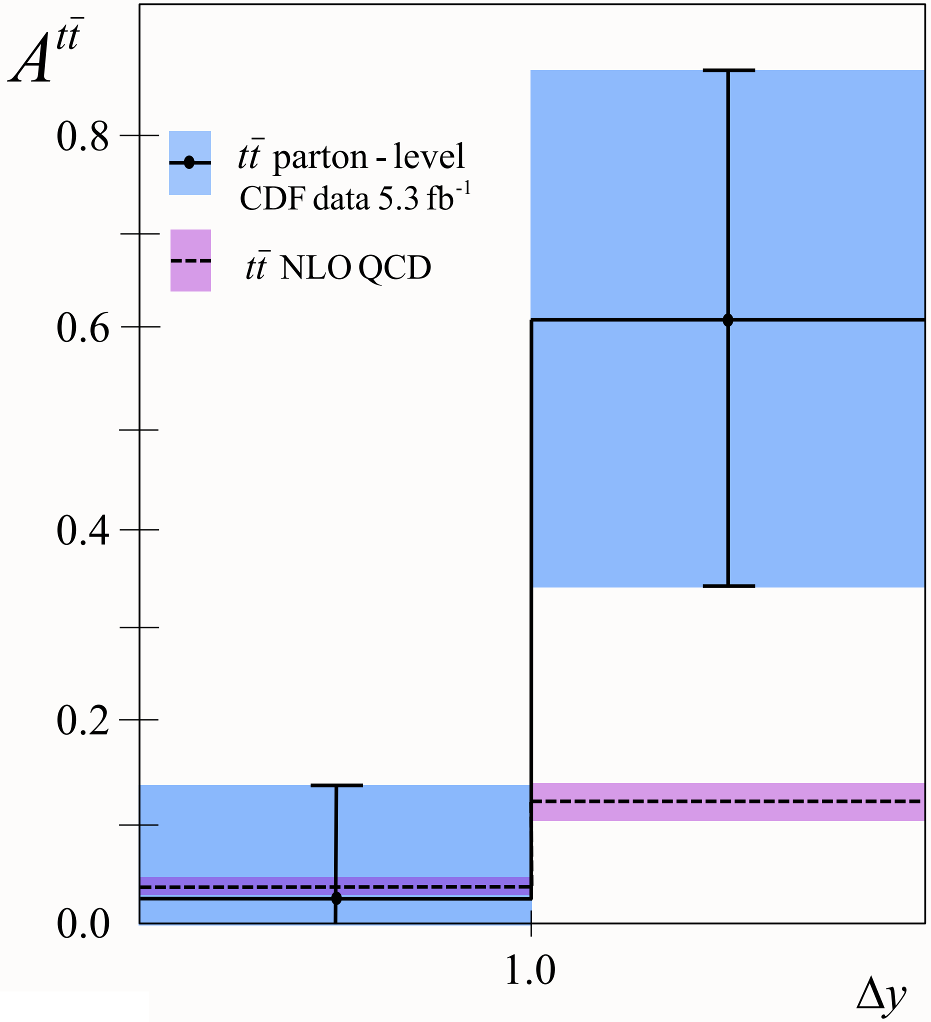

Construct helicity amplitude using Light-Front Perturbation theory; coalesce quarks via LFWFs

# Features of LF T-Matrix Formalism
## "Event Amplitude Generator"

- **Same principle as antihydrogen production: off-shell coalescence**
- **coalescence to hadron favored at equal rapidity, small transverse momenta**
- **leading heavy hadron production: D and B mesons produced at large z**
- **hadron helicity conservation if hadron LFWF has $L^z = 0$**
- **Baryon AdS/QCD LFWF has aligned and anti-aligned quark spin**



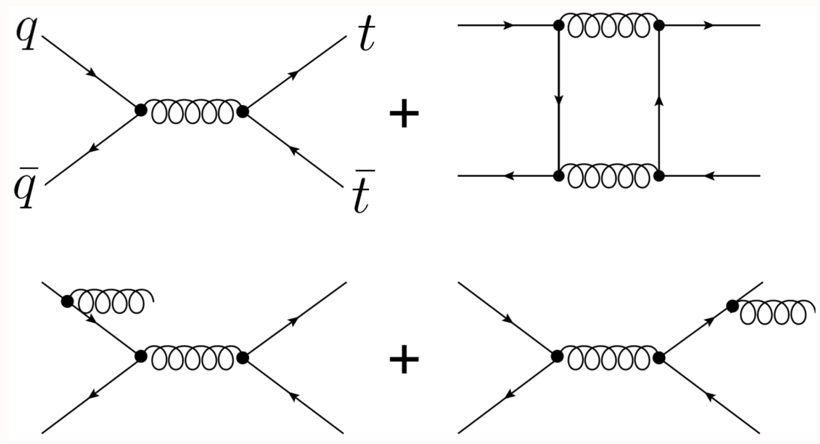
# Heavy Quark Asymmetries




$$A^{\mathrm{t\bar{t}}}(\Delta y_i) = \frac{N(\Delta y_i) - N(-\Delta y_i)}{N(\Delta y_i) + N(-\Delta y_i)}$$

Asymmetries in $\Delta y$ are identical to those in the $t$ production angle in the $t\bar{t}$ rest frame. We find a parton-level asymmetry of $A^{\mathrm{t\bar{t}}} = 0.158 \pm 0.075$ (stat+sys), which is somewhat higher than, but not inconsistent with, the NLO QCD expectation of $0.058 \pm 0.009$.

