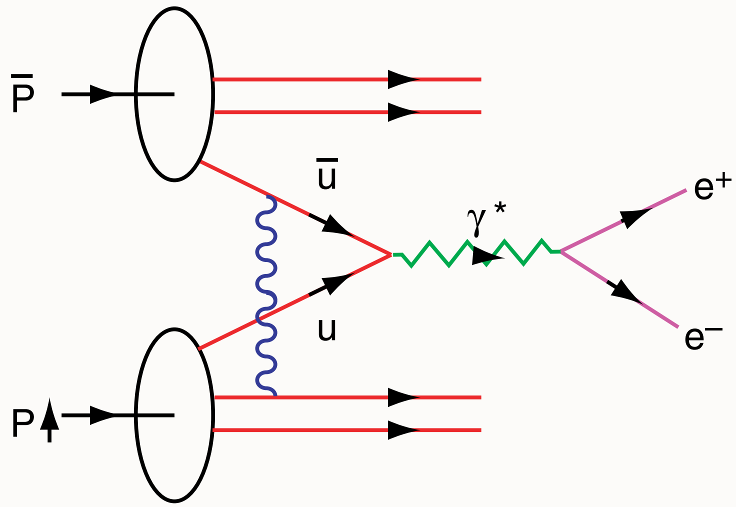
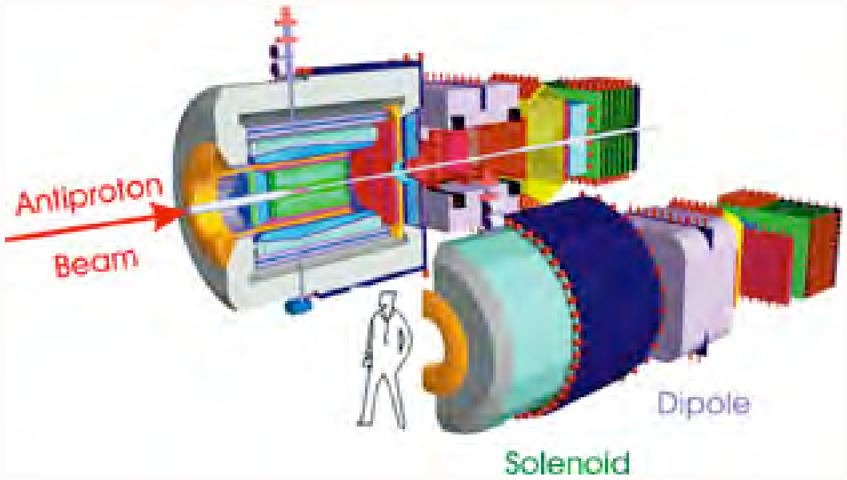
Novel Electromagnetic and QCD Physics at FAIR and New Insights from AdS/QCD

Stan Brodsky, SLAC

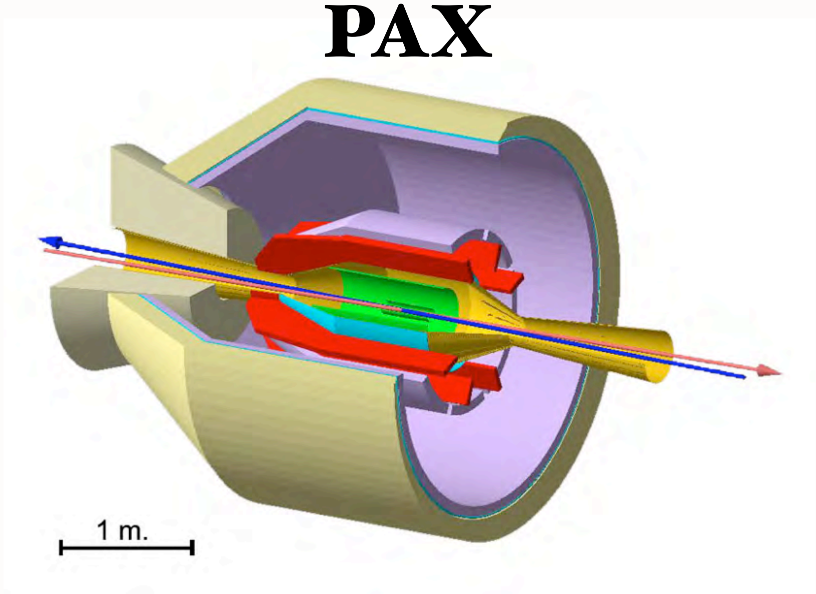


Ferrara Workshop on Electromagnetic Interactions at FAIR
October 15-16, 2007

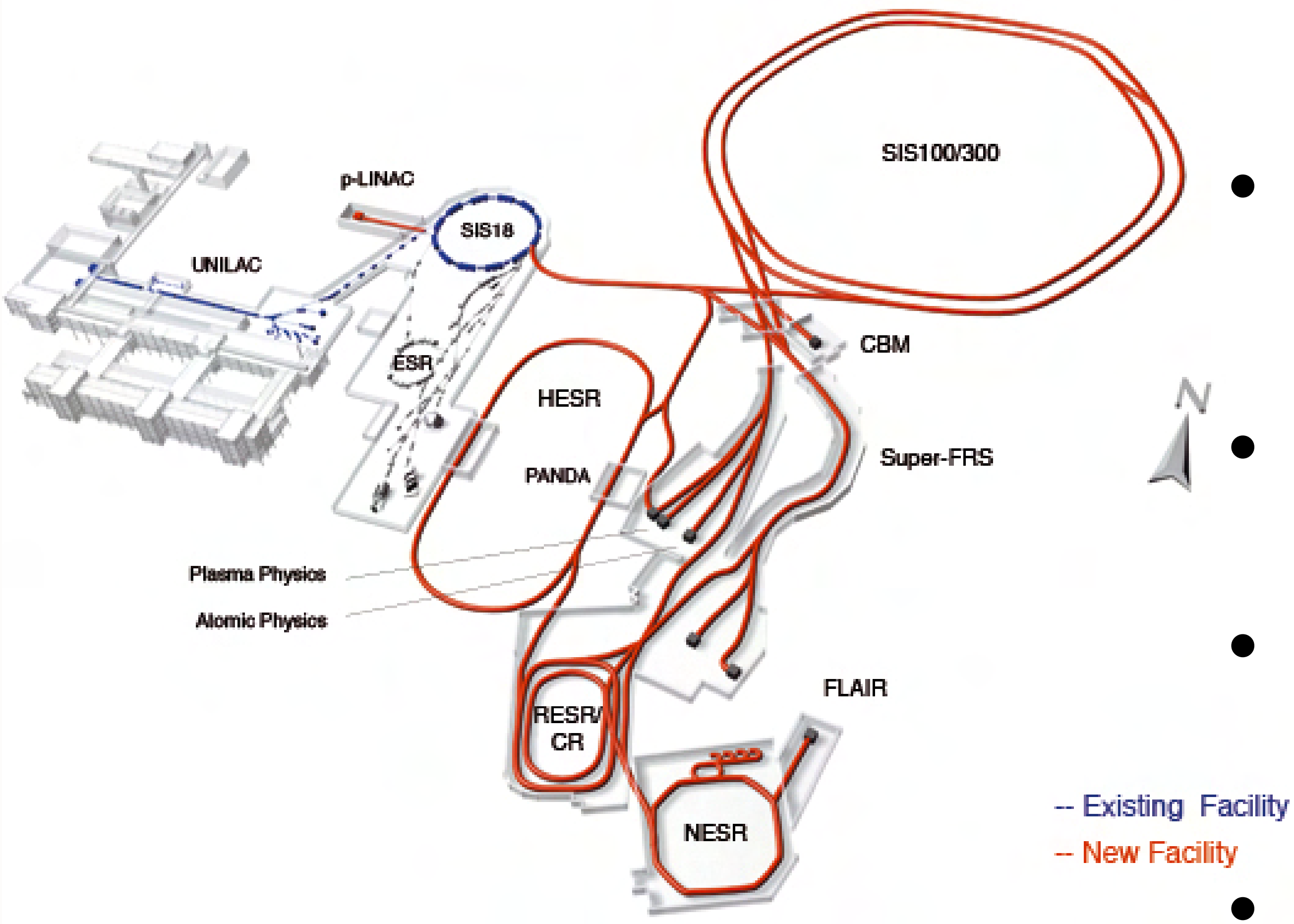
Panda



PAX



The anti-proton beam

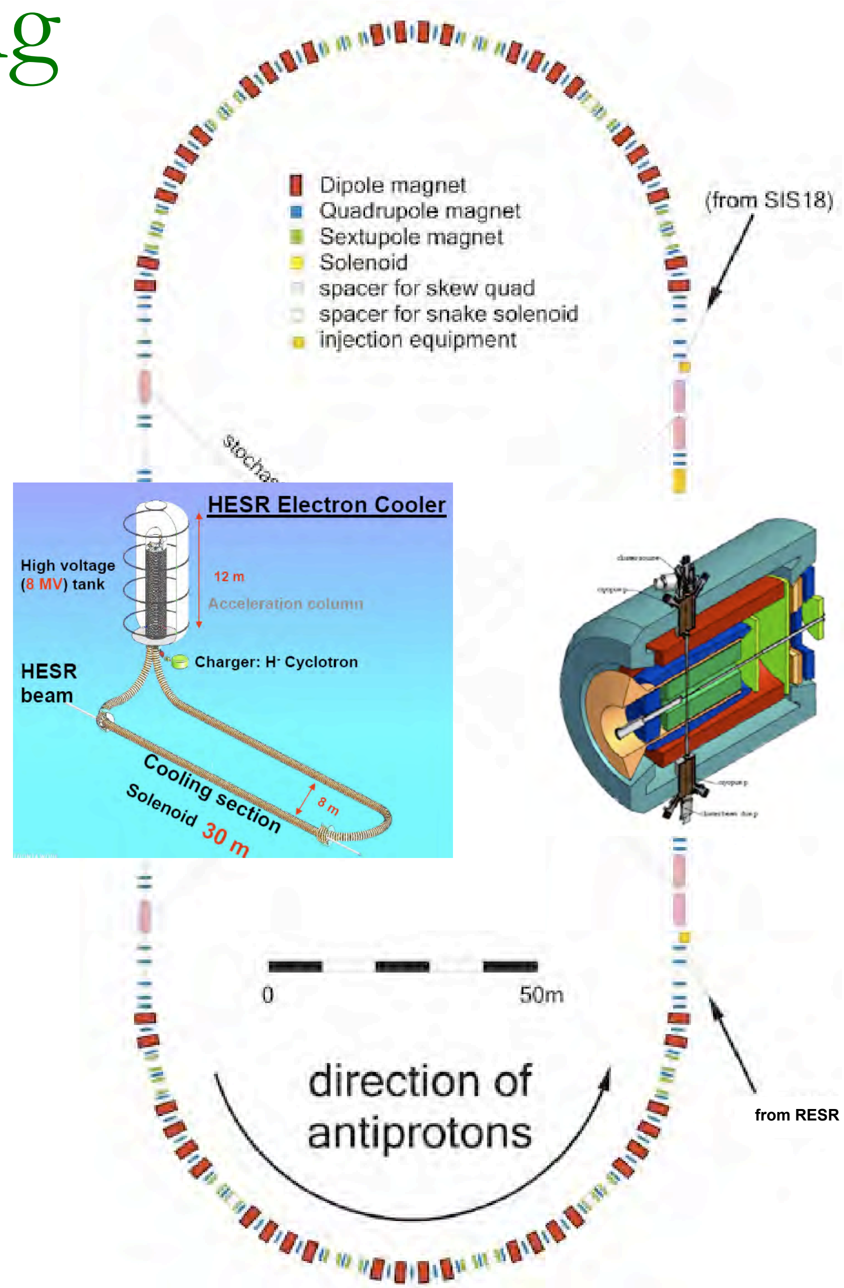


- Parallel operation for large physics programme
- FAIR will provide cooled anti-proton beams from 0 -15 GeV/c
- HESR: $N_p = 5 \times 10^{10}$
  1.5 GeV/c $< p_{beam} <$ 15 GeV/c
- High luminosity mode
  $\Delta p/p = 10^{-4}$ with stochastic cooling, $L = 10^{32} cm^{-2} s^{-1}$
- High precision mode
  $\Delta p/p = 3 \times 10^{-5}$ with electron cooling, $L = 10^{31} cm^{-2} s^{-1}$

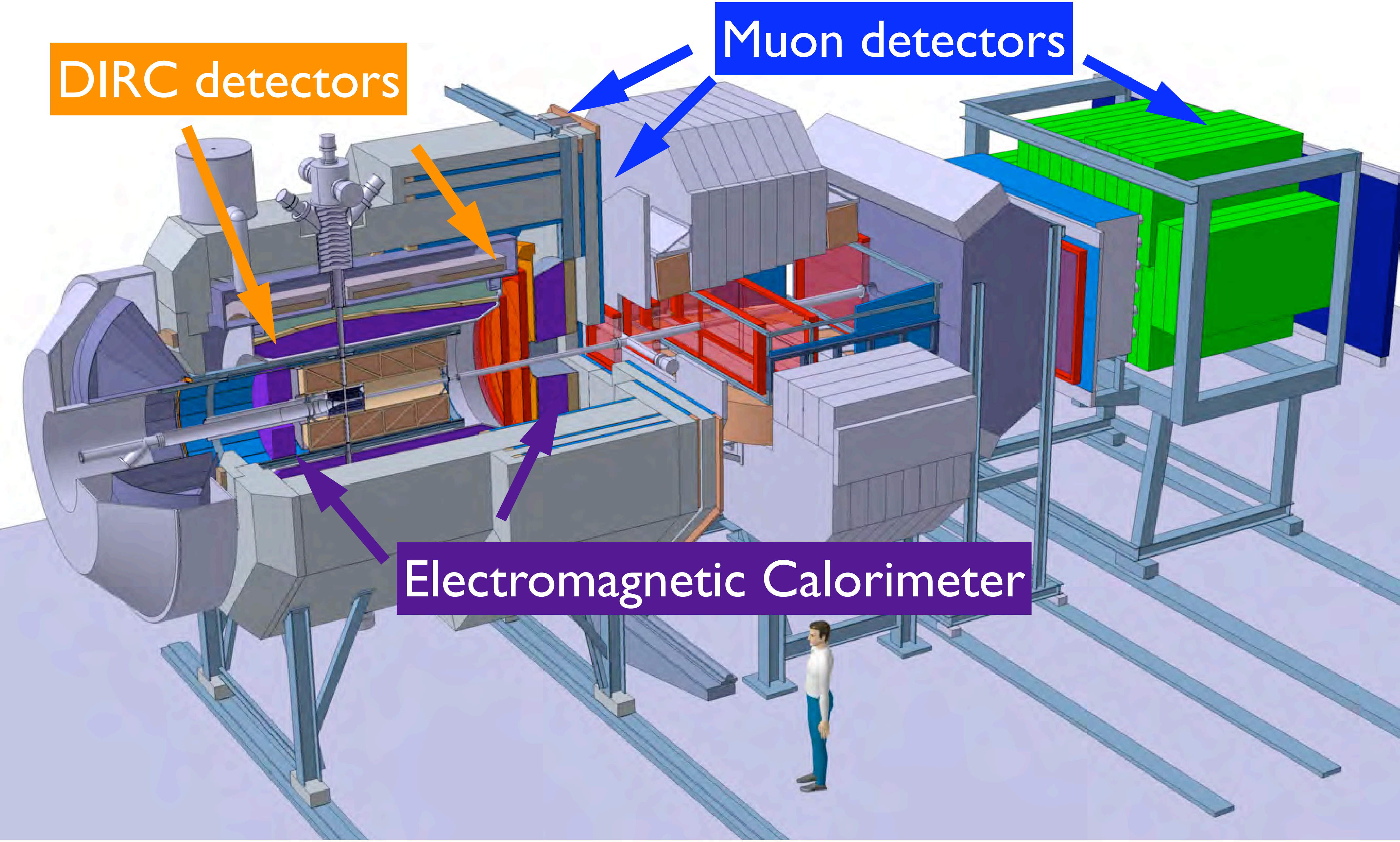
B. Seitz

High Energy Storage Ring

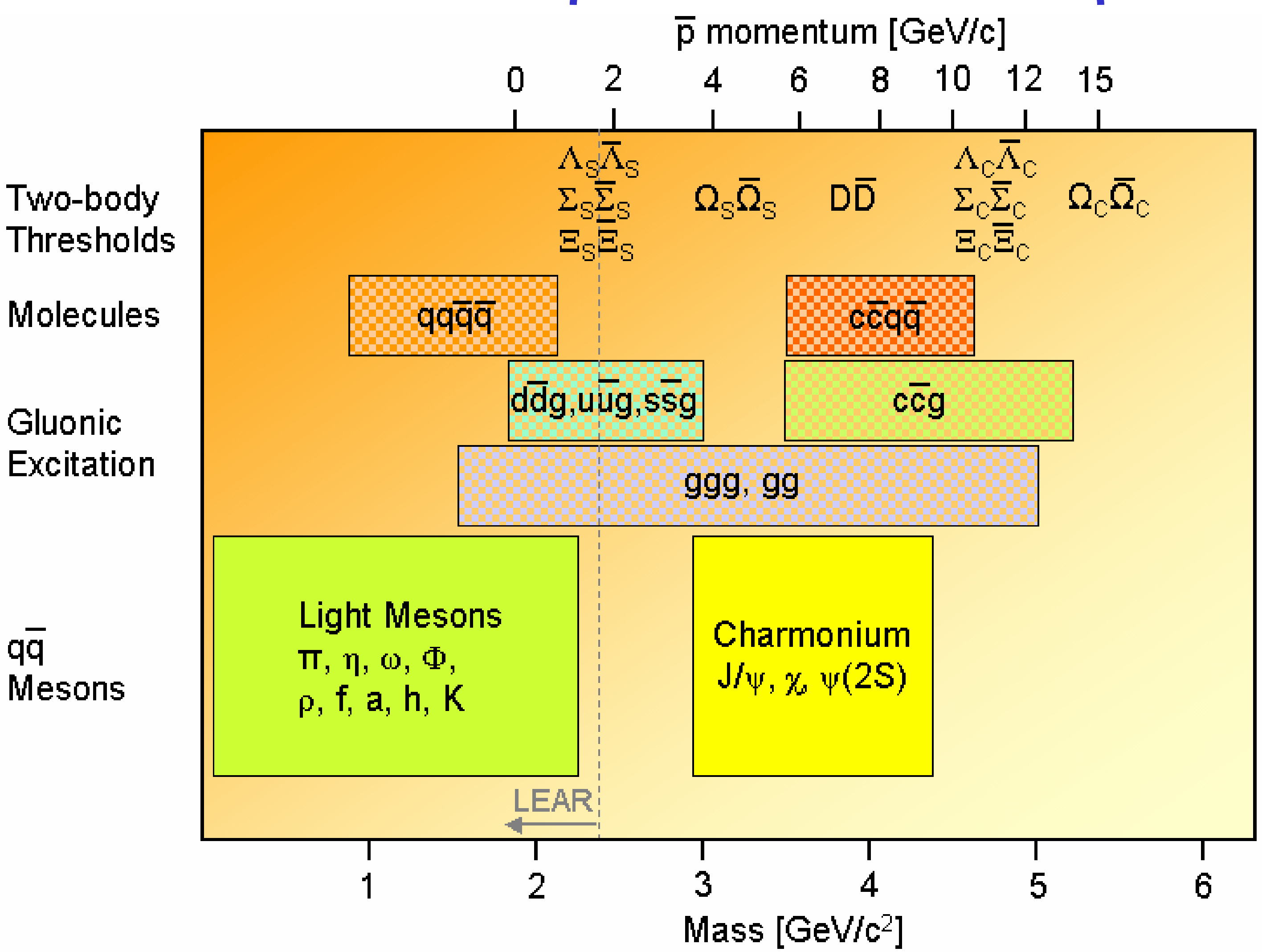
- Storage ring for p:
  - $N_p = 5\times10^{10}$, P_{beam}= 1.5-15 GeV/c;
- High density target:
  - pellet 10^{15} atoms/cm^3, cluster jet, wire;
- High luminosity mode:
  - $\Delta p/p = 10^{-4}$, stochastic cooling, $L = 10^{32}\ cm^{-2}s^{-1}$;
- High precision mode:
  - $\Delta p/p = 3\times10^{-5}$, electron cooling, $L = 10^{31}\ cm^{-2}s^{-1}$.