Parton level asymmetries at small and large $\Delta y$ compared to SM prediction of MCFM. The shaded bands represent the total uncertainty in each bin. The negative going uncertainty for $\Delta y < 1.0$ is suppressed.

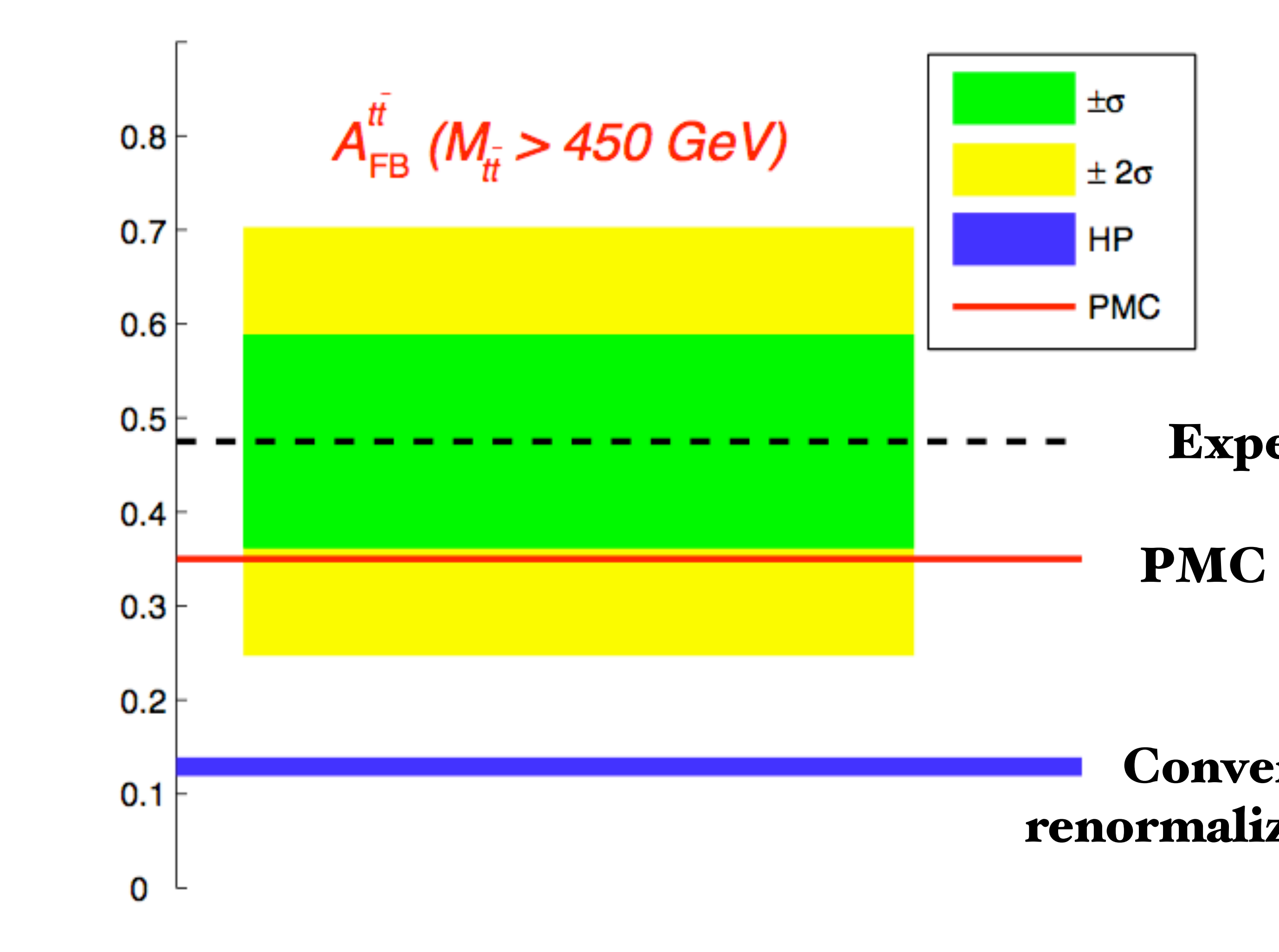



Fermilab-Pub-10-525-E

**Evidence for a Mass Dependent Forward-Backward Asymmetry in Top Quark Pair Production**

CDF Collaboration

*Eliminating the Renormalization Scale Ambiguity for Top-Pair Production Using the 'Principle of Maximum Conformality' (PMC)*





**Xing-Gang Wu**
**SJB**


**Experimental asymmetry**

**PMC Prediction**

**Conventional: guess for renormalization scale and range**

$t\bar{t}$ asymmetry predicted by pQCD NNLO within 1 $\sigma$ of CDF/D0 measurements using PMC/BLM scale setting

# Need to set multiple renormalization scales -- Lensing, DGLAP, ERBL Evolution ...

*Choose renormalization scheme; e.g.* $\alpha_s^R(\mu_R^{\rm init})$

↓

*Choose* $\mu_R^{init}$*; arbitrary initial renormalization scale*

↓

*Identify* $\{\beta_i^R\}$ *− terms using* $n_f$ *− terms*

*through the PMC − BLM correspondence principle*

↓

*Shift scale of* $\alpha_s$ *to* $\mu_R^{\rm PMC}$ *to eliminate* $\{\beta_i^R\}$ *− terms*

↓

*Conformal Series*

*Result is independent of* $\mu_R^{\rm init}$ *and scheme at fixed order*

## PMC/BLM

**No renormalization scale ambiguity!**

**Result is independent of Renormalization scheme and initial scale!**

**Same as QED Scale Setting**

**Apply to Evolution kernels, hard subprocesses**

**Eliminates unnecessary systematic uncertainty**

**Xing-Gang Wu**
**Leonardo di Giustino, SJB**

*Principle of Maximum Conformality*

$$\mathcal{M}_{ee\to ee}(++;++) = \frac{8\pi s}{t}\,\alpha(t) + \frac{8\pi s}{u}\,\alpha(u)$$

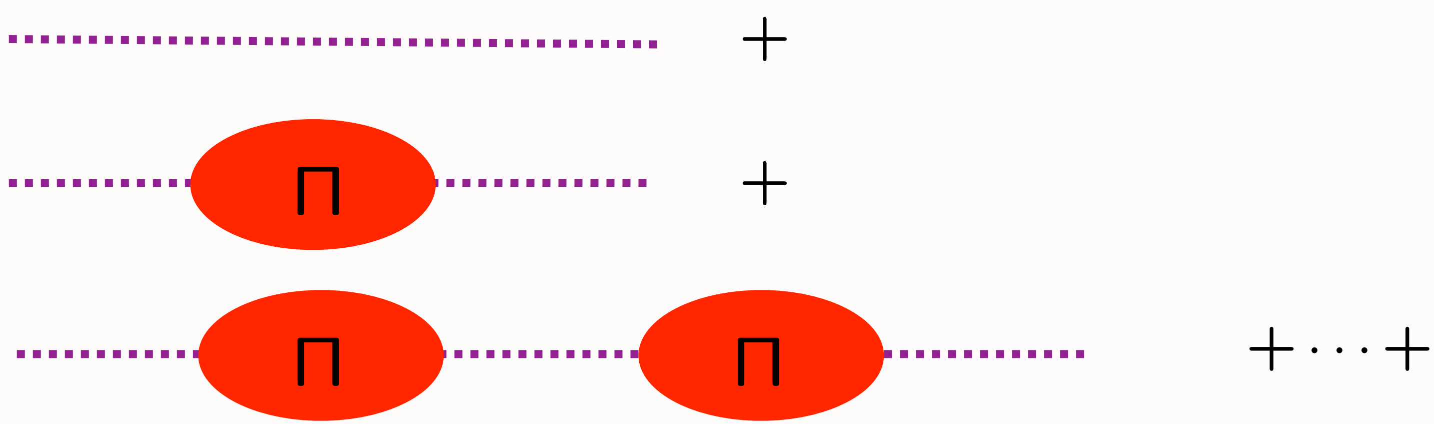

$$\alpha(t) = \frac{\alpha(0)}{1-\Pi(t)}$$

**Gell-Mann--Low Effective Charge**

# QED Effective Charge

$$\alpha(t) = \frac{\alpha(0)}{1 - \Pi(t)}$$

*All-orders lepton-loop corrections to dressed photon propagator*

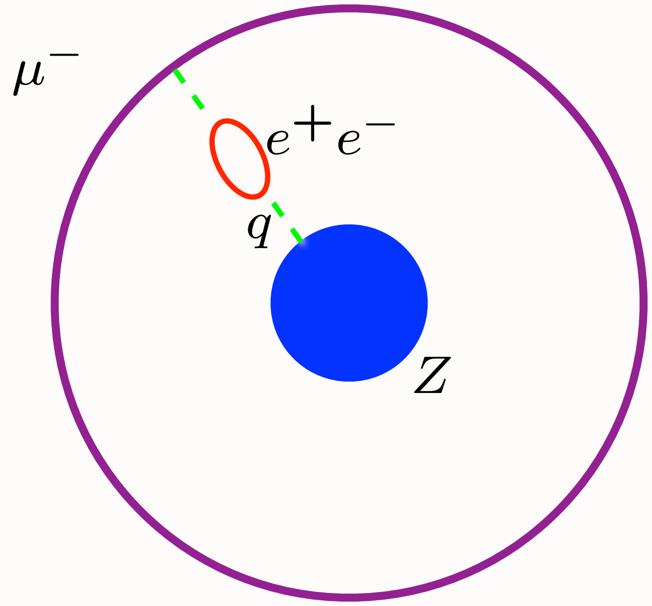



$$\alpha(t) = \frac{\alpha(t_0)}{1 - \Pi(t, t_0)}$$

$$\Pi(t, t_0) = \frac{\Pi(t) - \Pi(t_0)}{1 - \Pi(t_0)}$$

***Initial*** **scale $t_0$ is arbitrary -- Variation gives RGE Equations**
**Physical renormalization scale t not arbitrary!**