The PANDA Detector



Mass range of PANDA



- Production of open charm
- Charmed hybrids
- Glueballs
- Charmonium

Michael Düren

Search for exotic states

Naive Quark Model:

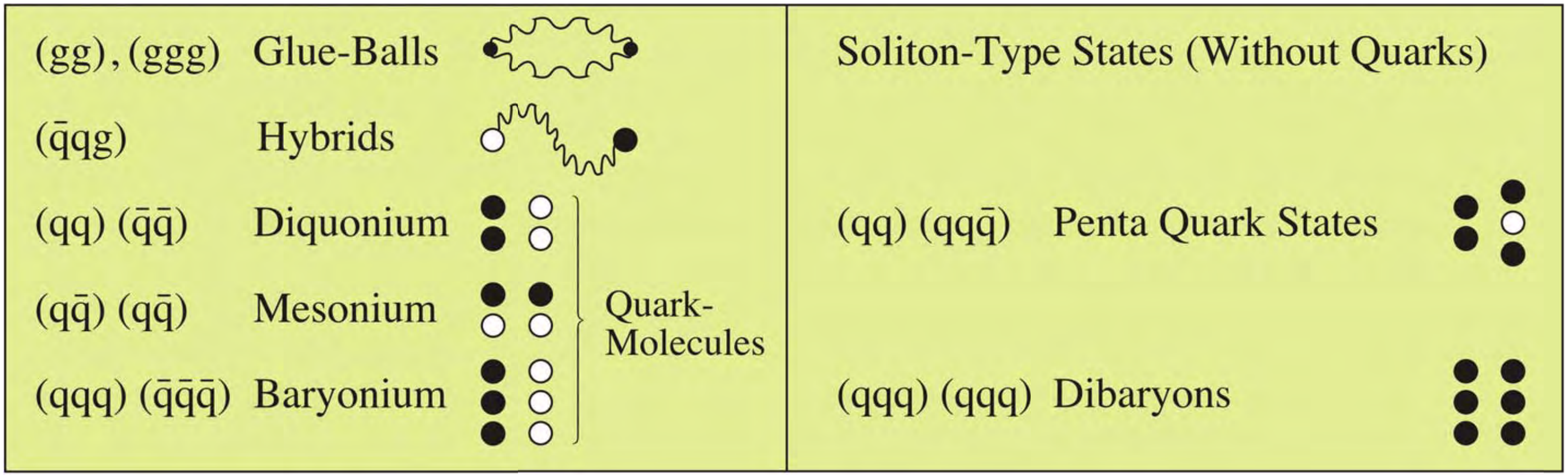
Mesons (Resonances) = $q\bar{q}$-states

Baryons (Resonances) = qqq-states

$$\bar{p}p \rightarrow \gamma + X[q\bar{q}\bar{q}q]$$

LQCD + Model calculations:

Existence of exotic states



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New feature:

Spin-exotic quantum numbers possible, not allowed in $\bar{q}q$ ($J^{PC} = 0^{+-}, 1^{-+}, \ldots$)

Why antiprotons?

Merits of antiprotons in hadron spectroscopy

- In $p\bar{p}$ -annihilation all mesons can be formed

Formation:

$\bar{p}p \rightarrow \chi_{1,2}$
$\quad\hookrightarrow \gamma\, J/\psi$
$\quad\quad\hookrightarrow \gamma\, e^+e^-$

- In e^+e^--annihilation only $J^{PC}=1^{--}$ mesons can be formed directly

Production:

$e^+e^- \rightarrow \psi'$
$\quad\hookrightarrow \gamma\, \chi_{1,2}$
$\quad\quad\hookrightarrow \gamma\,\gamma\, J/\psi$
$\quad\quad\quad\hookrightarrow \gamma\,\gamma\, e^+e^-$

- The comparison of results from e^+e^- and $p\bar{p}$ experiments allows important information about the quark and gluon content and the production mechanisms

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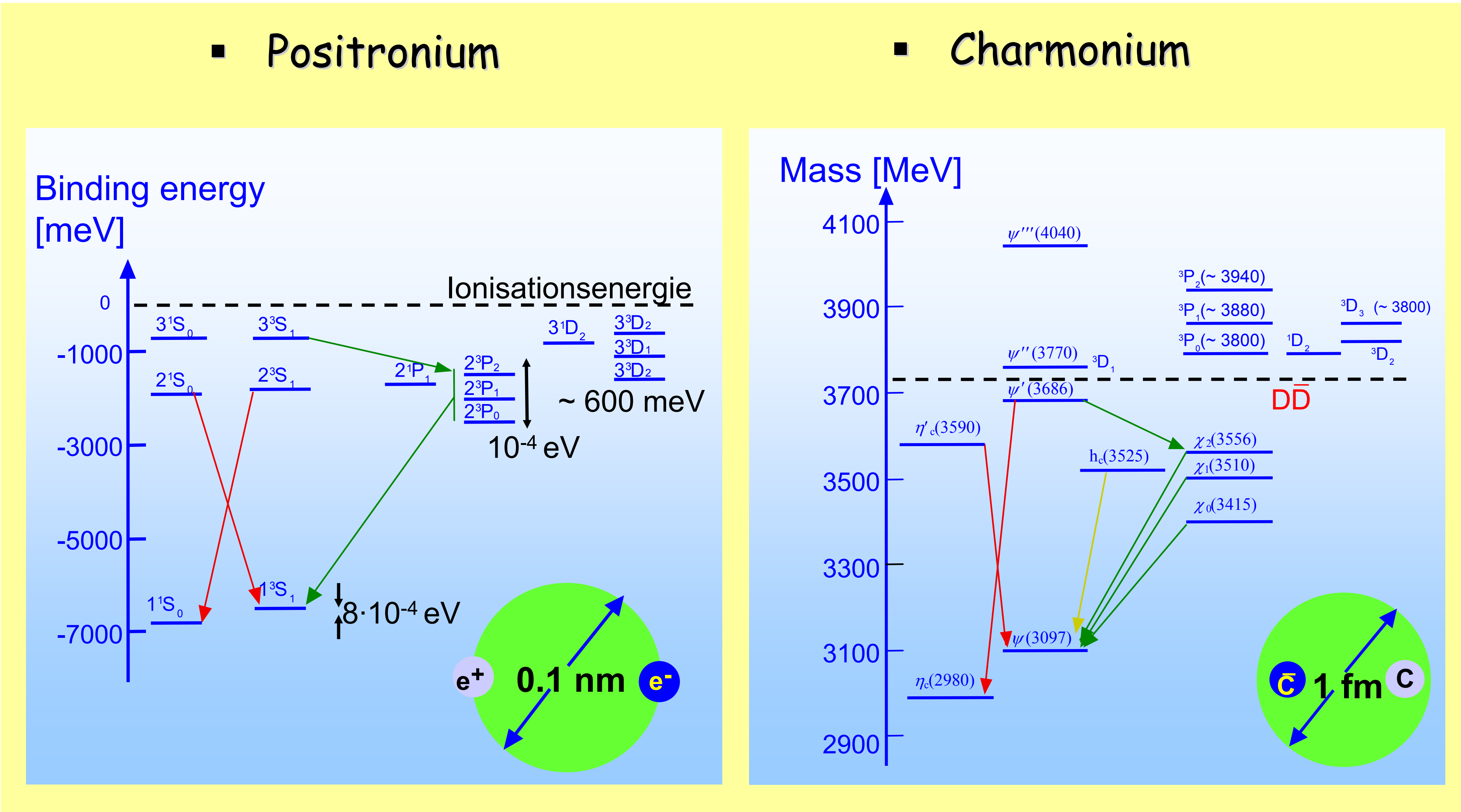
Charmonium – the Positronium of QCD



- Precision measurements of masses, widths and branching ratios
- Test of QCD and relativistic potential models

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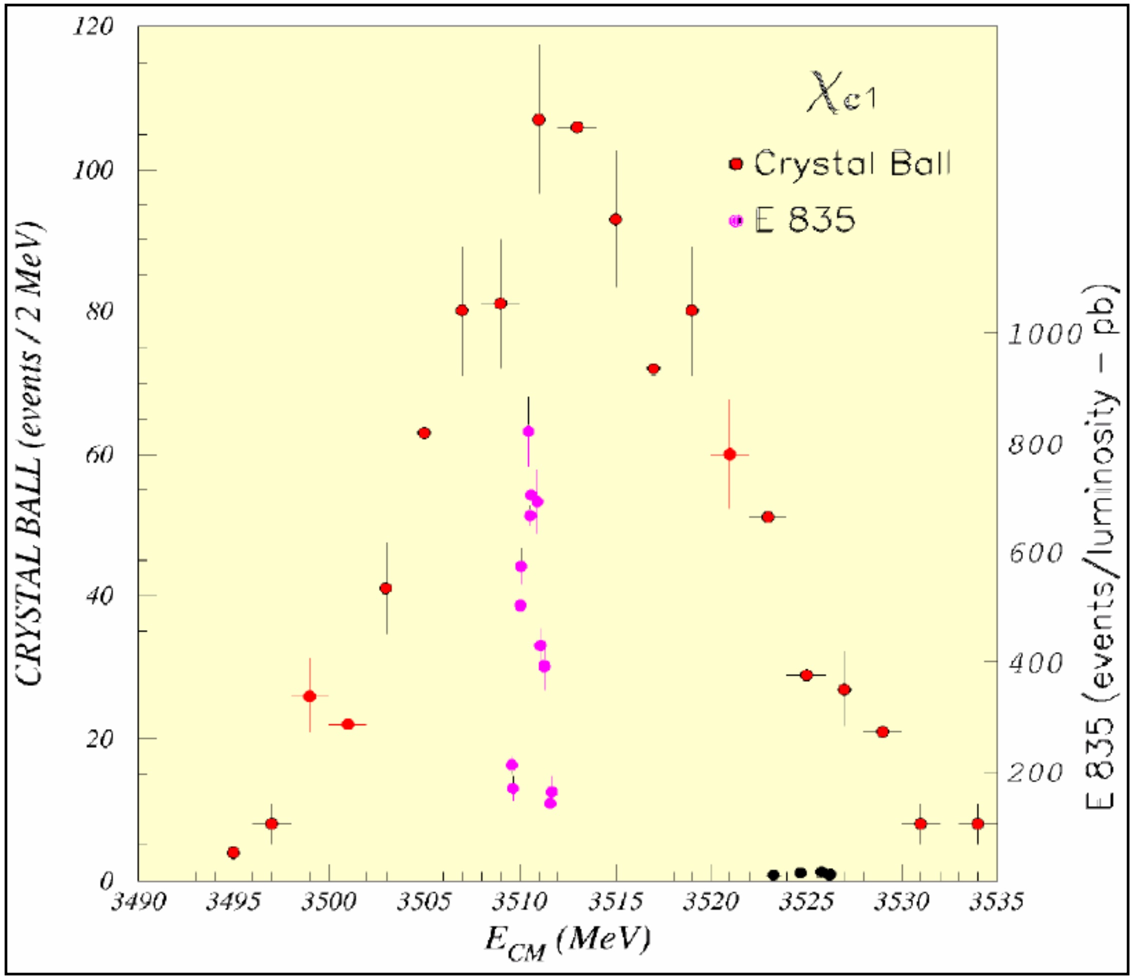
Merits of antiprotons in hadron spectroscopy
High Resolution of M and Γ

- Crystal Ball: typical resolution ~ 10 MeV
- Fermilab: 240 keV
- PANDA: ~20 keV



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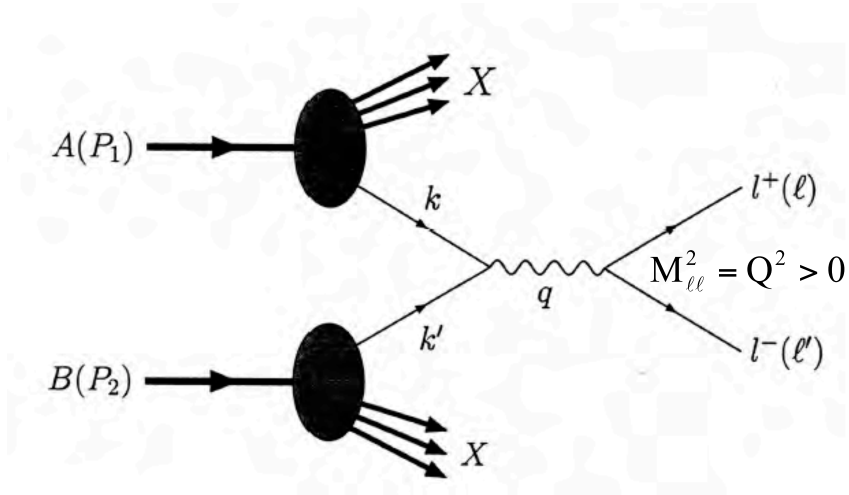
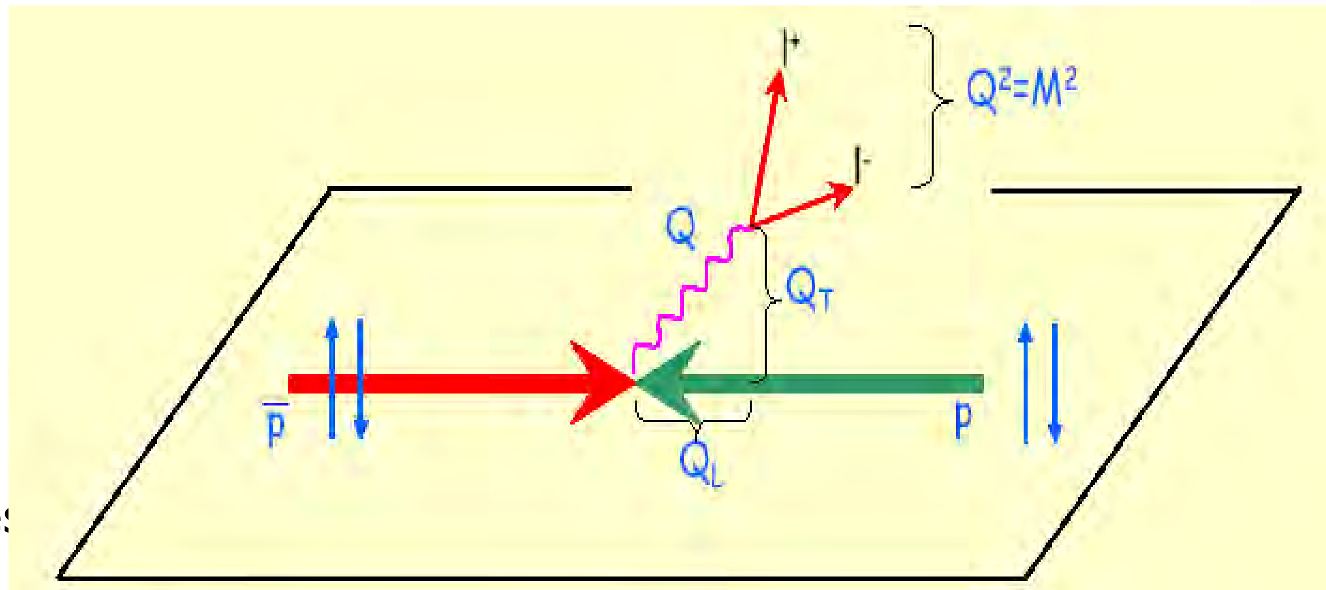
New Charmonium Resonances

- **X(3872),** Belle 09'2003, 1^{++}, χ_{c1}' or D^0D^* molecule
  - decays into $J/\psi\pi^+\pi^-$, $J/\psi\pi^+\pi^-\pi^0$, $J/\psi\gamma$, D^0D^*
- **Y(3940),** Belle 09'2004, JP^+, 2^3P_1 or Hybrid??
  - decays into $J/\psi\omega$
- **Y(4260),** BaBar 06'2005, 1^{--}, 2^3D_1 (BaBar) or 4^3S_1 (CLEO) or Hybrid
  - decays into e^+e^-, $J/\psi\pi^+\pi^-$, $J/\psi\pi^0\pi^0$, $J/\psi K^+K^-$
- **X(3943),** Belle 07'2005, 0^{-+}, η_c''
  - decays into D^0D^*
- **Z(3934),** Belle 07'2005, 2^{++}, χ_{c2}'
  - decays into $\gamma\gamma$, DD
- **ψ(4320),** BaBar 06'2006, ?, Hybrid

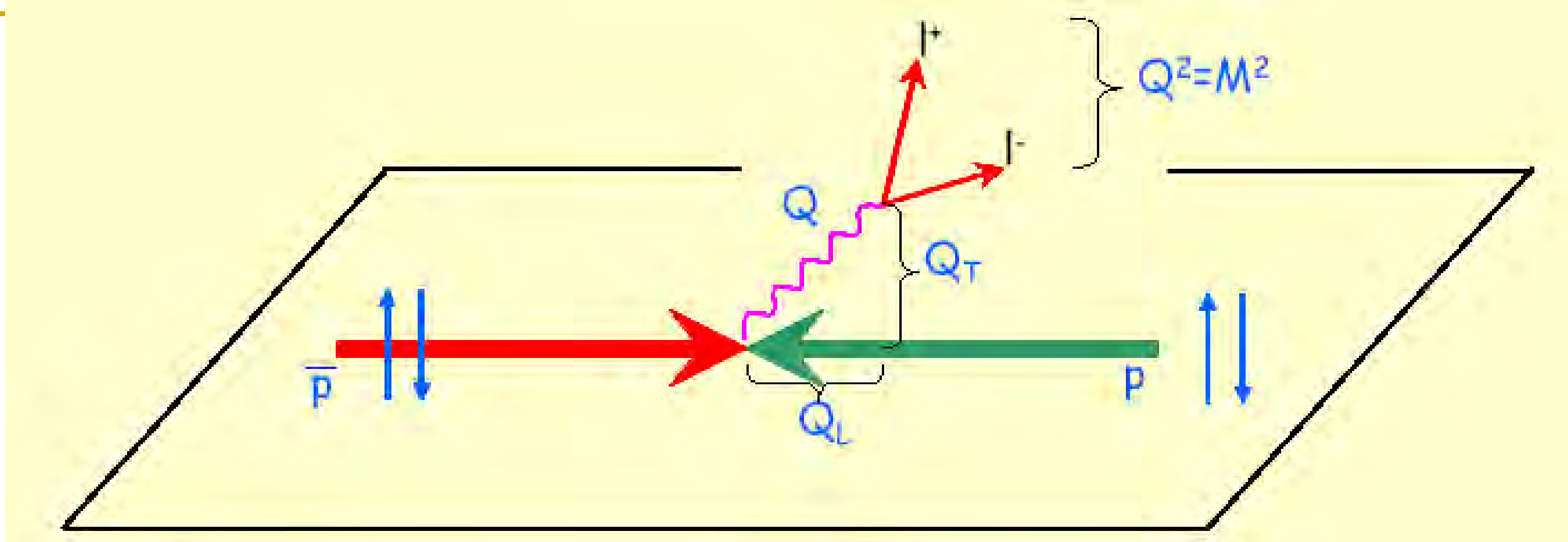
The Drell-Yan process

- process complementary to DIS
- cross section directly related to parton distribution functions
- no fragmentation functions involved
- all valence quarks will contribute in anti-proton annihilation
- wealth of (spin)-observables





B. Seitz



Elementary LO interaction:

$$\frac{d^2\sigma}{dM^2 dx_F} = \frac{4\pi\alpha^2}{9M^2 s}\frac{1}{x_1 + x_2}\sum_a e_a^2\left[q_a(x_1)\,\bar{q}_a(x_2) + \bar{q}_a(x_1)\,q_a(x_2)\right]$$

$$x_F = x_1 - x_2 \qquad x_1 x_2 = M^2 / s \equiv \tau \qquad x_F = 2Q_L / \sqrt{s}$$

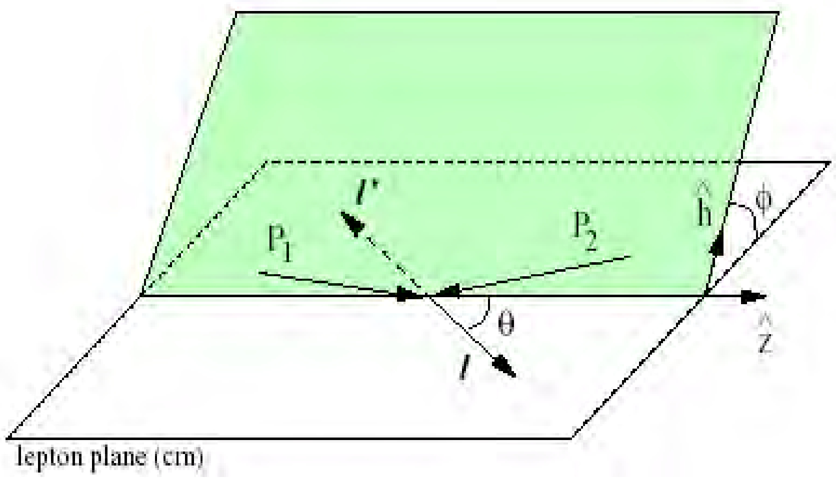
3 planes: plane ⊥ polarization vectors, p-γ* plane, $\mu^+\mu^-$ γ* plane