# Another Example in QED: Muonic Atoms




$$V(q^2) = -\frac{Z\alpha_{QED}(q^2)}{q^2}$$

$$\mu_R^2 \equiv q^2$$

$$\alpha_{QED}(q^2) = \frac{\alpha_{QED}(0)}{1-\Pi(q^2)}$$

**Scale is unique: Tested to ppm**

Gyulassy: Higher Order VP verified to 0.1% precision in $\mu$ Pb

# *Myths concerning scale setting*

- Renormalization scale "unphysical": No optimal physical scale
- Can ignore possibility of multiple physical scales
- Accuracy of PQCD prediction can be judged by taking arbitrary guess with an arbitrary range
- Factorization scale should be taken equal to renormalization scale

$$\mu_F = \mu_R$$

**Guessing the scale: Wrong in QED. Scheme dependent!**

# Features of BLM/PMC Scale Setting

**On The Elimination Of Scale Ambiguities In Perturbative Quantum Chromodynamics.**

**Lepage, Mackenzie, sjb** Phys.Rev.D28:228,1983

- **"Principle of Maximum Conformality"** **Di Giustino, Mojaza, Wu, sjb**
- **All terms associated with nonzero beta function summed into running coupling**
- **Standard procedure in QED**
- **Resulting series identical to conformal series**
- **Renormalon n! growth of PQCD coefficients from beta function eliminated!**
- *Scheme Independent* **!!!**
- **In general, BLM/PMC scales depend on all invariants**
- **Single Effective PMC scale at NLO**

# QCD Observables

$$\mathcal{O} = C(\alpha_s(\mu_0^2)) + B(\beta \log \frac{Q^2}{\mu_0^2}) + D(\frac{m_q^2}{Q^2}) + E(\frac{\Lambda^2_{QCD}}{Q^2}) + F(\frac{\Lambda^2_{QCD}}{m_Q^2}) + G(\frac{m_q^2}{m_Q^2})$$

**Scale-Free Conformal Series**

**Running Coupling Effects**

**Higher Twist from Hadron Dynamics**

**Intrinsic Heavy Quarks**

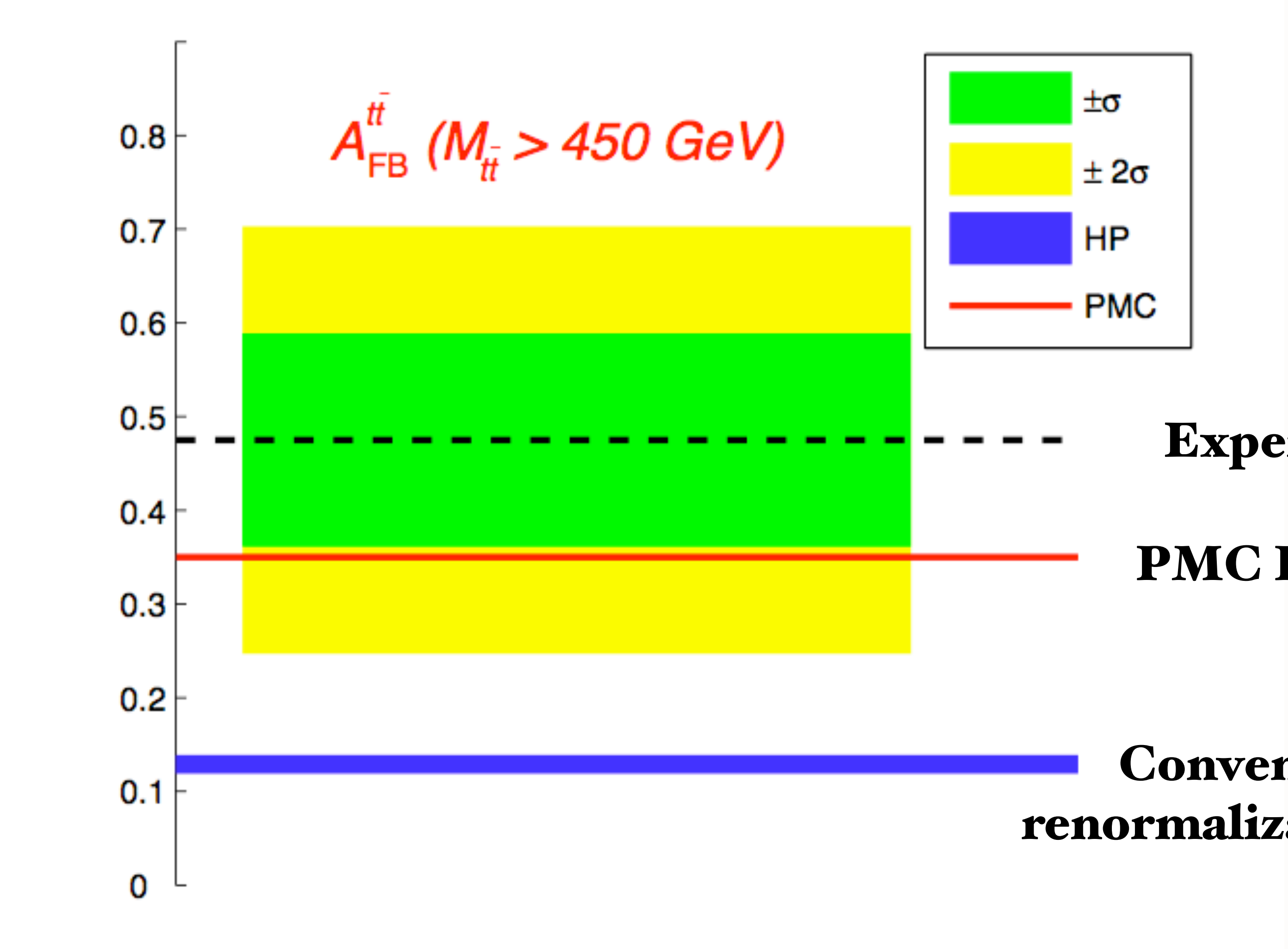
**Light by Light Loops**

***BLM/PMC: Absorb β-terms into running coupling***

$$\mathcal{O} = C(\alpha_s(Q^{*2})) + D(\frac{m_q^2}{Q^2}) + E(\frac{\Lambda^2_{QCD}}{Q^2}) + F(\frac{\Lambda^2_{QCD}}{m_Q^2}) + G(\frac{m_q^2}{m_Q^2})$$

***AFTER***

# *Eliminating the Renormalization Scale Ambiguity for Top-Pair Production Using the 'Principle of Maximum Conformality' (PMC)*




**Xing-Gang Wu**
**SJB**

**Experimental asymmetry**

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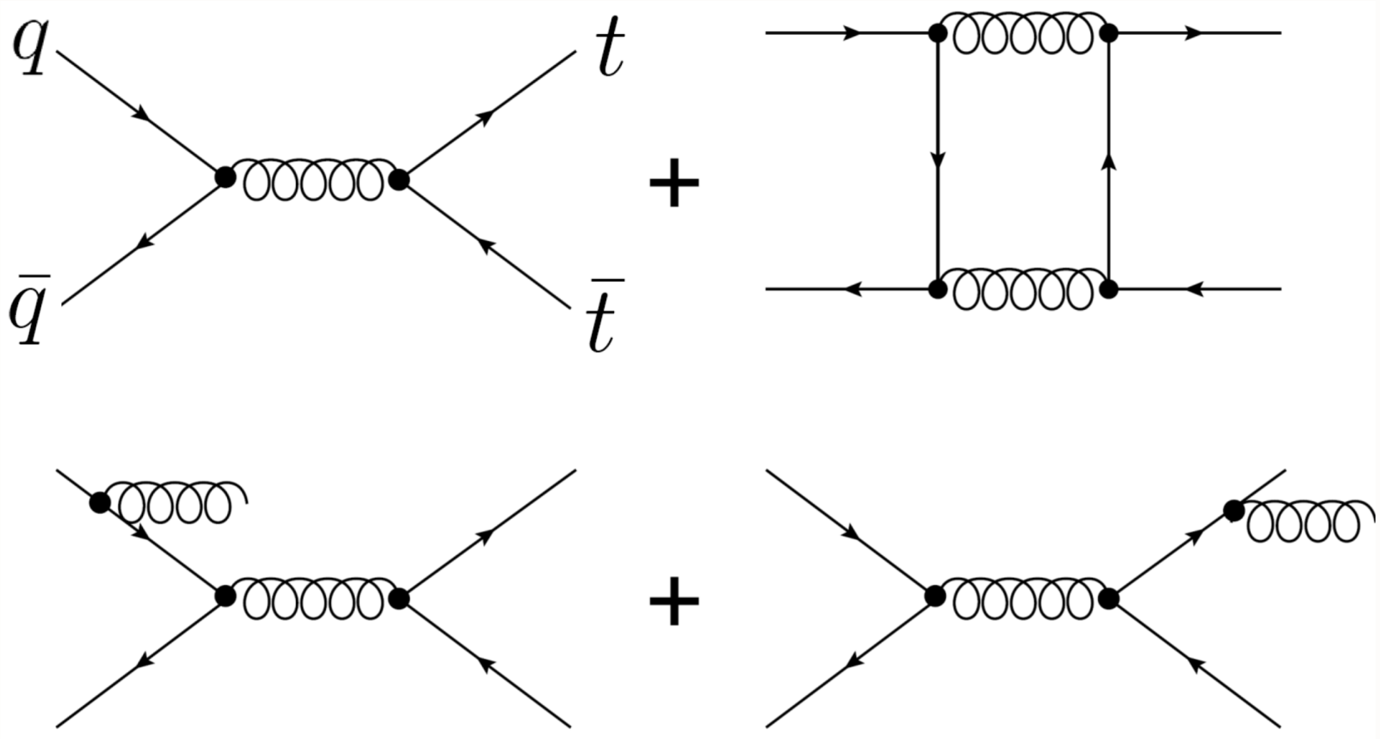
**Conventional: guess for renormalization scale and range**

$t\bar{t}$ asymmetry predicted by pQCD NNLO within 1 $\sigma$ of CDF/D0 measurements using PMC/BLM scale setting