⇒ many spin effects

Andrey Sokolov

Drell-Yan angular distribution

Unpolarized DY



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

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

$\text{experiment}: \ \nu \approx 0.3$

- 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

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

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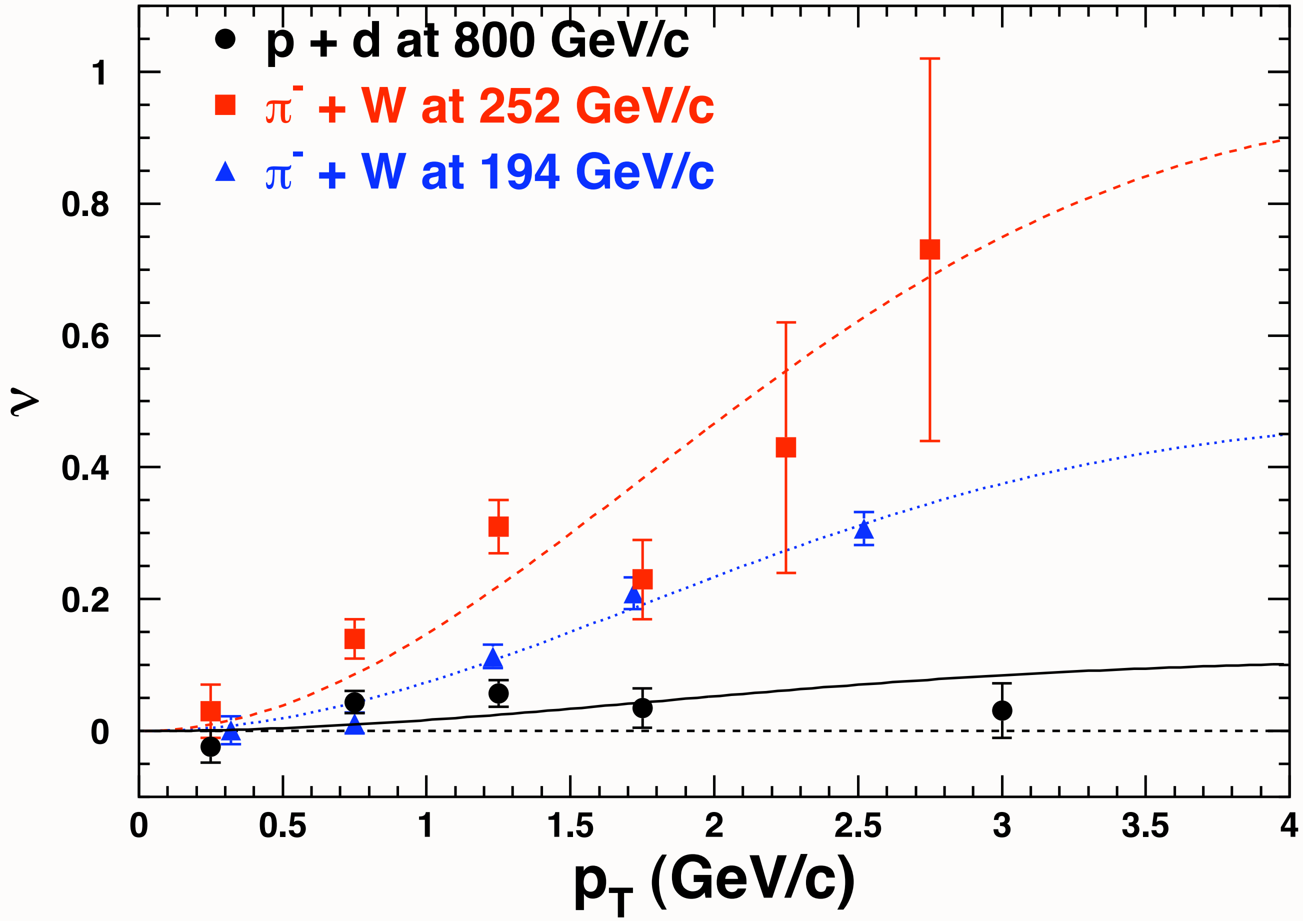
Measurement of Angular Distributions of Drell-Yan Dimuons in $p + d$ Interaction at 800 GeV/c

(FNAL E866/NuSea Collaboration)



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

Negligible Effect $pd \to \mu^+ \mu^- X$

Parameter ν 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.

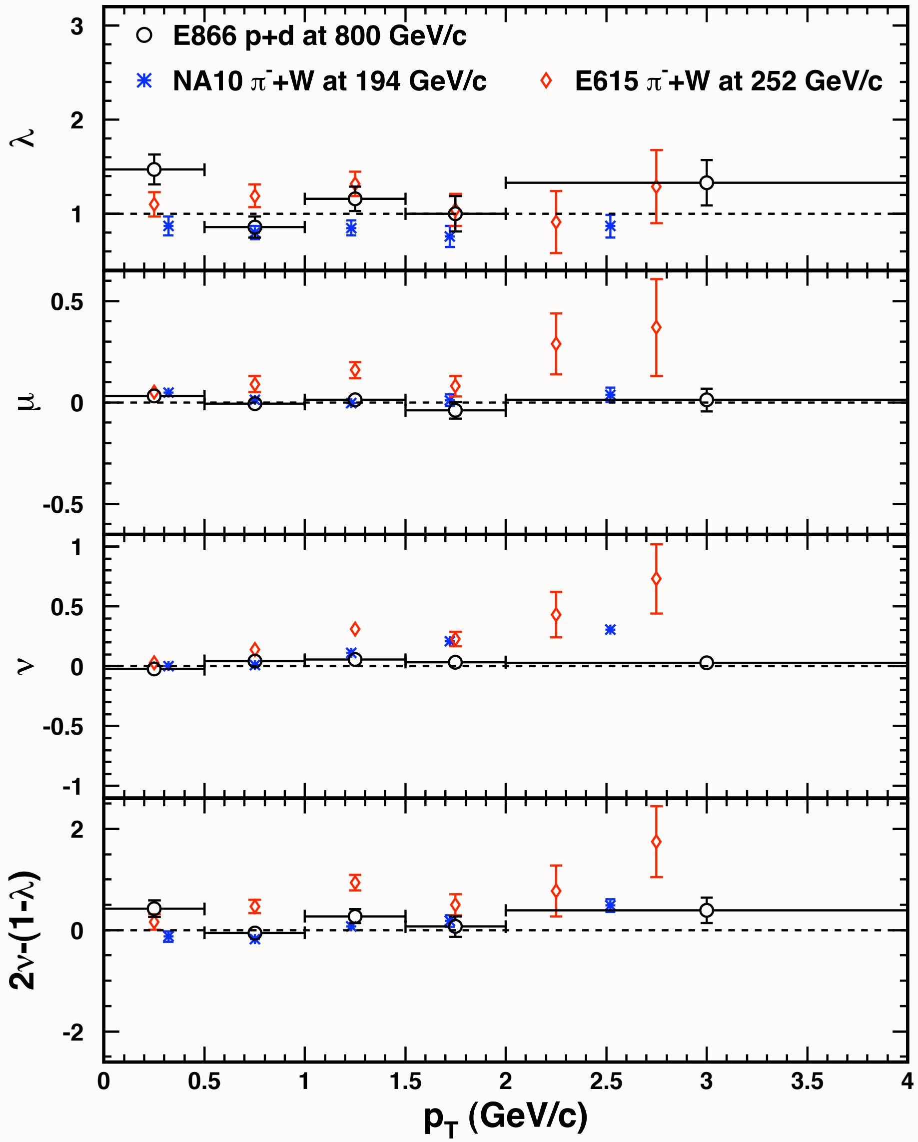


FIG. 1: Parameters λ, μ, ν and $2\nu - (1-\lambda)$ vs. p_T in the Collins-Soper frame. Solid circles are for E866 $p + d$ at 800 GeV/c, crosses are for NA10 $\pi^- + W$ at 194 GeV/c, and diamonds are E615 $\pi^- + W$ at 252 GeV/c. The error bars include the statistical uncertainties only.

Breakdown of Lam-Tung

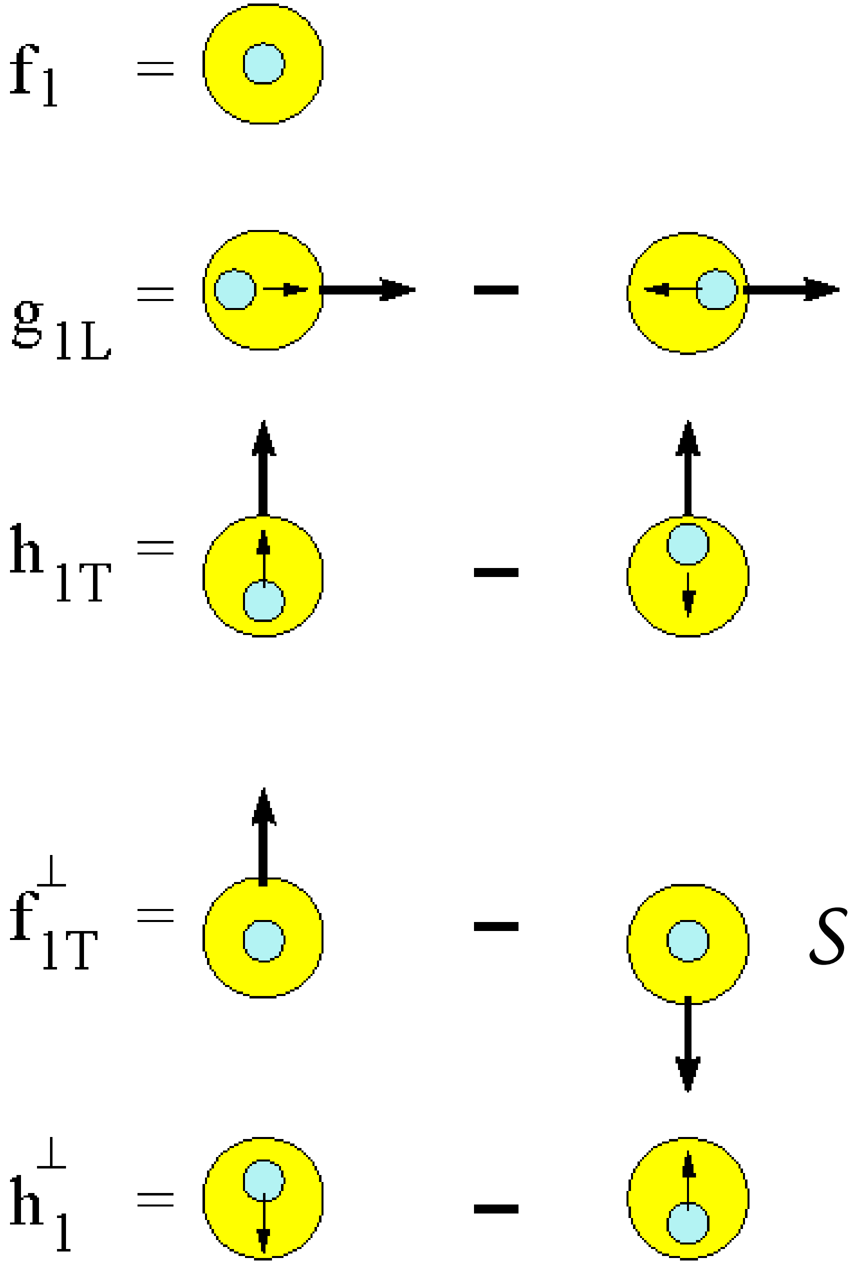
$2\nu - (1-\lambda) \neq 0$

Huge Effect in

$\pi W \to \mu^+ \mu^- X$

Negligible Effect in

$pd \to \mu^+ \mu^- X$



Unpolarized Distribution

Bj Sum Rule

Transversity

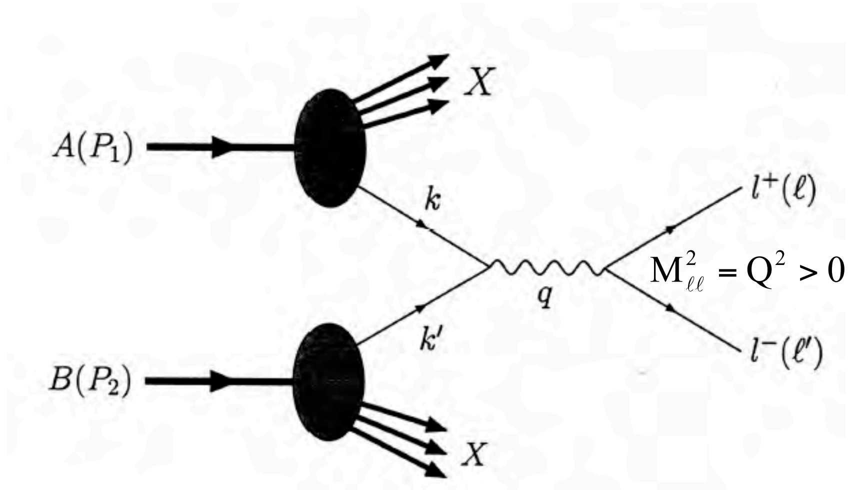
Sivers Function

Boer-Mulders Function

T-Odd: Require ISI or FSI

The Drell-Yan process

- process complementary to DIS
- cross section directly related to parton distribution functions
- no fragmentation functions involved
- all valence quarks will contribute in anti-proton annihilation
- wealth of (spin)-observables



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

$$\nu \propto \sum_q e_q^2 \frac{h_1^\perp \bar{h}_1^\perp}{f_1 \bar{f}_1}$$

$$A_{TT} \propto \frac{\sum_q e_q^2 \left(h_1 \bar{h}_1\right)}{\sum_q e_q^2 \left(f_1 \bar{f}_1\right)}$$

Transversity Test

B. Seitz

$$A_{TT} = \frac{d\sigma^{\uparrow\uparrow} - d\sigma^{\uparrow\downarrow}}{d\sigma^{\uparrow\uparrow} + d\sigma^{\uparrow\downarrow}} = \hat{a}_{TT} \frac{\sum_q e_q^2 \left[h_{1q}(x_1)h_{1\bar{q}}(x_2) + h_{1\bar{q}}(x_1)h_{1q}(x_2)\right]}{\sum_q e_q^2 \left[q(x_1)\bar{q}(x_2) + \bar{q}(x_1)q(x_2)\right]}$$

$$\bar{p}^{\uparrow} p^{\uparrow} \longrightarrow \bar{\ell}\ell X$$

$$\hat{a}_{TT} = \frac{d\hat{\sigma}^{\uparrow\uparrow} - d\hat{\sigma}^{\uparrow\downarrow}}{d\hat{\sigma}^{\uparrow\uparrow} + d\hat{\sigma}^{\uparrow\downarrow}} = \frac{\sin^2\vartheta}{1 + \cos^2\vartheta} \cos(2\varphi)$$

RHIC energies: $\sqrt{s} = 200\,\text{GeV} \quad M^2 \leq 100\ \text{GeV}^2$

➡ $\tau \leq 2 \times 10^{-3}$ small x_1 and/or x_2

$h_{1q}(x, Q^2)$ evolution much slower than

$\Delta q(x, Q^2)$ and $q(x, Q^2)$ at small x

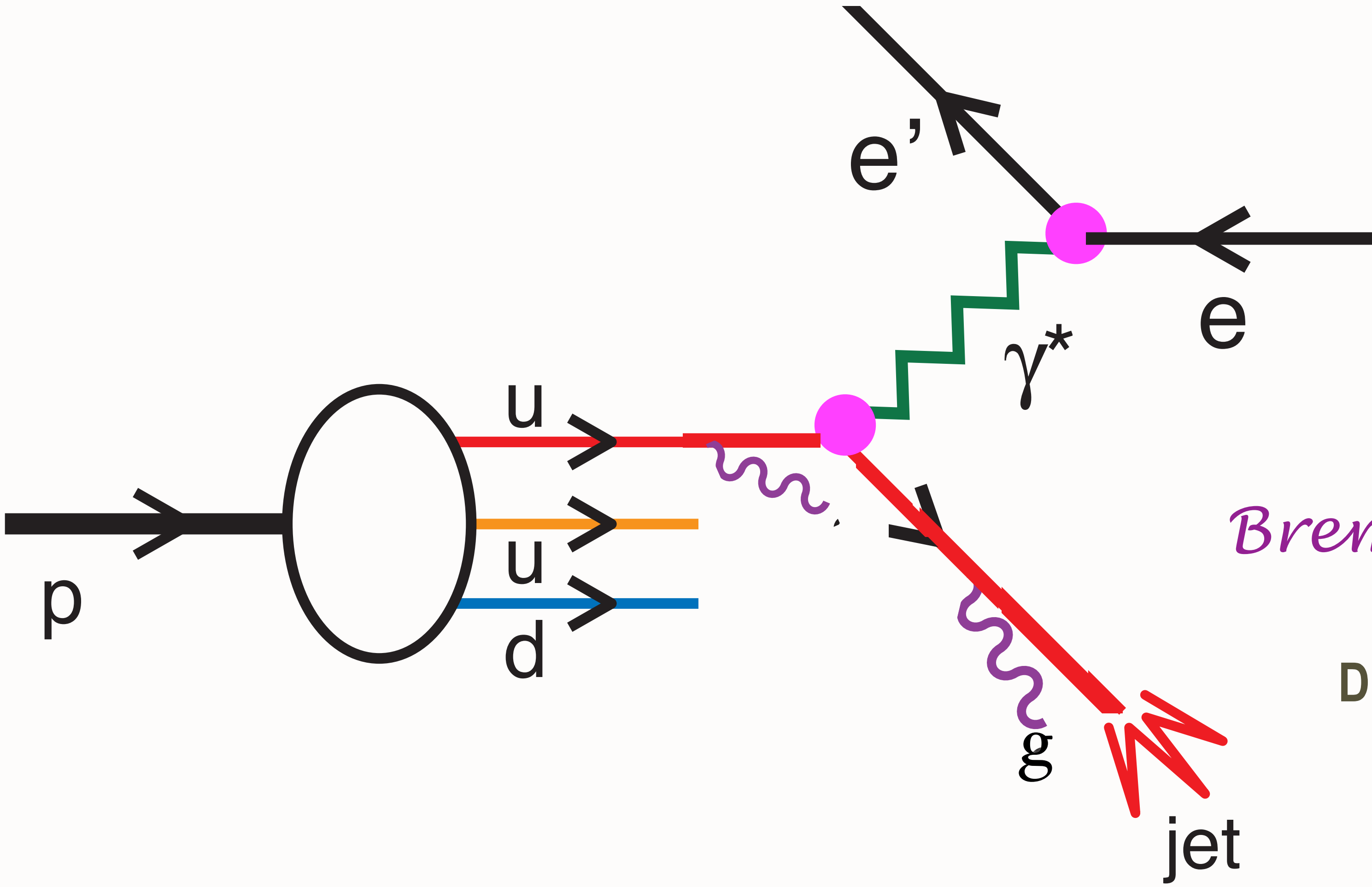
➡ A_{TT} at RHIC is very small

smaller s would help

Barone, Calarco, Drago

Martin, Schäfer, Stratmann, Vogelsang

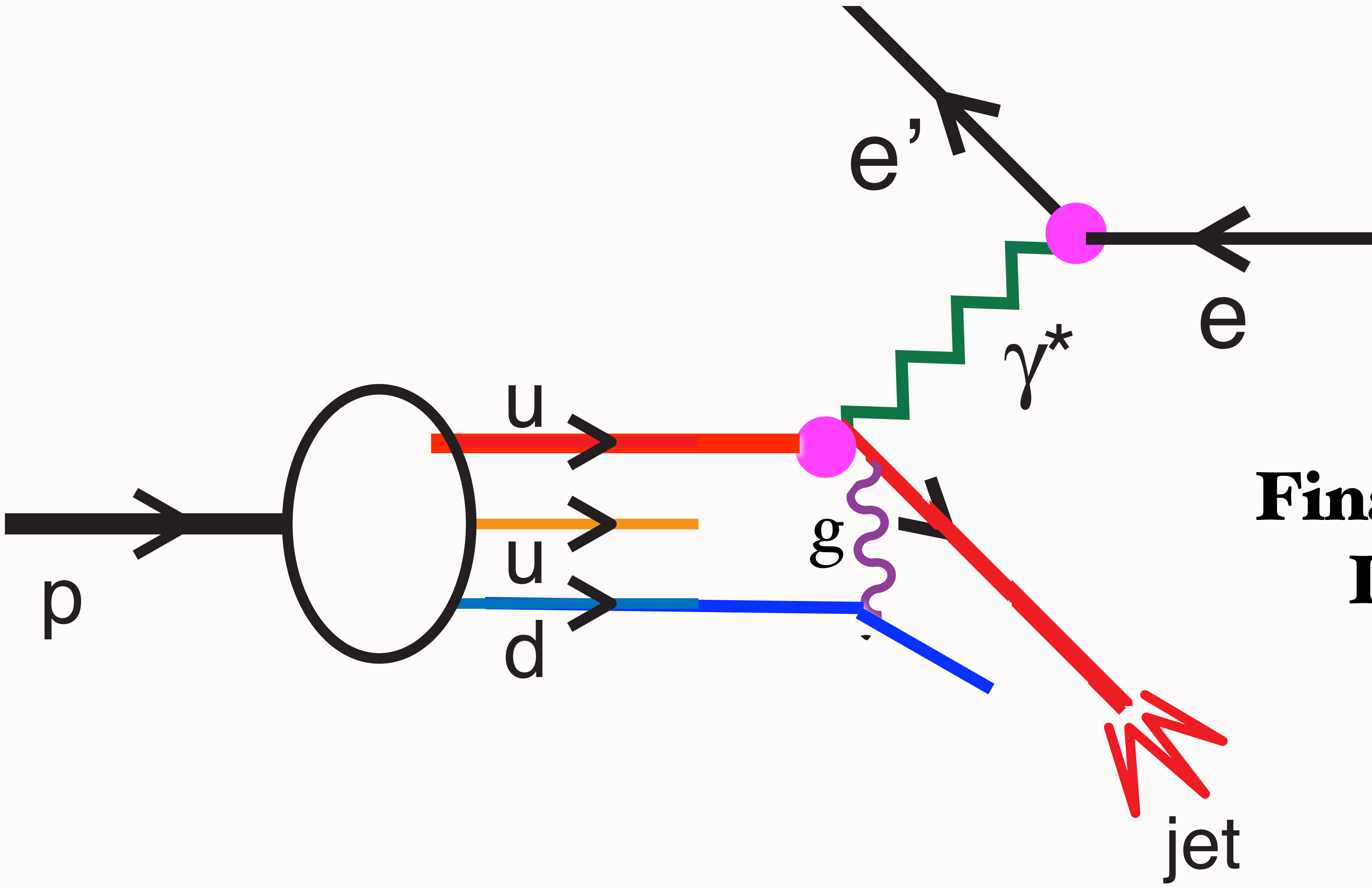
Deep Inelastic Electron-Proton Scattering



Gluonic Bremmstrahlung

DGLAP Evolution

Deep Inelastic Electron-Proton Scattering



Final-State QCD Interaction

Conventional wisdom:

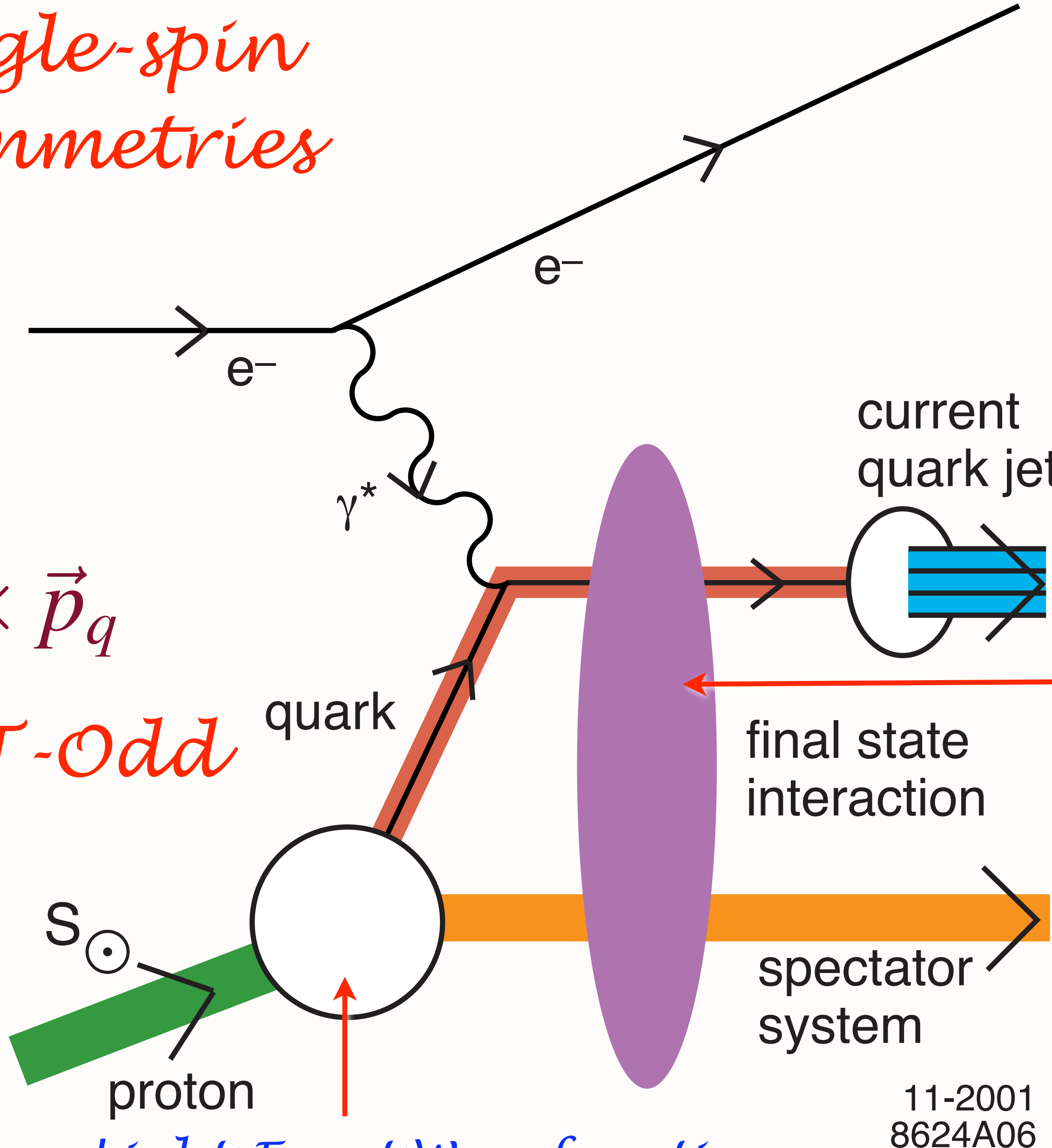
Final-state interactions of struck quark can be neglected

Leading Twist Sivers Effect

Single-spin asymmetries

Hwang, Schmidt, sjb

Collins, Burkardt Ji, Yuan



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

Pseudo-T-Odd

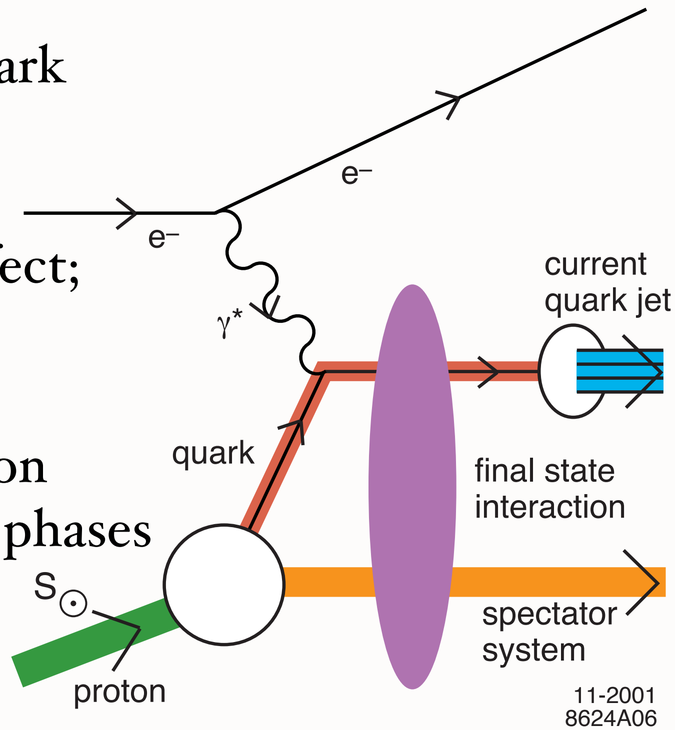
QCD S- and P-Coulomb Phases --Wilson Line

Light-Front Wavefunction S and P- Waves

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

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

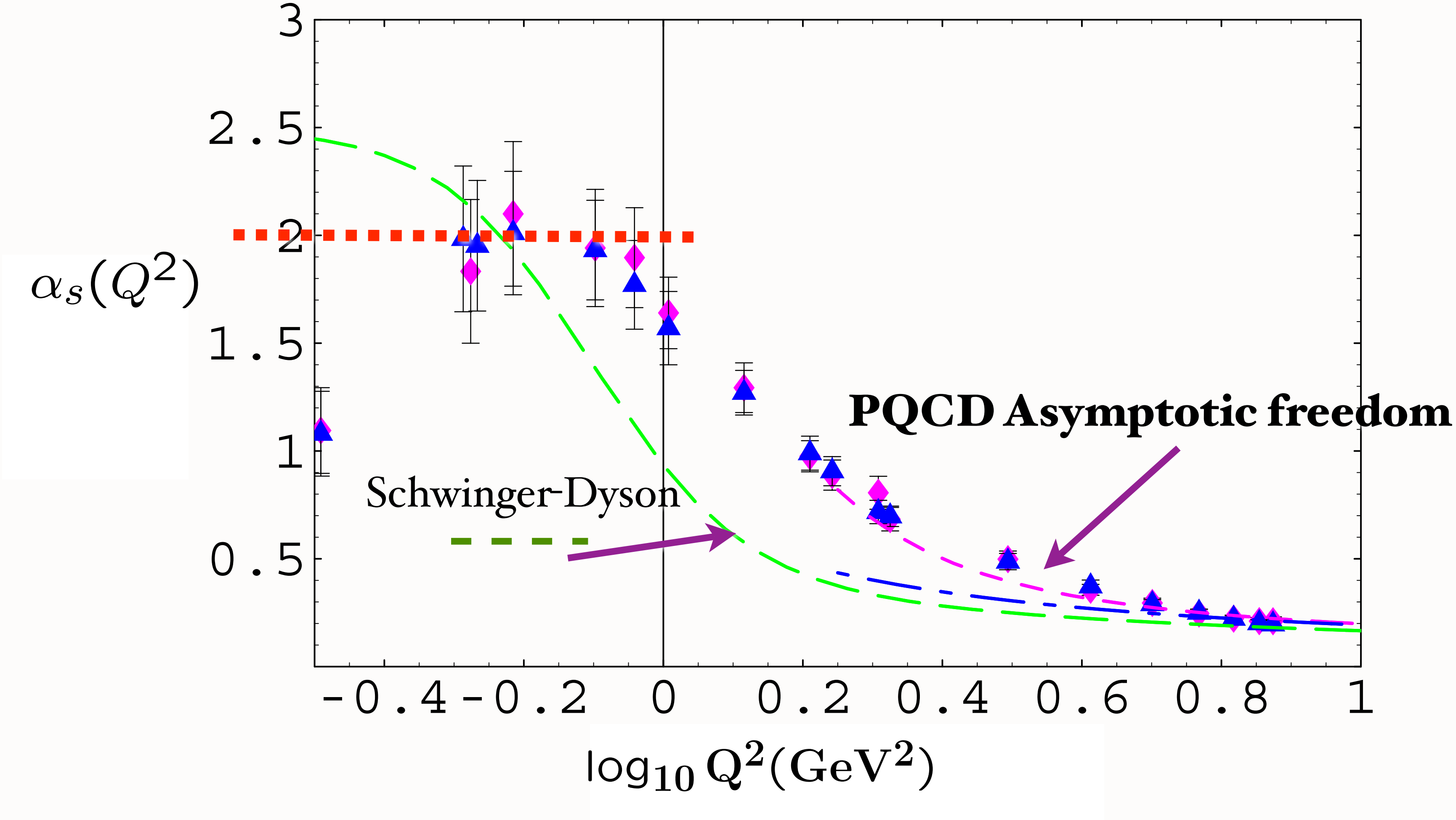
- Leading-Twist Bjorken Scaling!
- Requires nonzero orbital angular momentum of quark
- Arises from the interference of Final-State QCD Coulomb phases in S- and P- waves; Wilson line effect; gauge independent
- Relate to the quark contribution to the target proton anomalous magnetic moment and final-state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



Conformal window

Infrared fixed-point

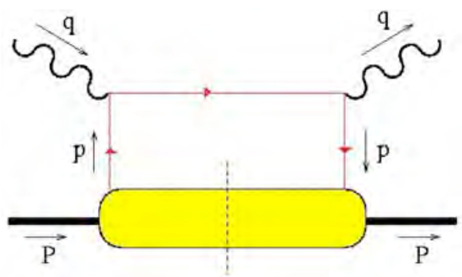
$$\beta(Q^2) = \frac{d\alpha_s(Q^2)}{d\log Q^2} \to 0$$



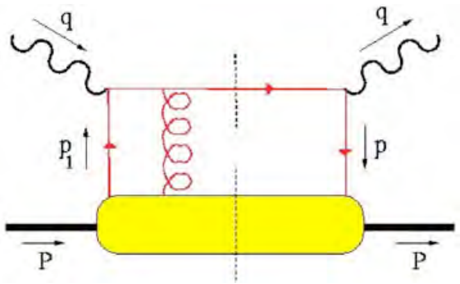
Shirkov
Gribov
Dokshitser
Siminov
Maxwell
Cornwall

lattice: Furui, Nakajima (MILC)

DSE: Alkofer, Fischer, von Smekal et al.



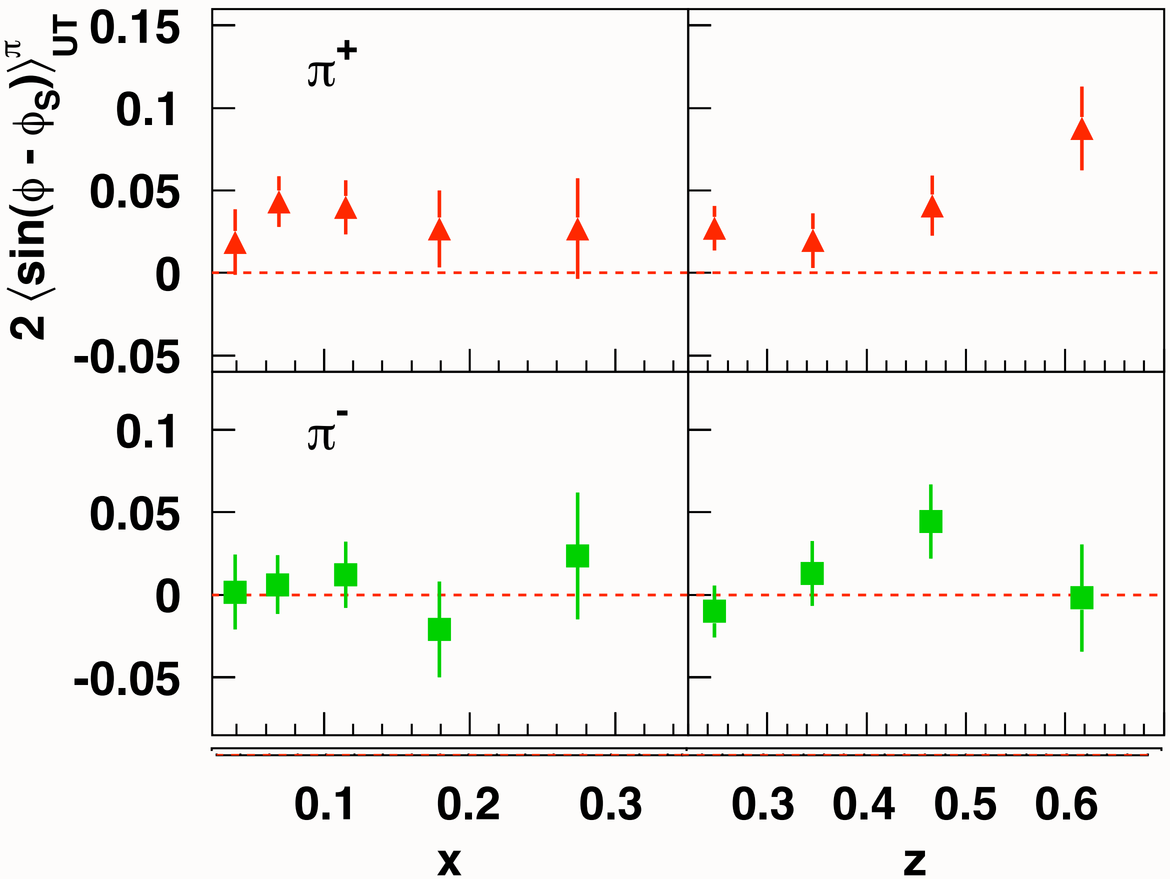
can interfere with



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

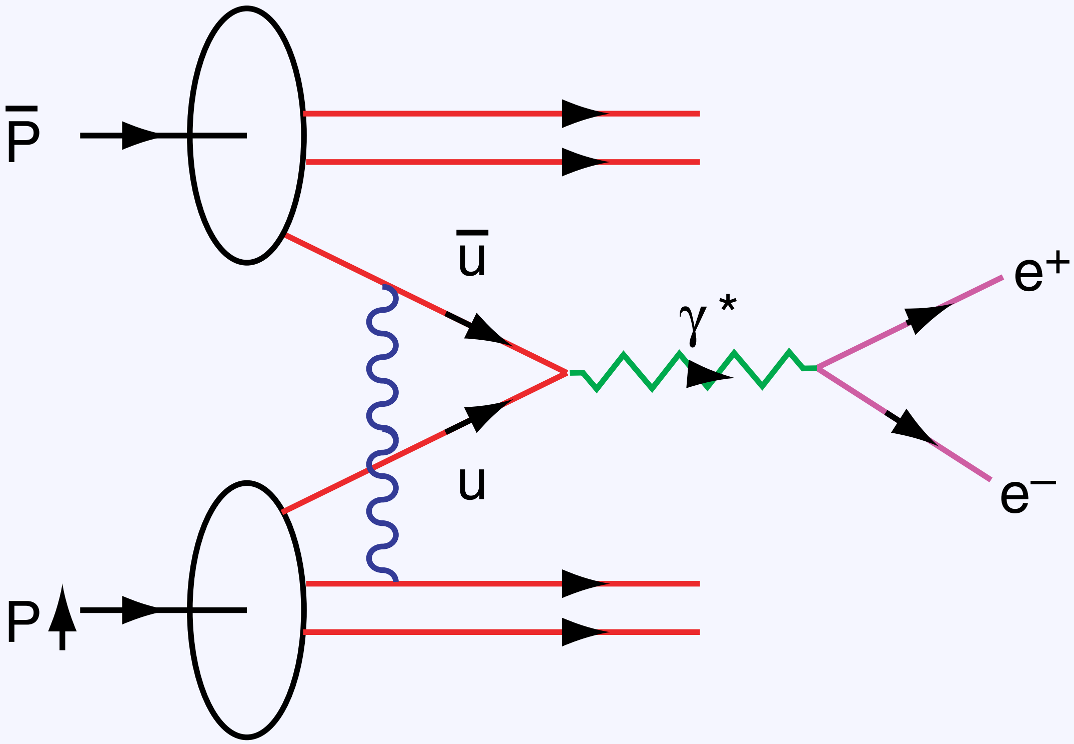


- First evidence for non-zero Sivers function!
- ⇒ presence of non-zero **quark orbital angular momentum**!
- Positive for **π⁺**... Consistent with zero for **π⁻**...

Gamberg: Hermes data compatible with BHS model

Schmidt, Lu: Hermes charge pattern follow quark contributions to anomalous moment

Predict Opposite Sign SSA in DY !