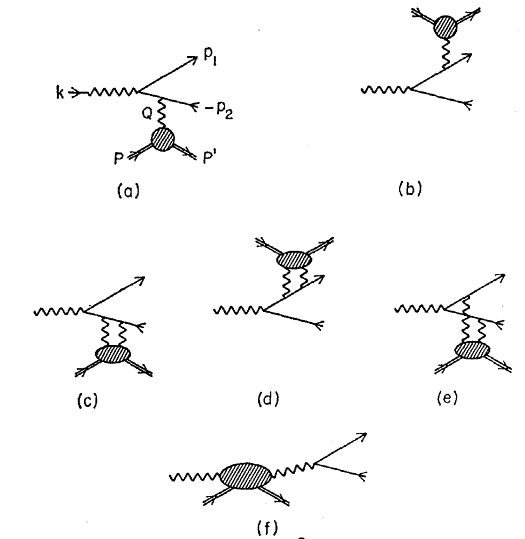


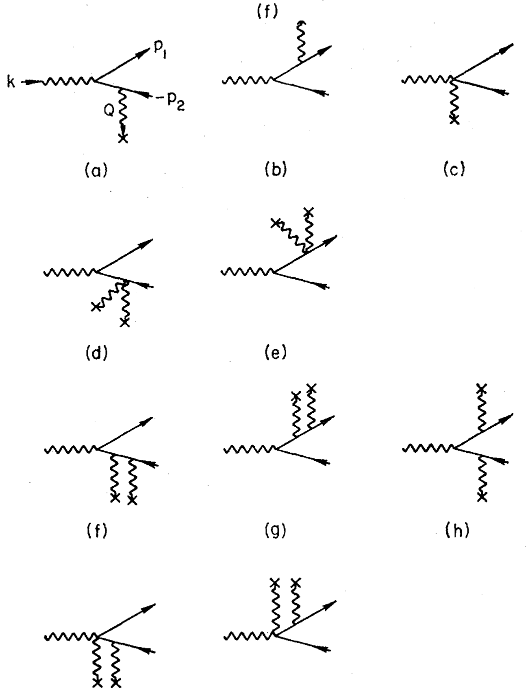

Conventional pQCD approach

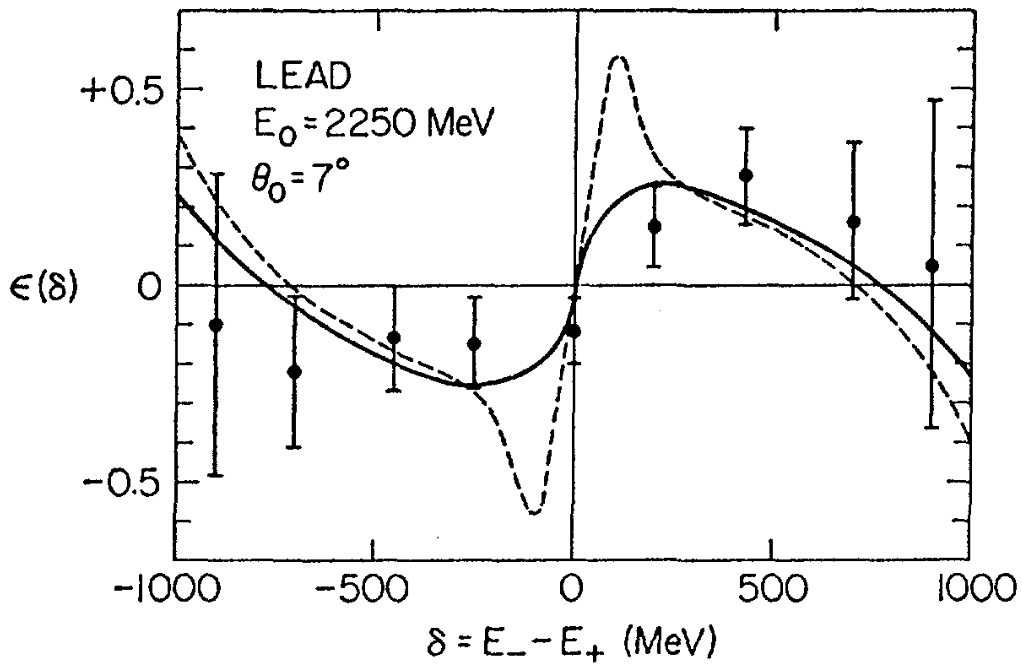
# Second Born Corrections to Wide-Angle High-Energy Electron Pair Production and Bremsstrahlung*

J. Gillespie and sjb

PR 173 1011 (1968)




[4] J. G. Asbury, W. K. Bertram, U. Becker, P. Joos, M. Rohde, A. J. S. Smith, S. Friedlander, C. L. Jordan, and S. C. C. Ting, Phys. Rev. **161**, 1344 (1967), and references therein.

$$\mathcal{R} \equiv \frac{d\sigma_{\rm int}}{d\sigma_{\rm Born}} = \tfrac{1}{4} Z\alpha\pi |\mathbf{Q}| \times \left[\frac{(E_2 - E_1)Q^2 + 2E_2 k\cdot p_2 - 2E_1 k \cdot p_1}{E_1 E_2 Q^2 + (k\cdot p_1)(k\cdot p_2)}\right] + O(Z\alpha)^3$$

(spin zero, point nucleus). (4.9)

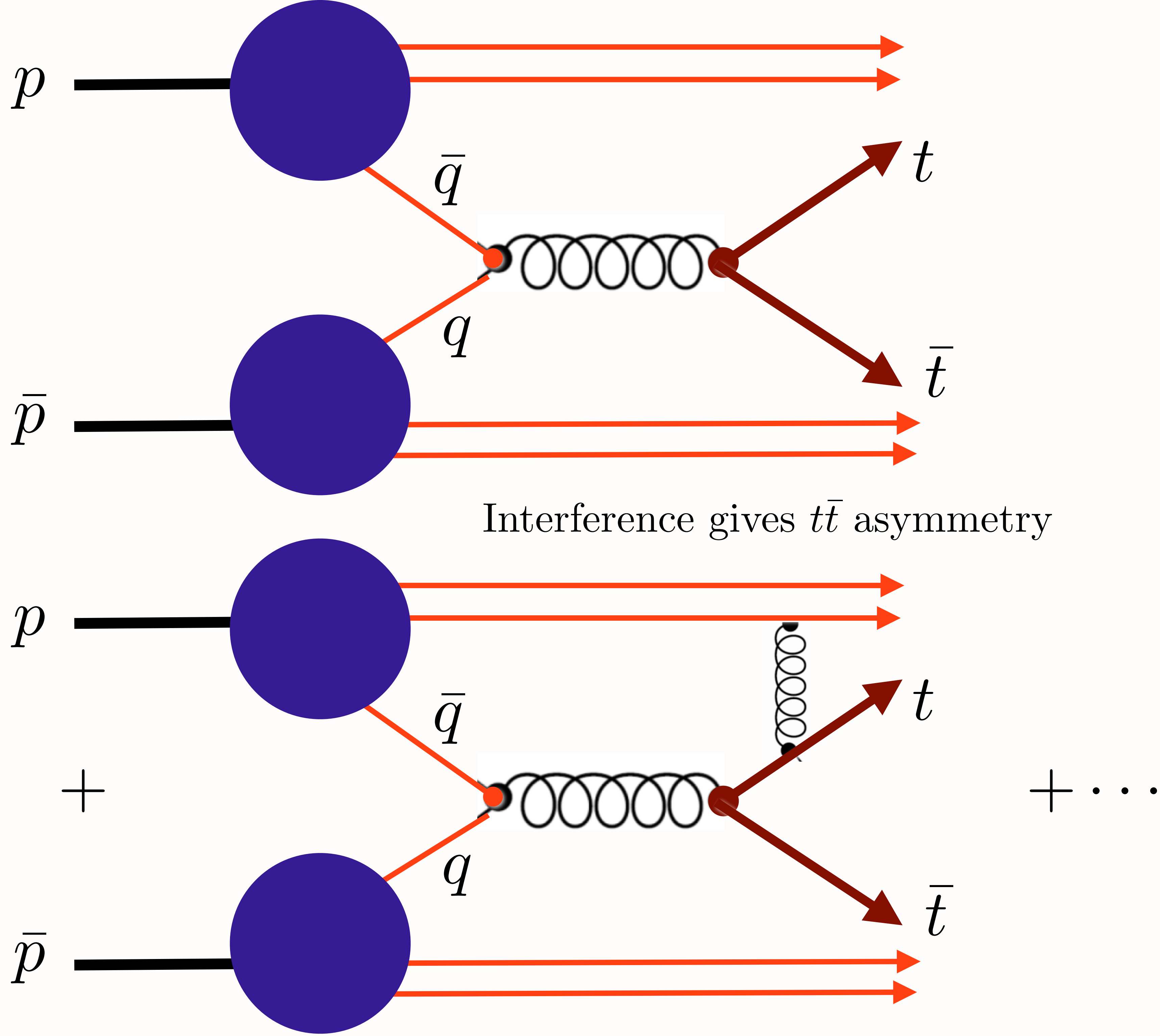
# *QCD Analysis of heavy quark asymmetries*

B. von Harling, Y. Zhao, sjb

- **Include Radiation Diagrams**
- **FSI similar to Sivers Effect**

$$\pi Z\alpha \longrightarrow \pi C_F \alpha_s$$

- **Renormalization scale relatively soft**



$p$
$\bar{q}$
$t$
$q$
$\bar{t}$
$\bar{p}$
Interference gives $t\bar{t}$ asymmetry
$p$
$\bar{q}$
$t$
$+$
$+\cdots$
$q$
$\bar{t}$
$\bar{p}$

# *QCD Analysis of heavy quark asymmetries*

B. von Harling, Y. Zhao, sjb

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# QCD Myths

- Anti-Shadowing is Universal
- ISI and FSI are higher twist effects and universal
- High transverse momentum hadrons arise only from jet fragmentation -- baryon anomaly!
- heavy quarks only from gluon splitting
- renormalization scale cannot be fixed
- QCD condensates are vacuum effects
- Infrared Slavery
- Nuclei are composites of nucleons only
- Real part of DVCS arbitrary



***AFTER***

# Fixed Target Physics with the LHC Beams

AFTER @ LHC

- 7 TeV proton beam, nuclear beams
- Full Range of Nuclear and Polarized Targets
- Cosmic Ray simulations!
- Single-Spin Asymmetries, Transversity Studies, $A_N$
- High-$x_F$ Dynamics
- High-$x_F$ Heavy Quark Phenomena
- Production of ccc to bbb baryons
- Quark-Gluon Plasma in Nuclear Rest System