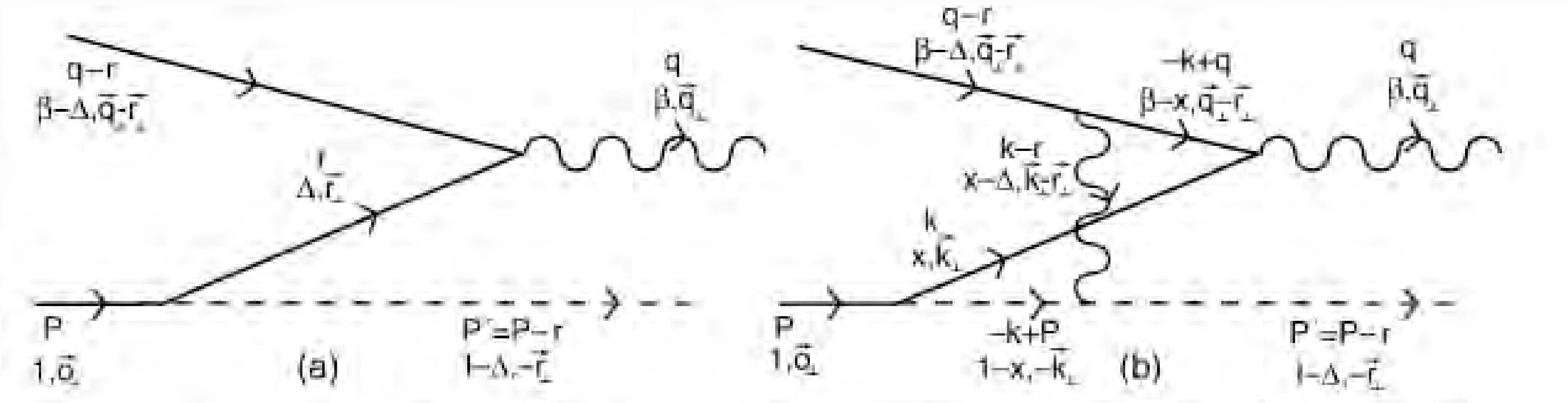
Collins; Hwang, Schmidt. sjb

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 α_s.
Opposite Sign to DIS! No Factorization

Initial-state interactions and single-spin asymmetries in Drell–Yan processes ☆

Stanley J. Brodsky [a], Dae Sung Hwang [a,b], Ivan Schmidt [c]

Nuclear Physics B 642 (2002) 344–356



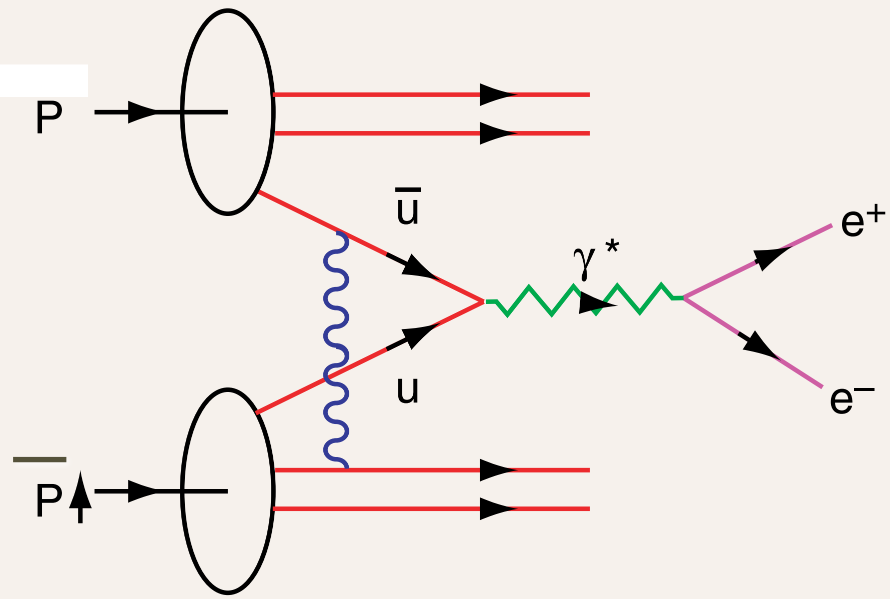
$$\mathcal{P}_y = -\frac{e_1 e_2}{8\pi}\frac{2(\Delta M + m) r^1}{[(\Delta M+m)^2 + \vec r_\perp^{\,2}]}\left[\vec r_\perp^{\,2} + \Delta(1-\Delta)\left(-M^2+\frac{m^2}{\Delta}+\frac{\lambda^2}{1-\Delta}\right)\right]$$

$$\times \frac{1}{\vec r_\perp^{\,2}}\ln\frac{\vec r_\perp^{\,2} + \Delta(1-\Delta)(-M^2+\frac{m^2}{\Delta}+\frac{\lambda^2}{1-\Delta})}{\Delta(1-\Delta)(-M^2+\frac{m^2}{\Delta}+\frac{\lambda^2}{1-\Delta})}.$$

Here $\Delta = \frac{q^2}{2P\cdot q} = \frac{q^2}{2M\nu}$ where ν is the energy of the lepton pair in the target rest frame.

Key QCD Experiment at FAIR

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!

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

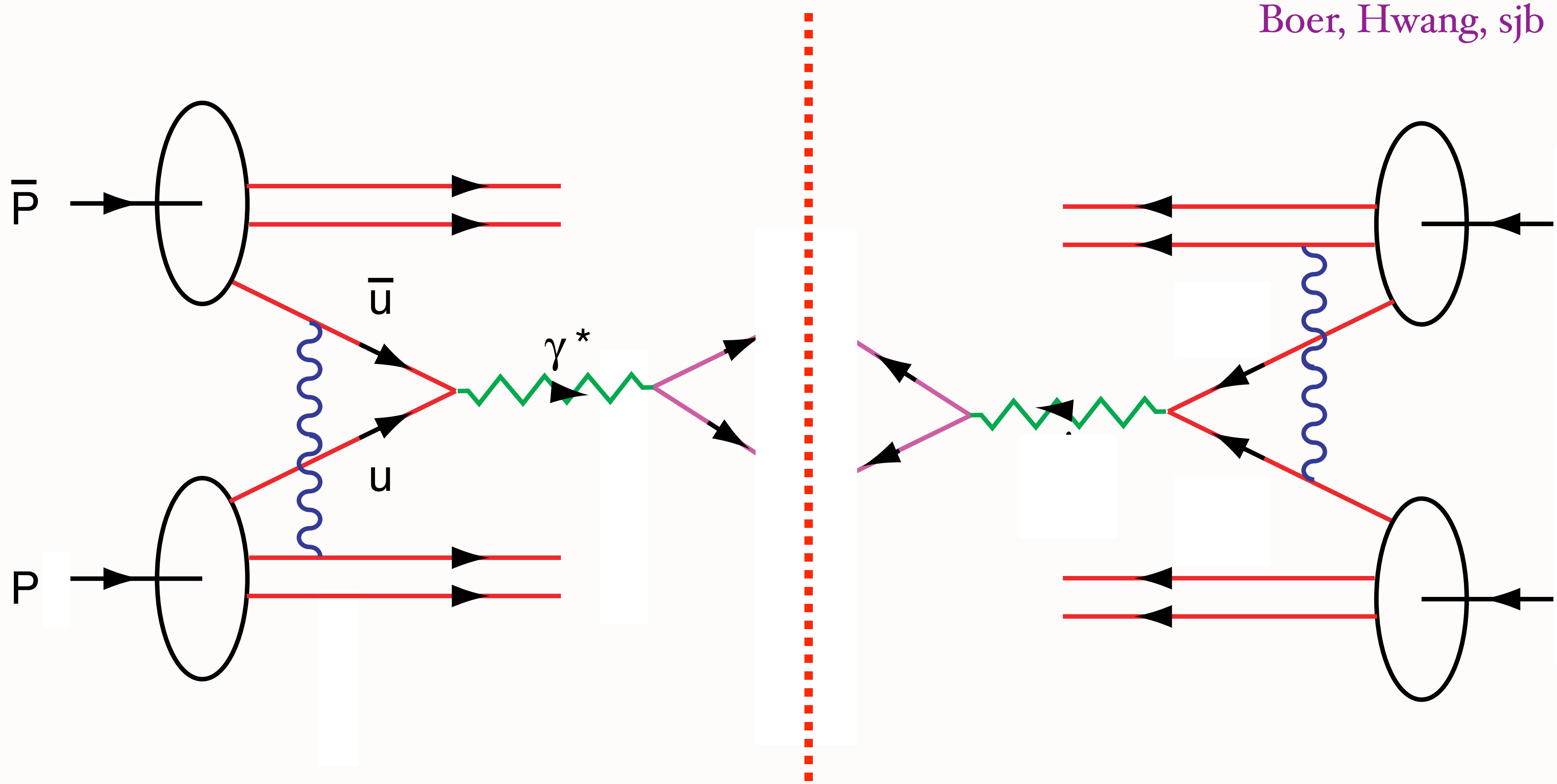
$$Q^2 = x_1 x_2 s$$

$$Q^2 = 4 \text{ GeV}^2, s = 80 \text{ GeV}^2$$

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

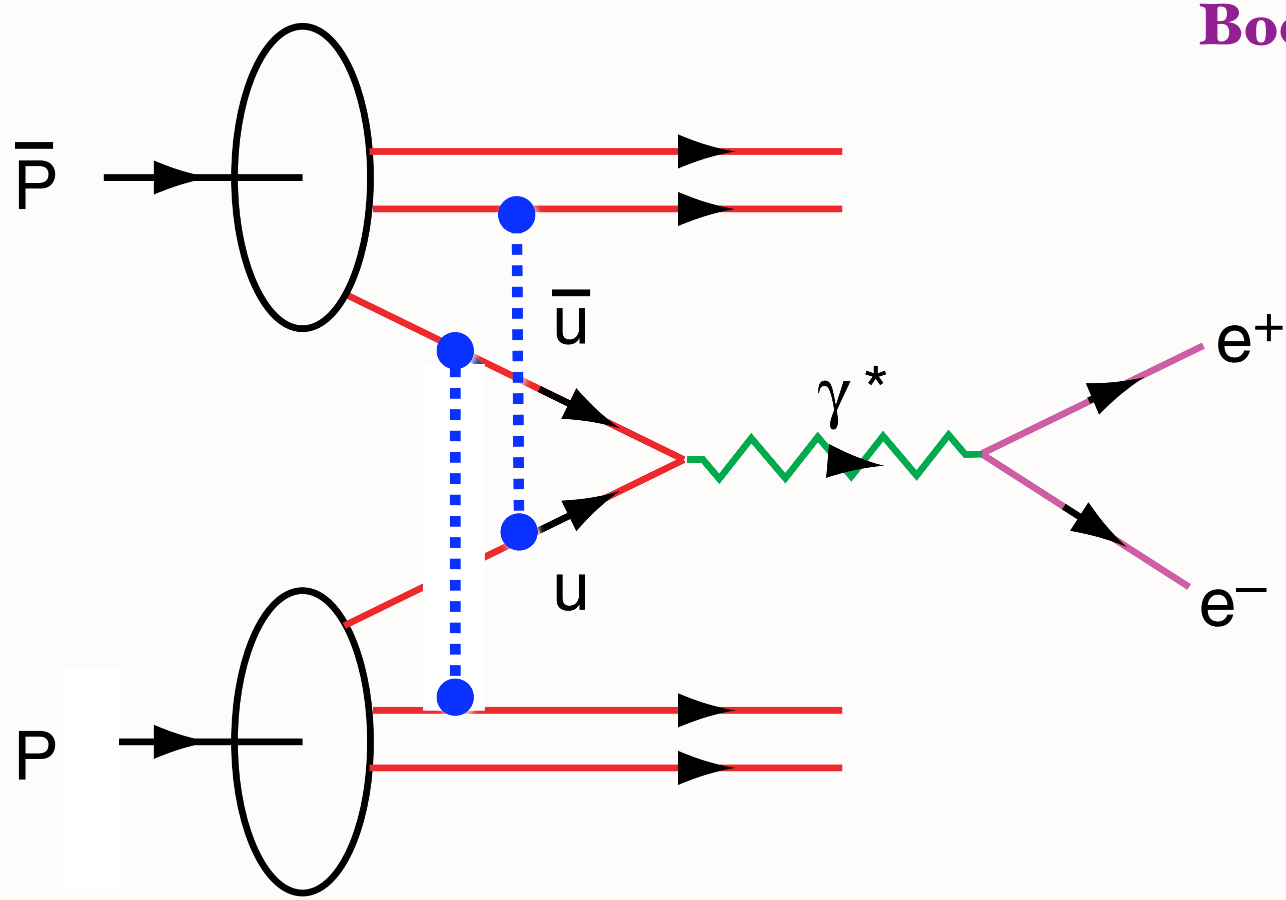
$$x_1 x_2 = .05, x_F = x_1 - x_2$$

Boer, Hwang, sjb



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

Boer, Hwang, sjb

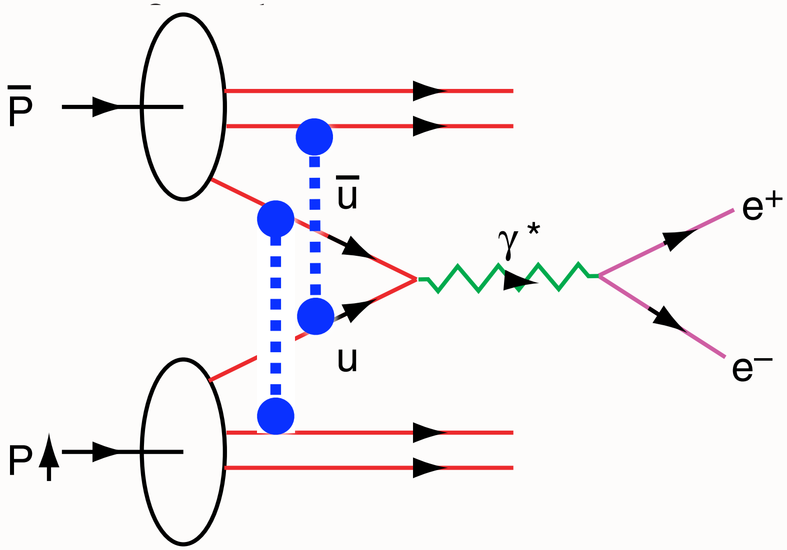


DY $\cos 2\phi$ correlation at leading twist from double ISI

Product of Boer - Mulders Functions

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

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



Product of Boer - Mulders Functions

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

$$F\equiv\mathcal{F}[(2\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_\perp\ \hat{\boldsymbol{h}}\cdot\boldsymbol{k}_\perp-\boldsymbol{p}_\perp\cdot\boldsymbol{k}_\perp)h_1^\perp\bar{h}_1^\perp]$$

$$=\int d^2\boldsymbol{p}_\perp d^2\boldsymbol{k}_\perp\,\delta^2(\boldsymbol{p}_\perp+\boldsymbol{k}_\perp-\boldsymbol{q}_\perp)(2\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_\perp\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_\perp-\boldsymbol{p}_\perp\cdot\boldsymbol{k}_\perp)$$

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

(40

$$\nu=\frac{2}{M_1M_2}\frac{\sum_{a,\bar{a}}e_a^2F_a}{\sum_{a,\bar{a}}e_a^2G_a}.$$

$$G\equiv\mathcal{F}[f_1\bar{f}_1]$$

$$=\int d^2\boldsymbol{p}_\perp\ d^2\boldsymbol{k}_\perp\,\delta^2(\boldsymbol{p}_\perp+\boldsymbol{k}_\perp-\boldsymbol{q}_\perp)f_1(\Delta,\boldsymbol{p}_\perp^2)\bar{f}_1(\bar{\Delta},\boldsymbol{k}_\perp^2),$$

Boer, Hwang, sjb

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

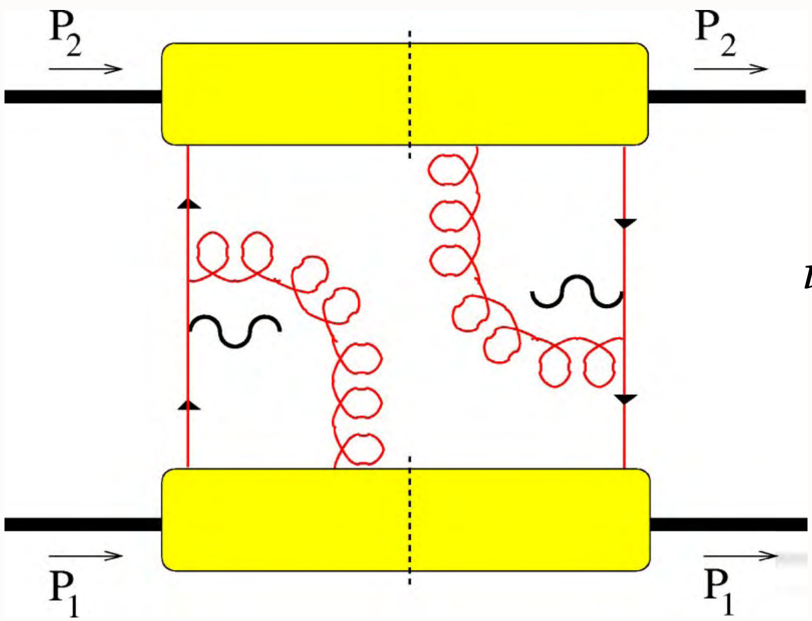
Boer, Hwang, sjb

Drell-Yan planar correlations

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

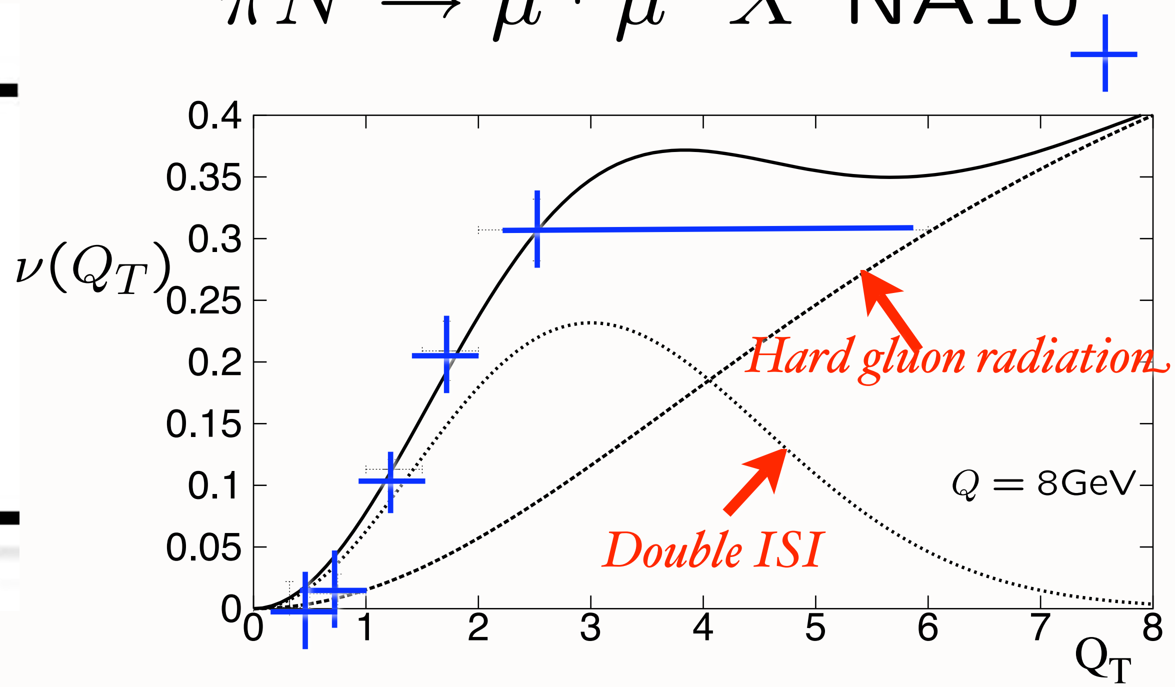
PQCD Factorization (Lam Tung): $1 - \lambda - 2\nu = 0$

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



Violates Lam-Tung relation!

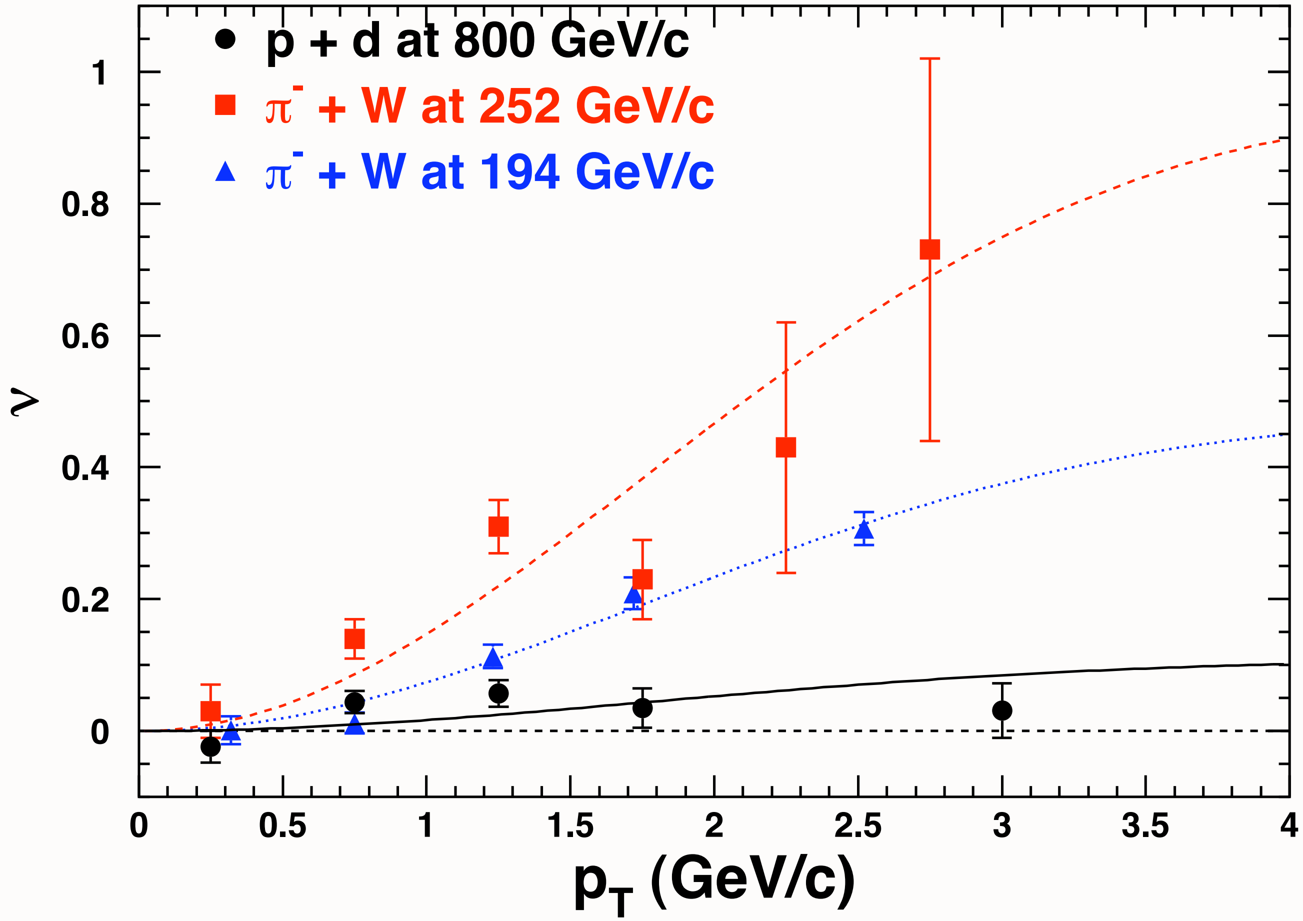
$\pi N \to \mu^+ \mu^- X$ NA10



Model: Boer,

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

(FNAL E866/NuSea Collaboration)



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

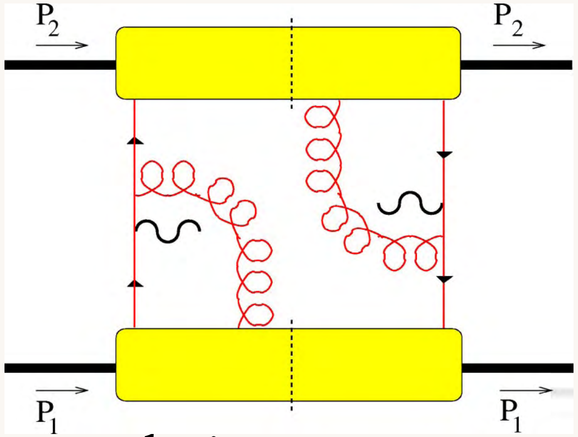
Negligible Effect $pd \to \mu^+ \mu^- X$

Parameter ν 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.