# Fixed-Target Physics with the LHC Beams

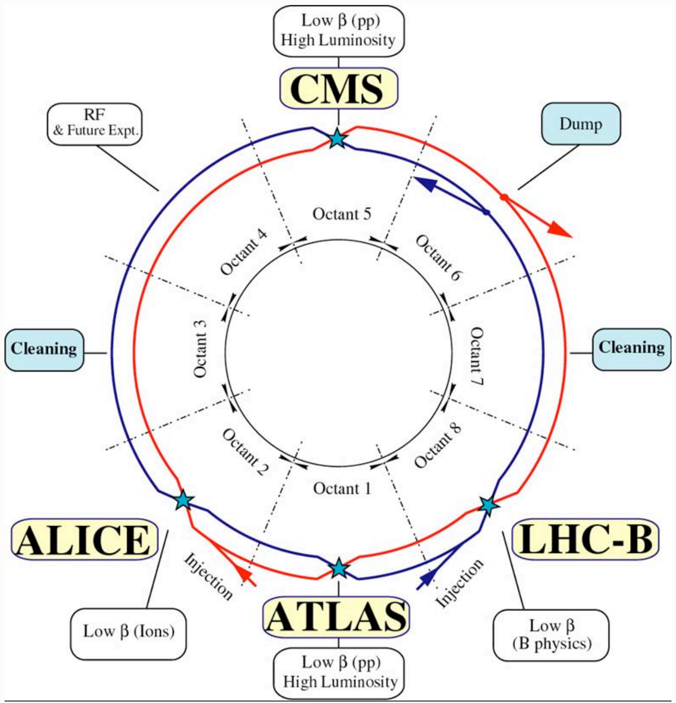
- 7 TeV proton beam, 3 TeV nuclear beams
- Full Range of Nuclear and Polarized Targets
- Cosmic Ray simulations
- Sterile Neutrinos -- Dark Matter Candidates
- Single-Spin Asymmetries, Transversity Studies, $A_N$
- High-$x_F$ Dynamics --Correlations, Diffraction
- High-$x_F$ Heavy Quark and quarkonium phenomena
- Production of ccq to ccc to bbb baryons
- Quark-Gluon Plasma in Nuclear Rest System:
  e.g. Ridge Physics at Extreme Rapidities
- Anti-Shadowing: Flavor Specific?
- Higgs at Threshold using nuclear Fermi motion

# Fixed Target Physics with the LHC Beams

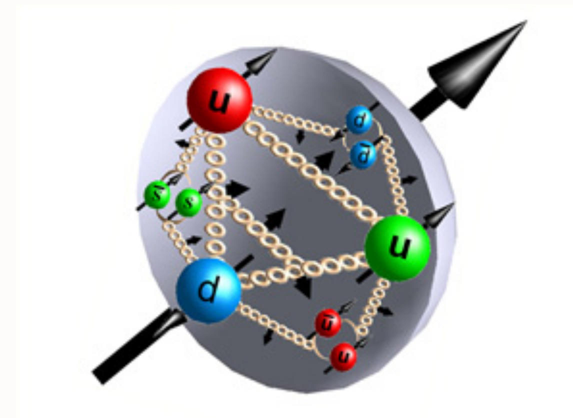
*AFTER @ LHC*

- **Many Novel QCD Effects never thoroughly investigated**
- **"Lensing" Effects: Exceptions to Factorization Theorems**
- **Violation of Scaling Laws**
- **Dynamic versus Static Structure Functions**
- **Production of charm, bottom and exotics**
- **Novel Nuclear Dynamics**
- **Novel Diffractive Processes**
- **High Rapidity: Maximal Spin, Flavor Correlations**
- **High AFTER energy domain well-matched to QCD**

# Physics Flagships for AFTER: Fixed Target ExpeRiments @ the LHC



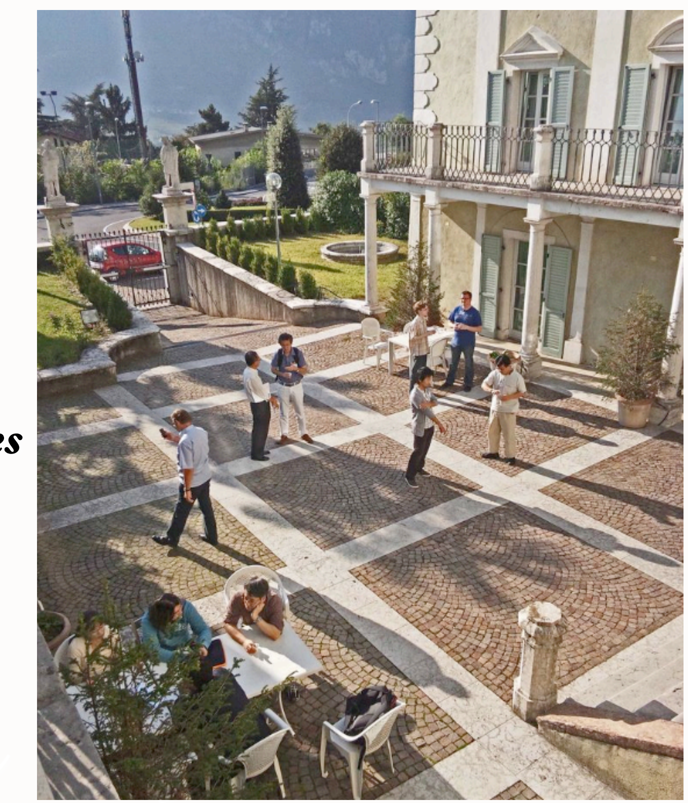

## AFTER @ LHC




### ECT* Workshop

**February 4-8, 2013**

*European Center for Theoretical Studies in Nuclear Physics and Related Areas*




Stan Brodsky



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