Anomalous effect from Double ISI in Massive Lepton Production

Boer, Hwang, sjb

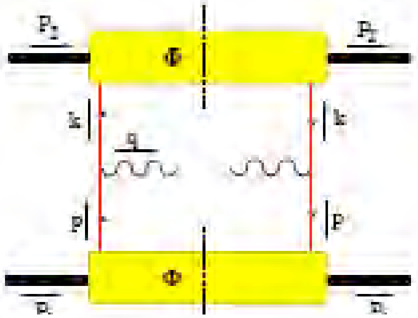
$\cos 2\phi$ correlation

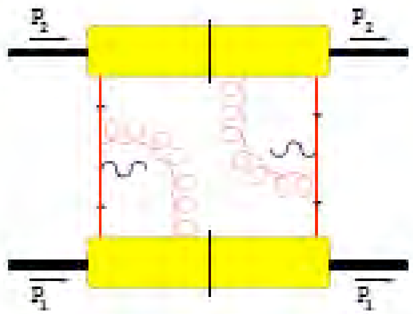


- Leading Twist, valence quark dominated
- Violates Lam-Tung Relation!
- Not obtained from standard PQCD subprocess analysis
- Normalized to the square of the single spin asymmetry in semi-inclusive DIS
- No polarization required
- Challenge to standard picture of PQCD Factorization

Key QCD Experiment at FAIR

$\cos 2\phi$ correlation in DY from double ISI

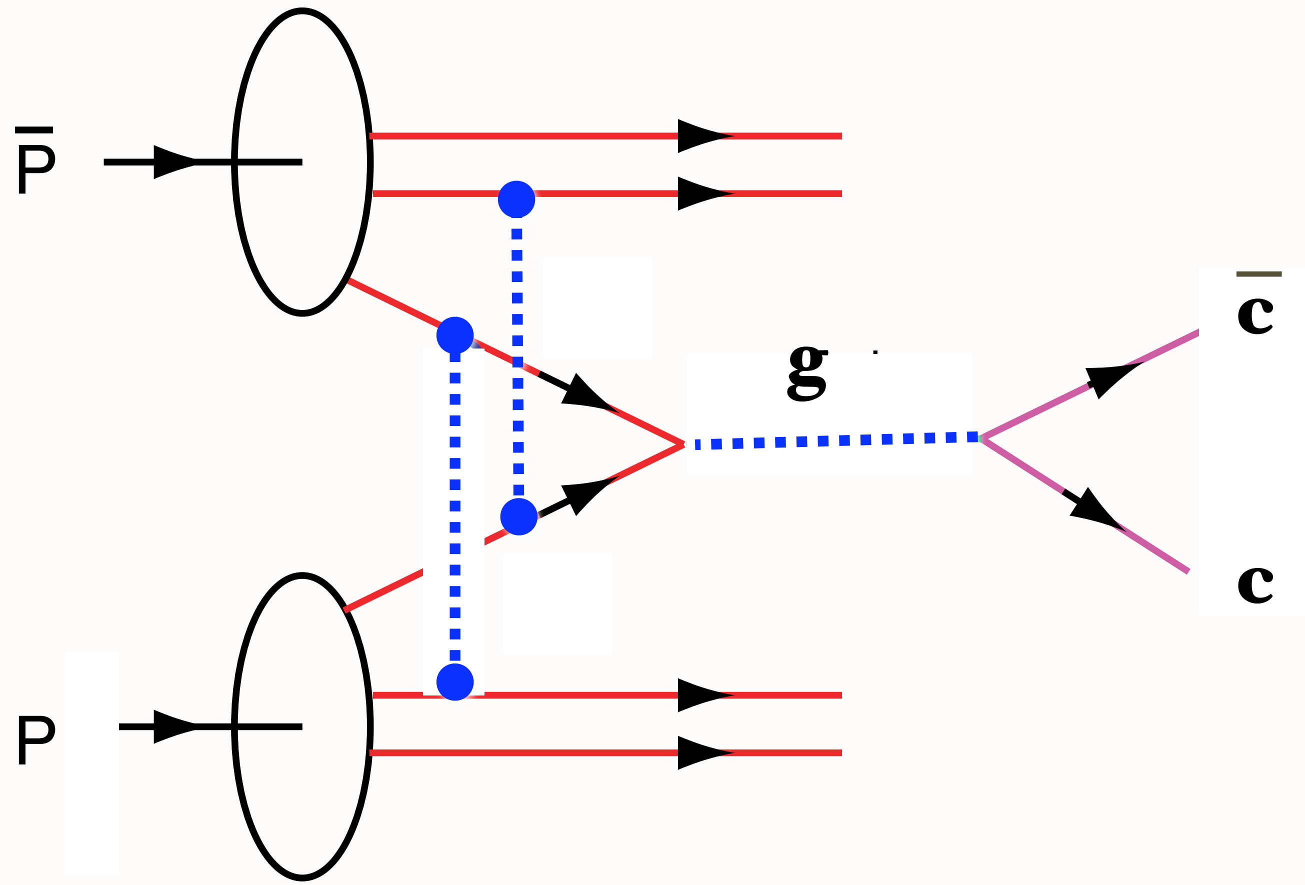




Boer, Hwang, sjb

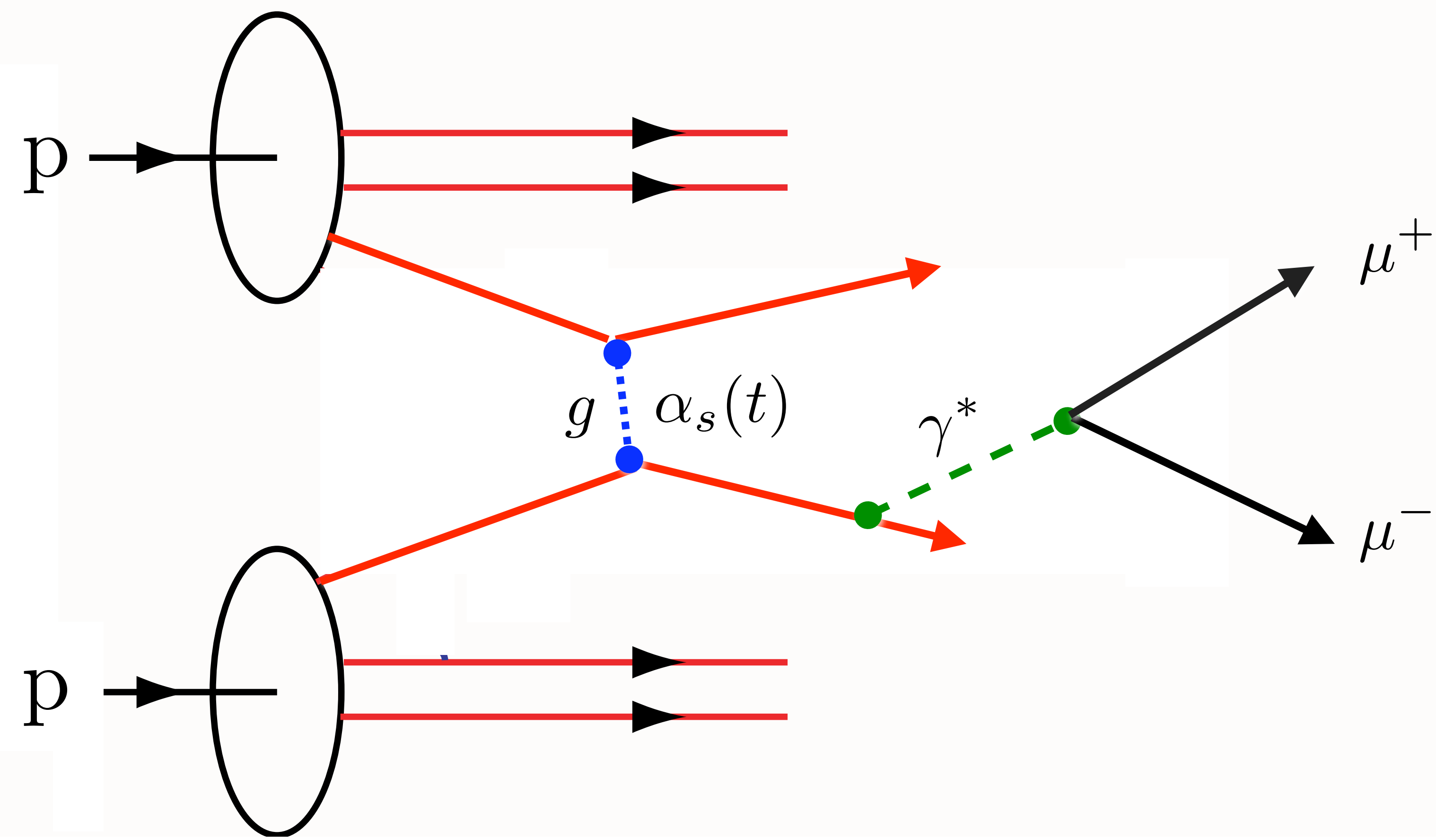
Abstract

We show that initial-state interactions contribute to the $\cos 2\phi$ distribution in unpolarized Drell-Yan lepton pair production $p\,p$ and $p\overline{p} \to \ell^+\ell^- X$, without suppression. The asymmetry is expressed as a product of chiral-odd distributions $h_1^\perp(x_1, \boldsymbol{p}_\perp^2) \times \overline{h}_1^\perp(x_2, \boldsymbol{k}_\perp^2)$, where the quark-transversity function $h_1^\perp(x, \boldsymbol{p}_\perp^2)$ is the transverse momentum dependent, light-cone momentum distribution of transversely polarized quarks in an *unpolarized* proton. We compute this (naive) T-odd and chiral-odd distribution function and the resulting $\cos 2\phi$ asymmetry explicitly in a quark-scalar diquark model for the proton with initial-state gluon interaction. In this model the function $h_1^\perp(x, \boldsymbol{p}_\perp^2)$ equals the T-odd (chiral-even) Sivers effect function $f_{1T}^\perp(x, \boldsymbol{p}_\perp^2)$. This suggests that the single-spin asymmetries in the SIDIS and the Drell-Yan process are closely related to the $\cos 2\phi$ asymmetry of the unpolarized Drell-Yan process, since all can arise from the same underlying mechanism. This provides new insight regarding the role of quark and gluon orbital angular momentum as well as that of initial- and final-state gluon exchange interactions in hard QCD processes.



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

Bremsstrahlung Contribution to Lepton Pair Production

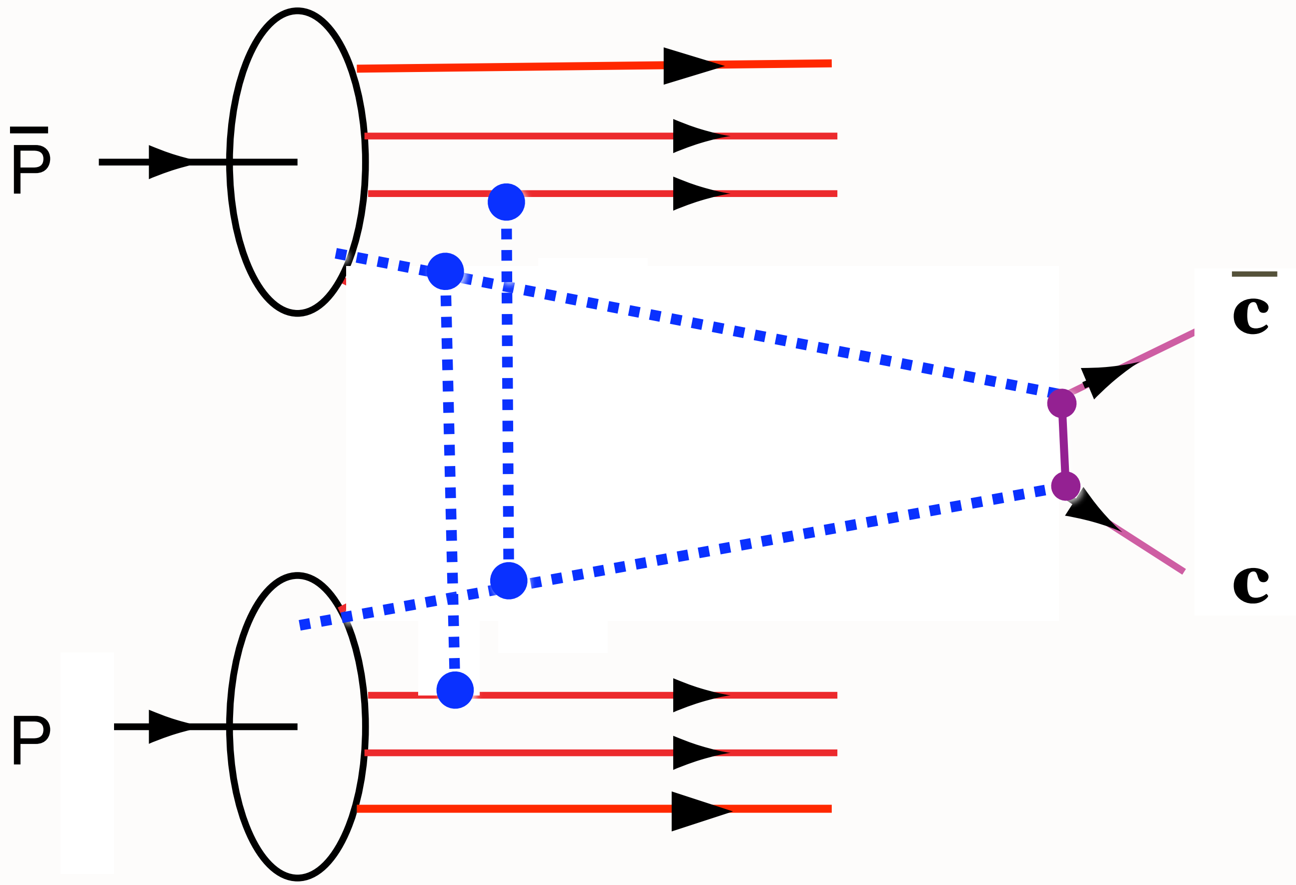


Possibly Dominant Contribution to Di-muon Pair Production in $pp \to \mu^+\mu^- X$

$\alpha_s(t)$ at $\sqrt{-t}_{min} \simeq \frac{Q^2}{2p_{lab}} = \frac{MQ^2}{s}$

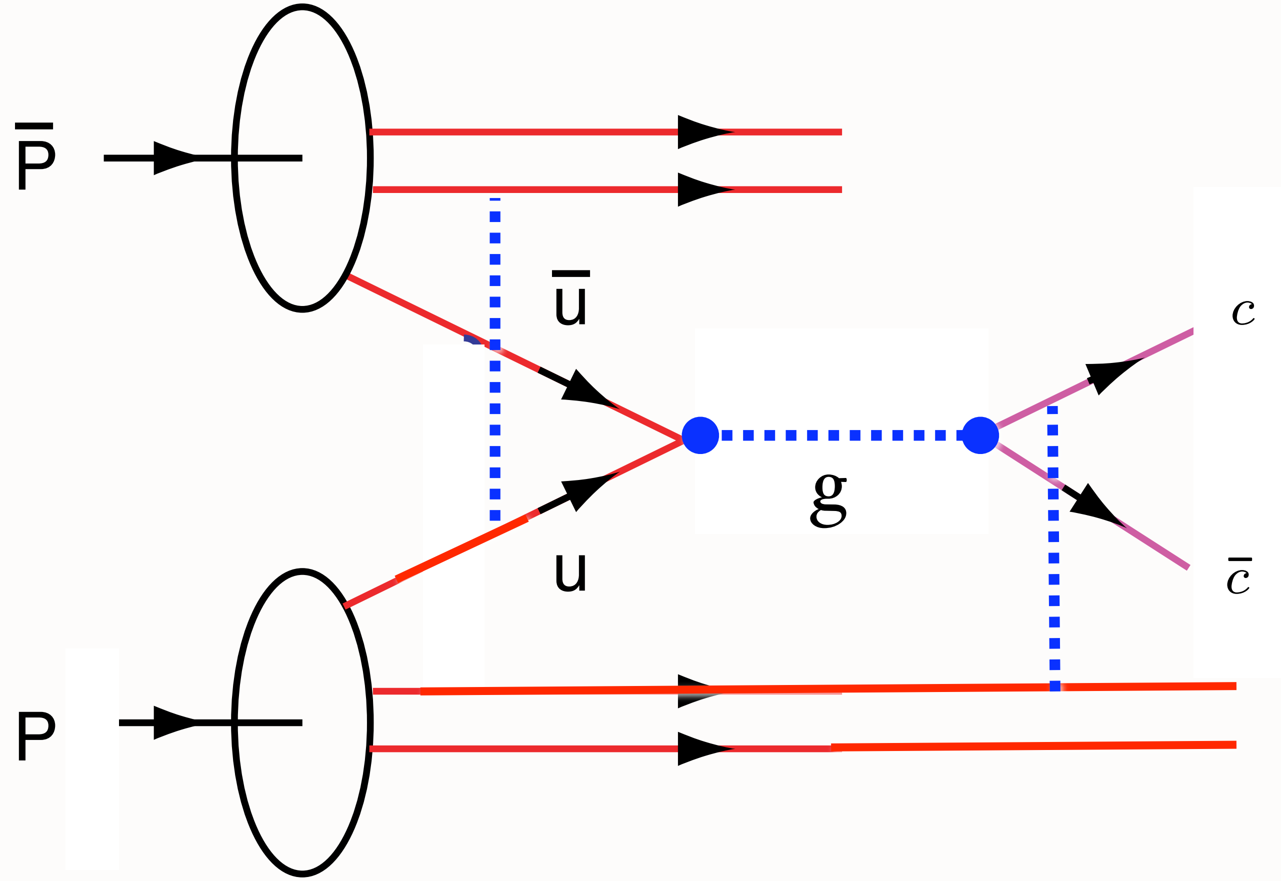
Explains why ν is small at high s?

Feng Yuan and sjb



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

Enhanced by gluon color charge

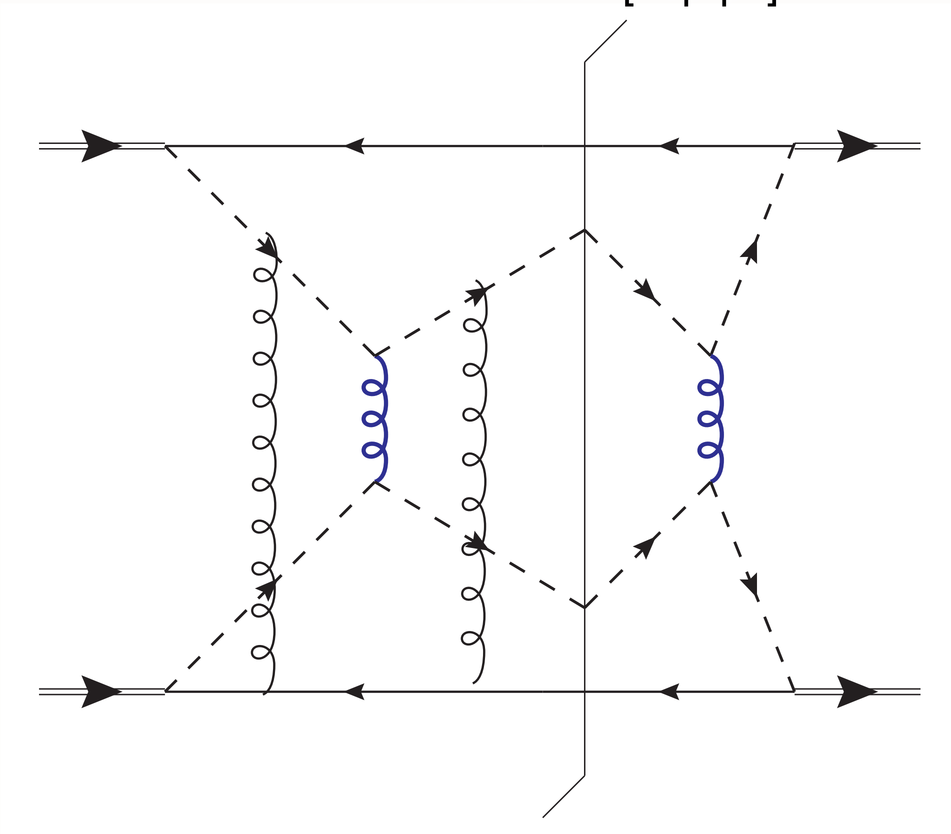


Problem for factorization when both ISI and FSI occur

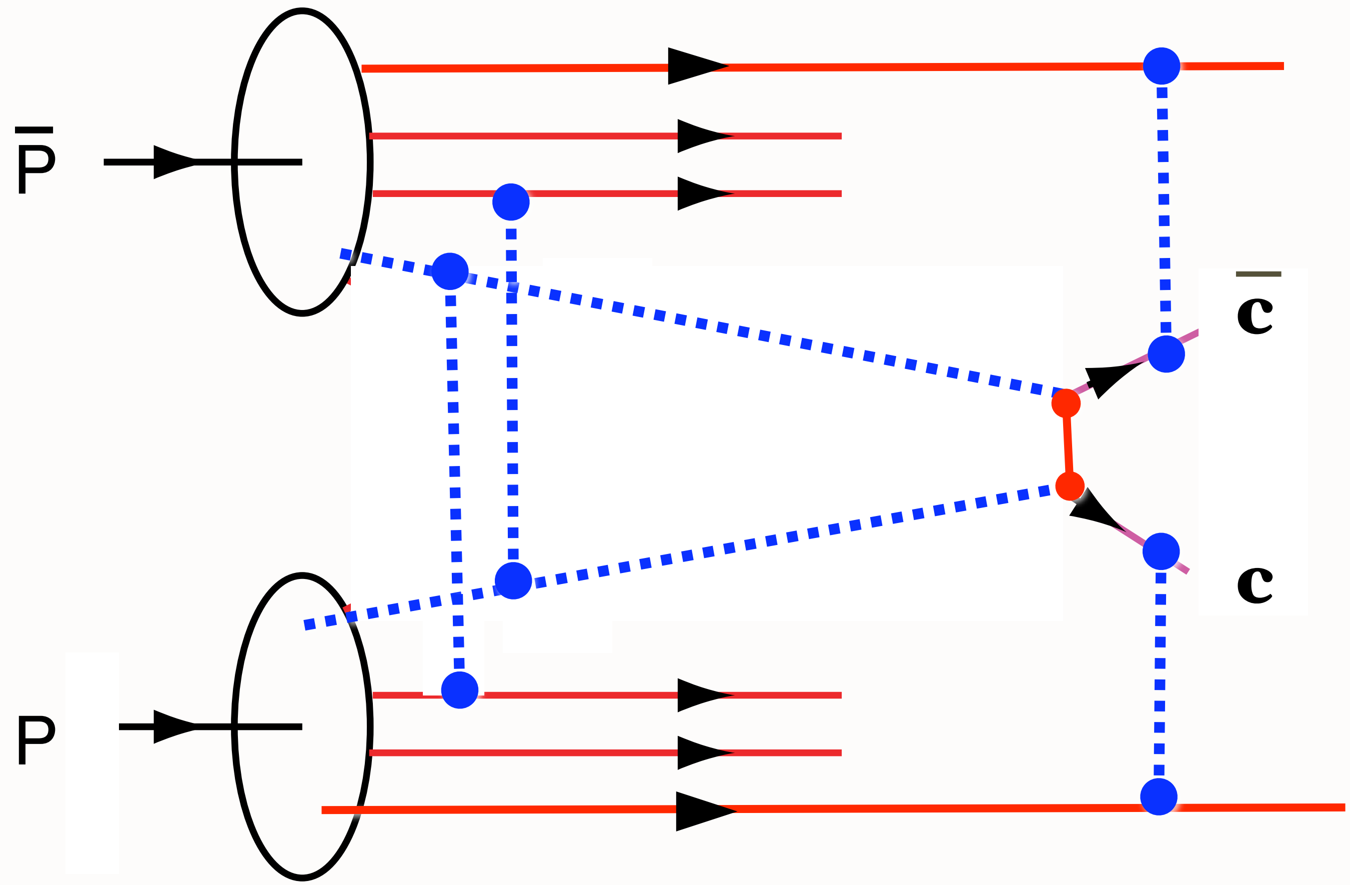
Factorization is violated in production of high-transverse-momentum particles in hadron-hadron collisions

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.



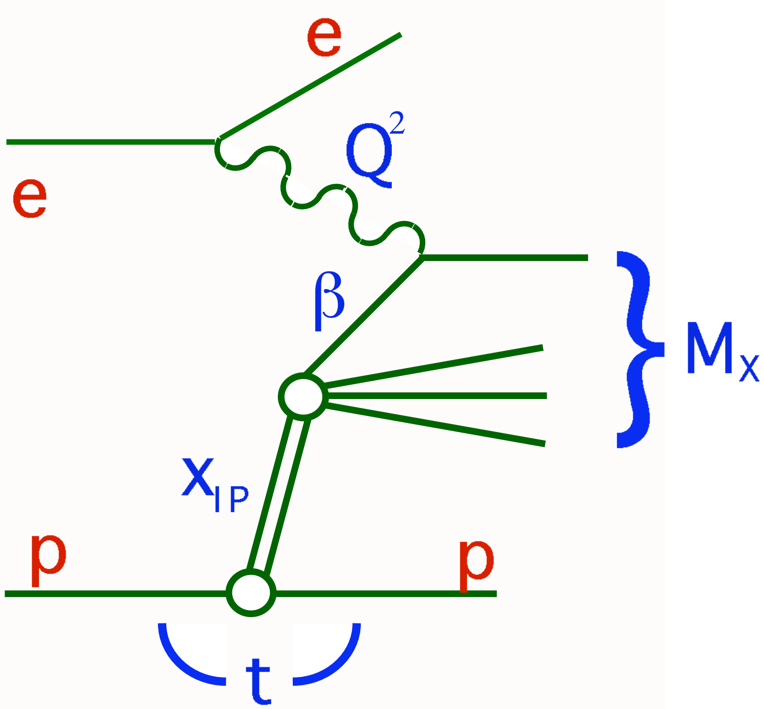
$\cos 2\phi$ correlation for quarkonium production at leading twist from double ISI

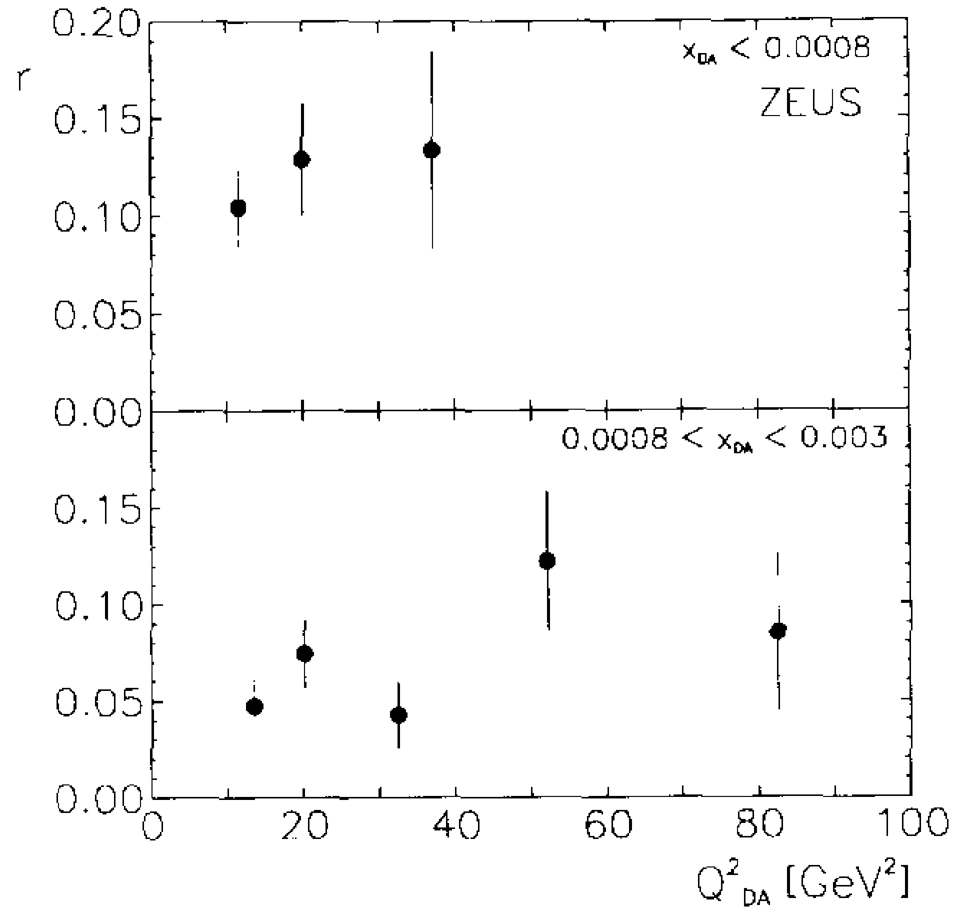
Enhanced by gluon color charge
Also possible FSI

Physics of Rescattering

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

Remarkable observation at HERA



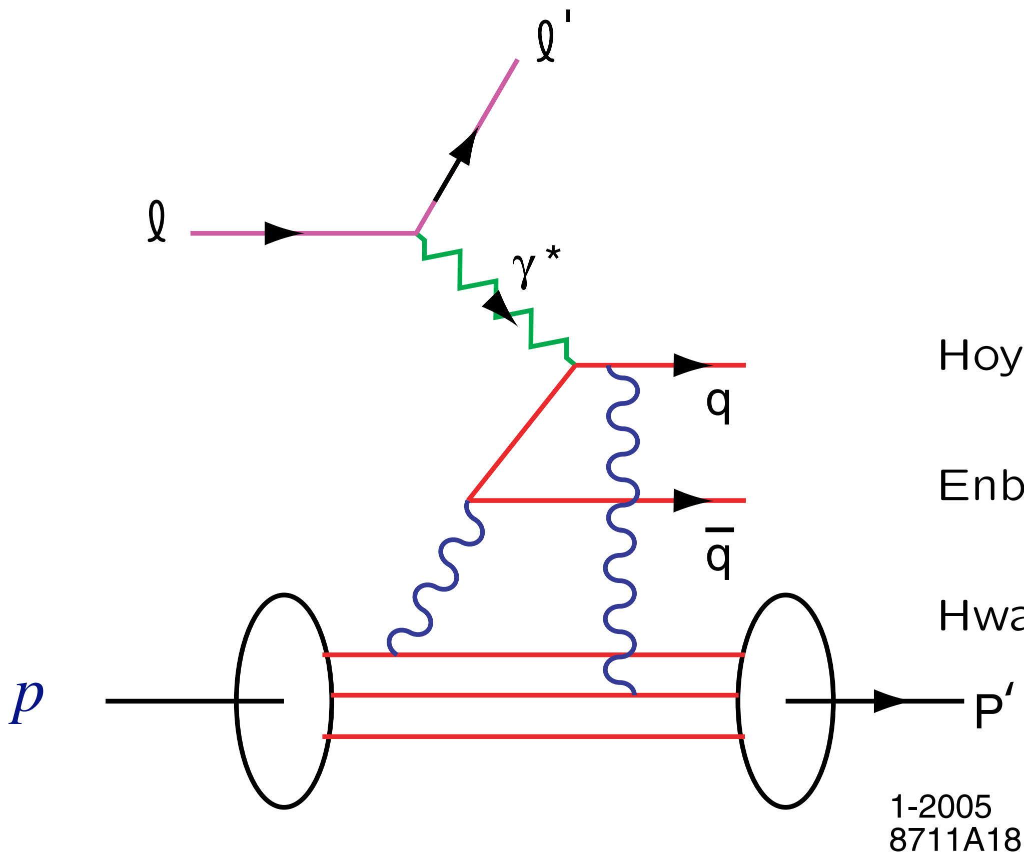


Fraction r of events with a large rapidity gap, $\eta_{\max} < 1.5$, as a function of Q^2_{DA} for two ranges of x_{DA}. No acceptance corrections have been applied.

10% to 15% of DIS events are diffractive !

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

Final-State Interaction Produces Diffractive DIS



Quark Rescattering

Hoyer, Marchal, Peigne, Sannino, SJB (BHM

Enberg, Hoyer, Ingelman, SJB

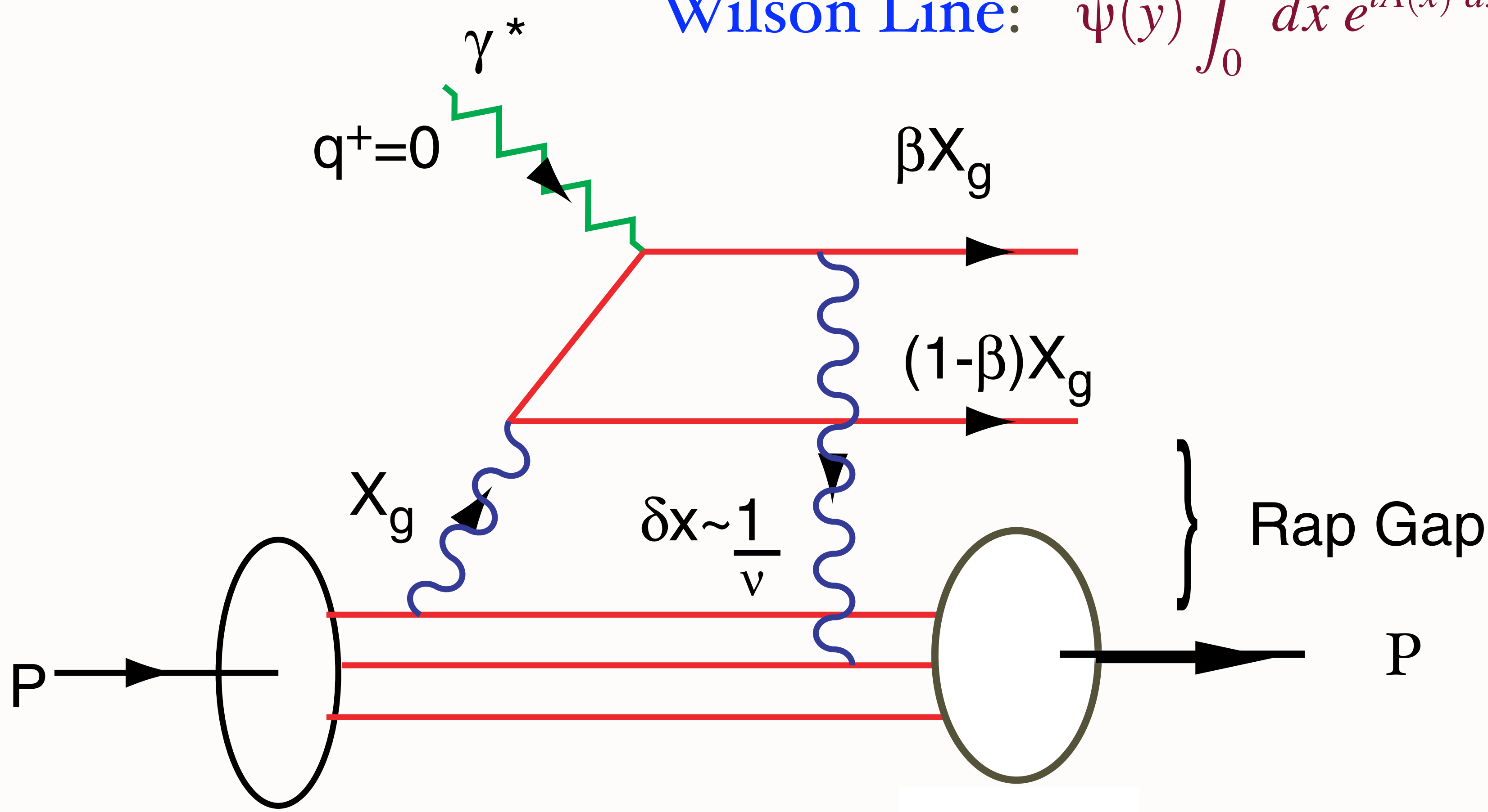
Hwang, Schmidt, SJB

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

Key QCD Experiment at FAIR

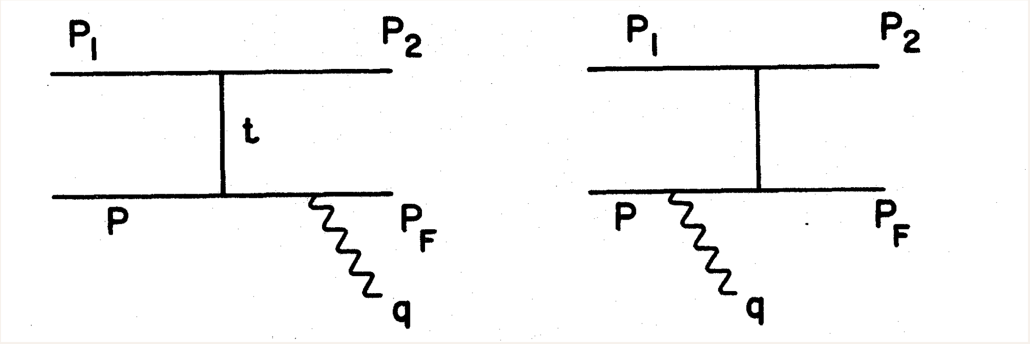
Double-Diffractive Drell-Yan

$$\bar{p}p \to \bar{p} + \ell^+\ell^- + p$$

Large-Mass Timelike Muon Pairs in Hadronic Interactions

S. M. Berman*, D. J. Levy, and T. L. Neff§

Phys. Rev. Lett. 23, 1363–1365 (1969)



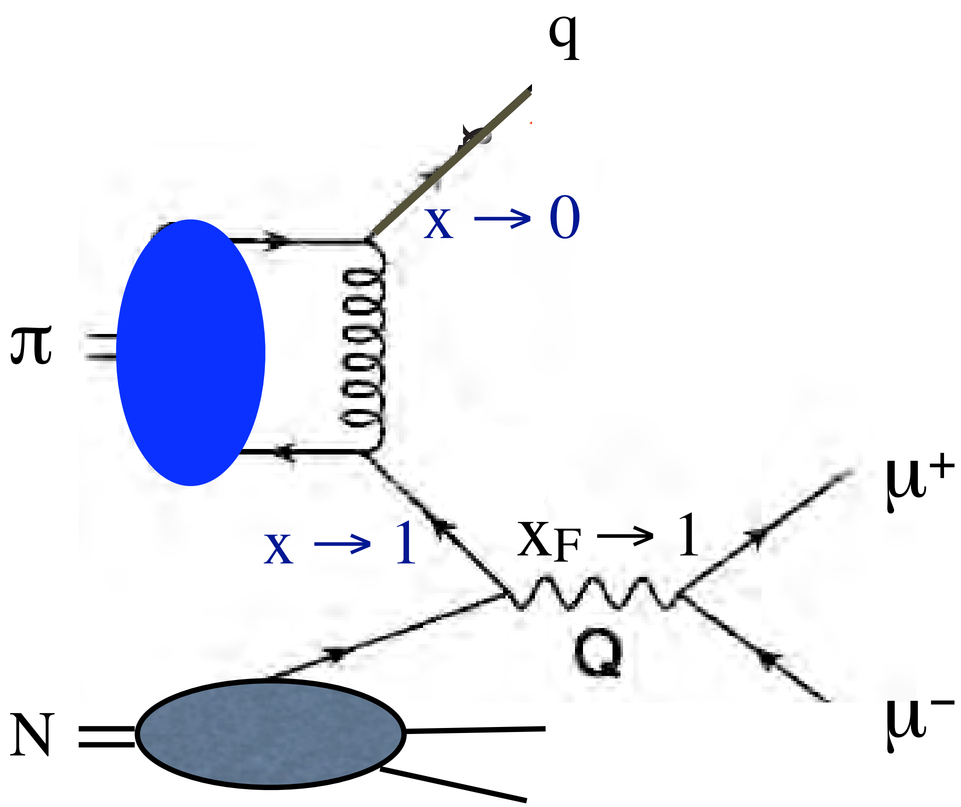
Prototype for exclusive Higgs production

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

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

Direct Higher Twist Subprocess

Entire pion wf contributes to hard process



Virtual photon is longitudinally polarized

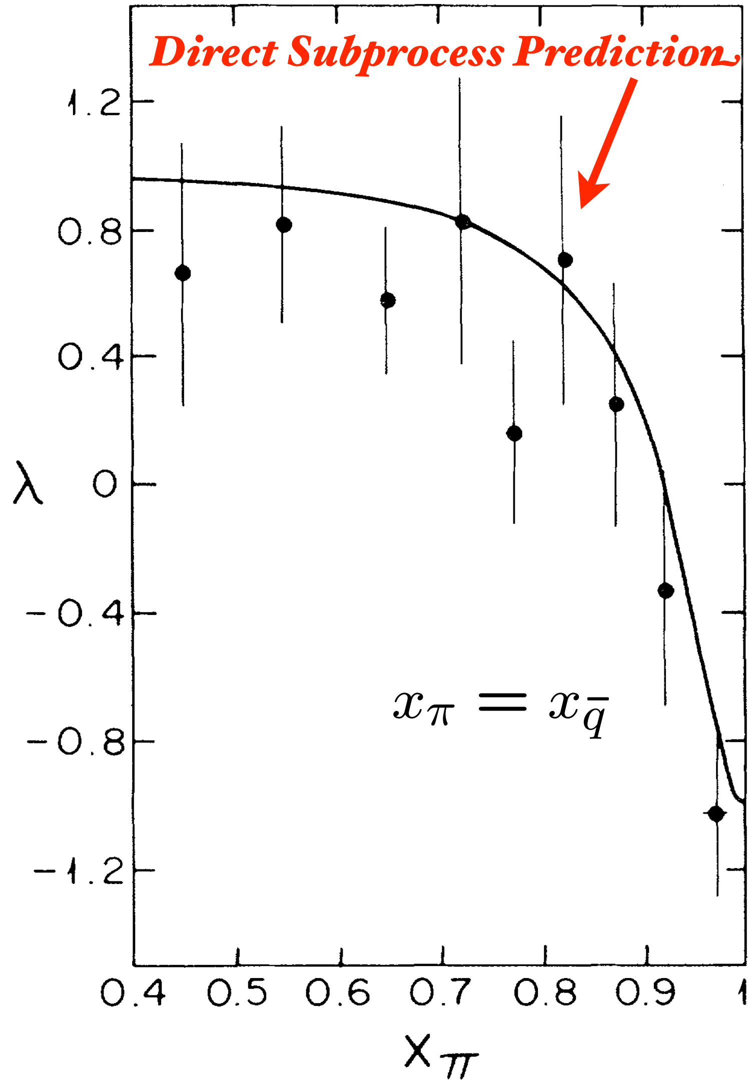
Berger and Brodsky, PRL 42 (1979) 940

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

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

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

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



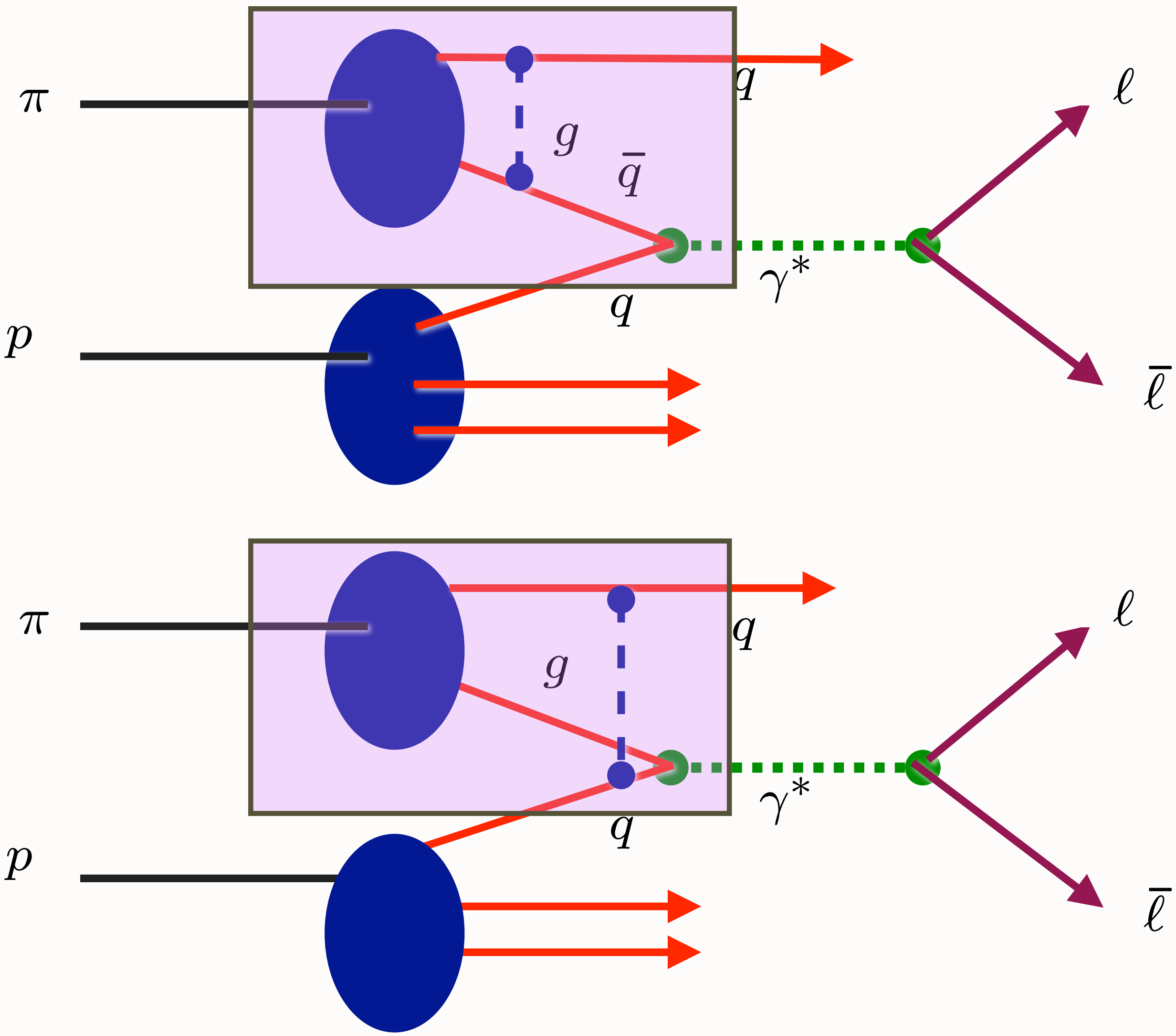
Dramatic change in angular distribution at large x_F

Example of a higher-twist direct subprocess

Chicago-Princeton Collaboration

Phys.Rev.Lett.55:2649,1985

Berger, Lepage, sjb



$$\pi q \rightarrow \gamma^* q$$

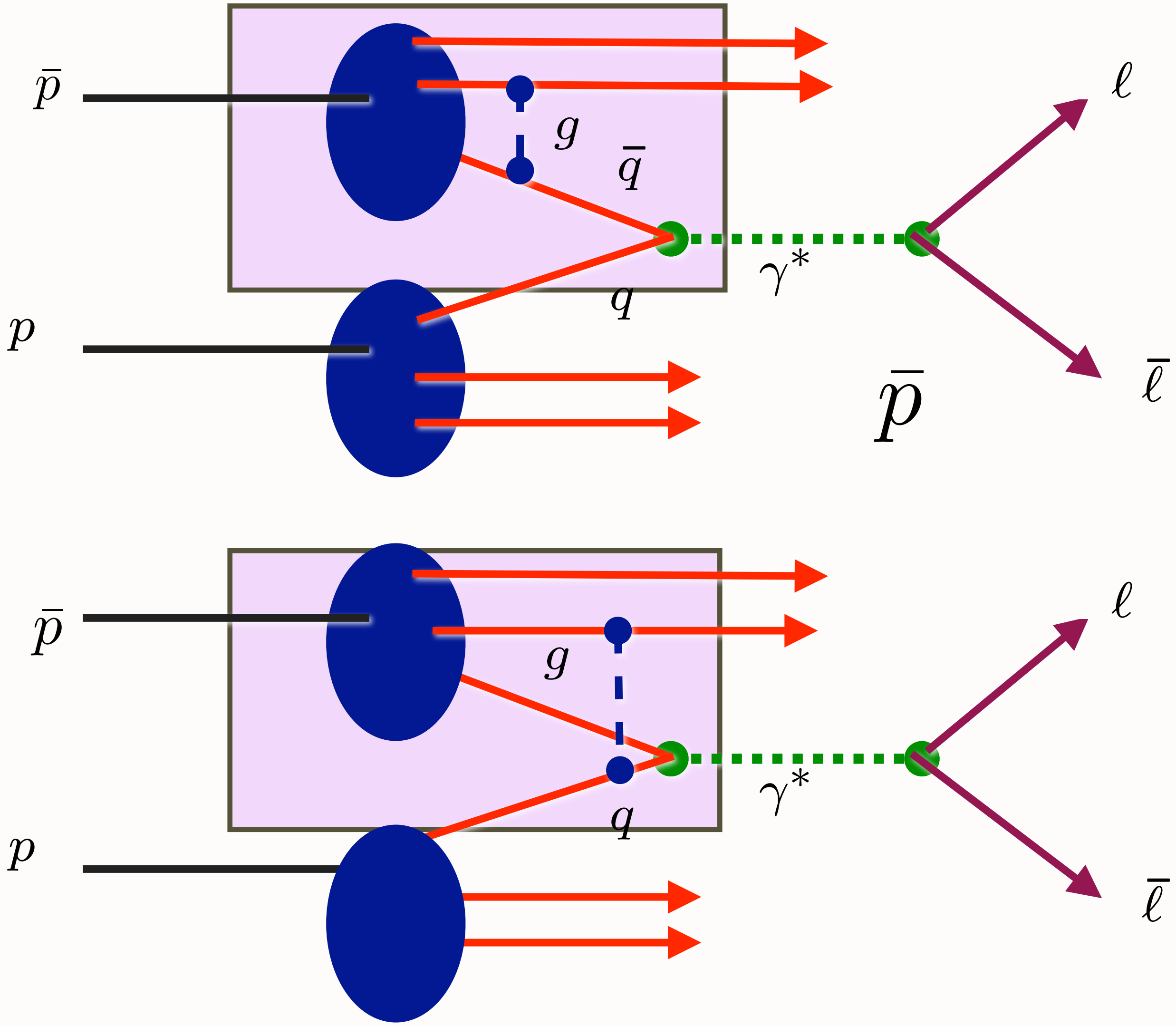
Initial State Interaction

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

$$A(1-x)^3(1+\cos^2\theta) + B\frac{(1-x)\sin^2\theta}{Q^2} + C\frac{(1+\cos^2\theta)}{(1-x)Q^4}$$



$$[\bar{q}\bar{q}]q \to \gamma^* \bar{q}$$

Diquark appears directly in subprocess

All of the diquark's momentum is transferred to the lepton pair

Lepton Pair is produced longitudinally polarized

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

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

The Light Front Fock State Wavefunctions

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

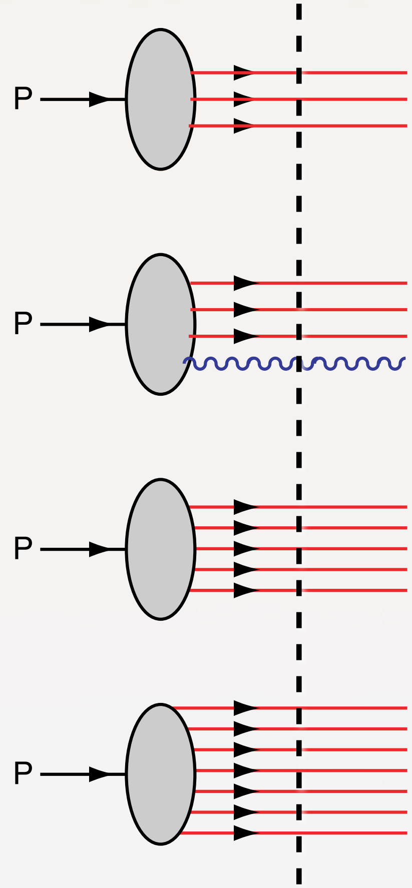
are boost invariant; they are independent of the hadron's energy and momentum P^μ.

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.

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



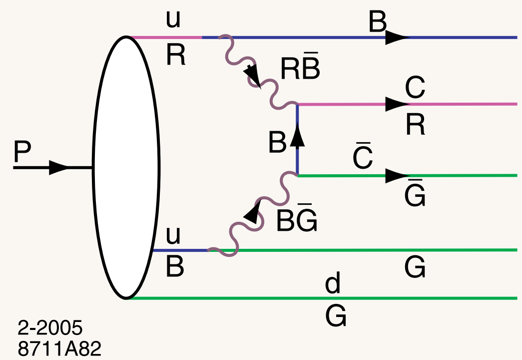
Fixed LF time

Intrinsic heavy quarks, $\bar{s}(x) \neq s(x)$

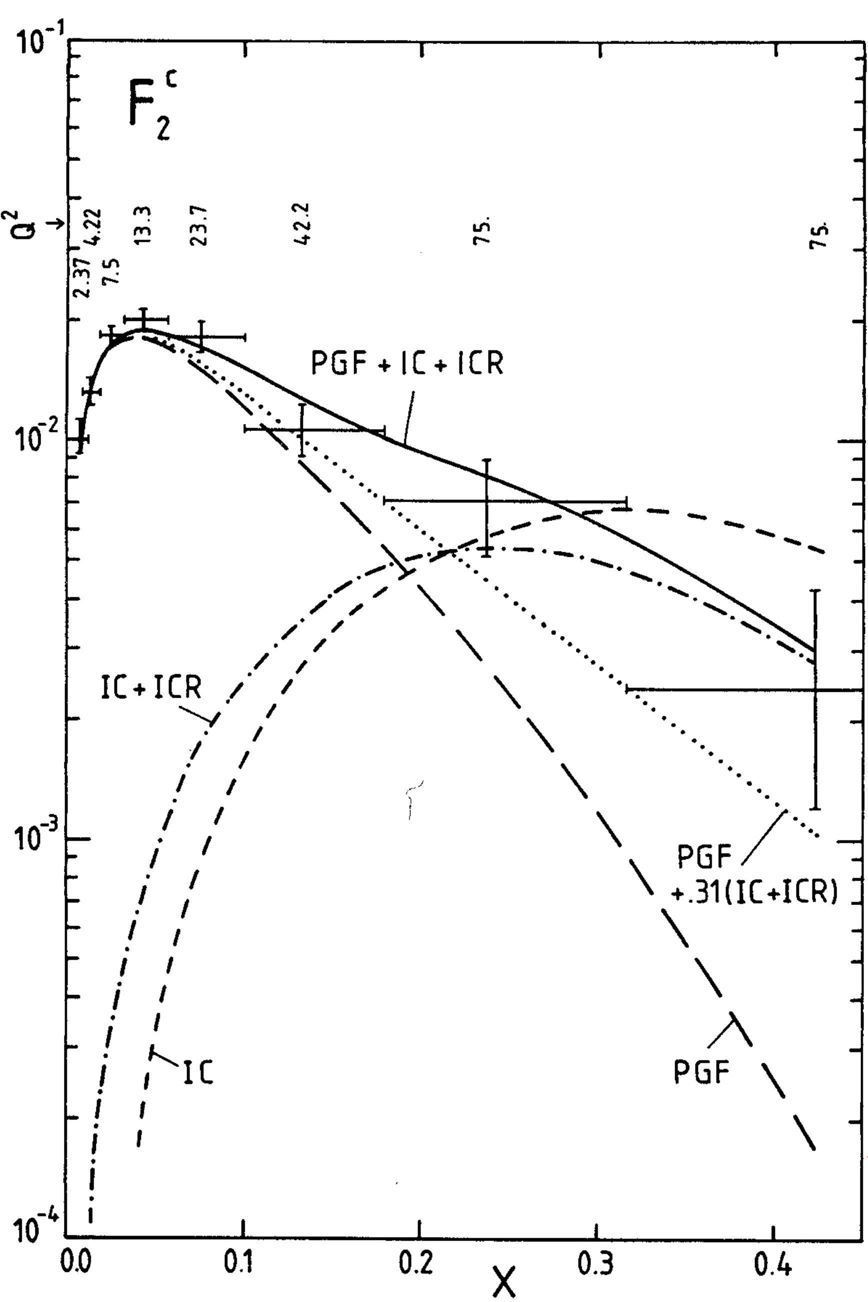
$\bar{u}(x) \neq \bar{d}(x)$

Hoyer, Peterson, Sakai, sjb

Intrinsic Heavy-Quark Fock States



- Rigorous prediction of QCD, OPE
- Color-Octet Color-Octet Fock State!
- Probability $P_{Q\bar{Q}} \propto \frac{1}{M_Q^2}$ $P_{Q\bar{Q}Q\bar{Q}} \sim \alpha_s^2 P_{Q\bar{Q}}$ $P_{c\bar{c}/p} \simeq 1\%$
- Large Effect at high x
- Greatly increases kinematics of colliders such as Higgs production (Kopeliovich, Schmidt, Soffer, sjb)
- Severely underestimated in conventional parameterizations of heavy quark distributions (Pumplin, Tung)
- Many empirical tests

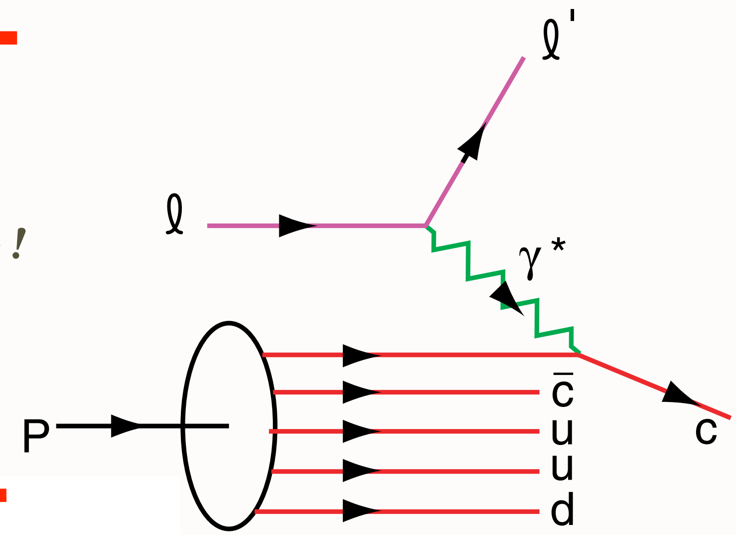


Measurement of Charm Structure Function

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

factor of 30 !



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

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

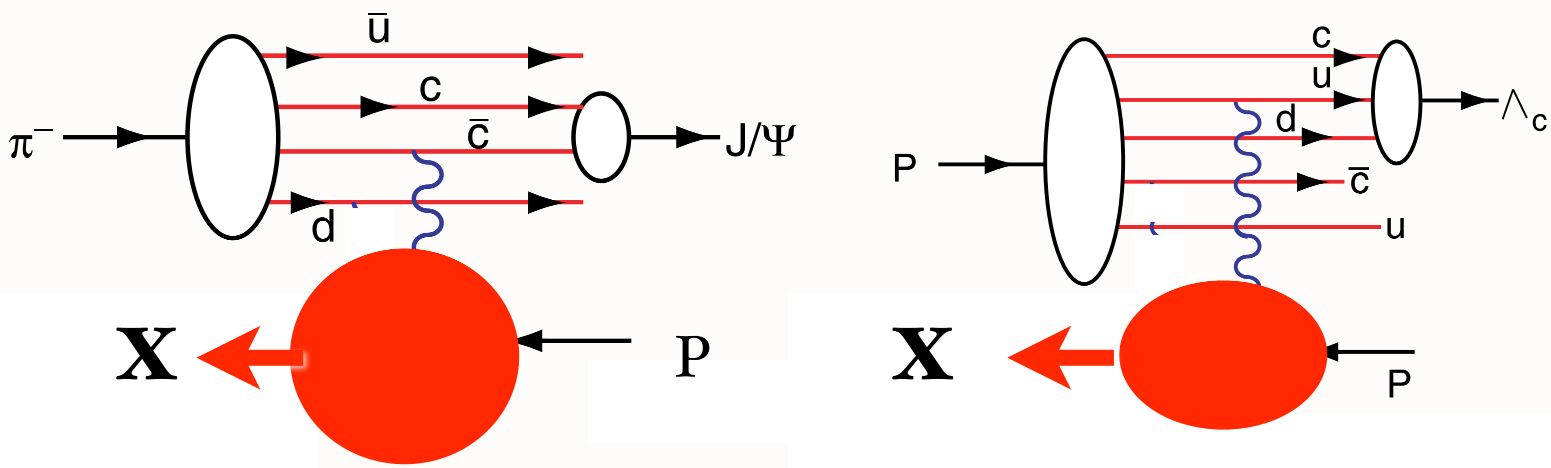
- High x_F $pp \to \Lambda_c X$

- High x_F $pp \to \Lambda_b X$

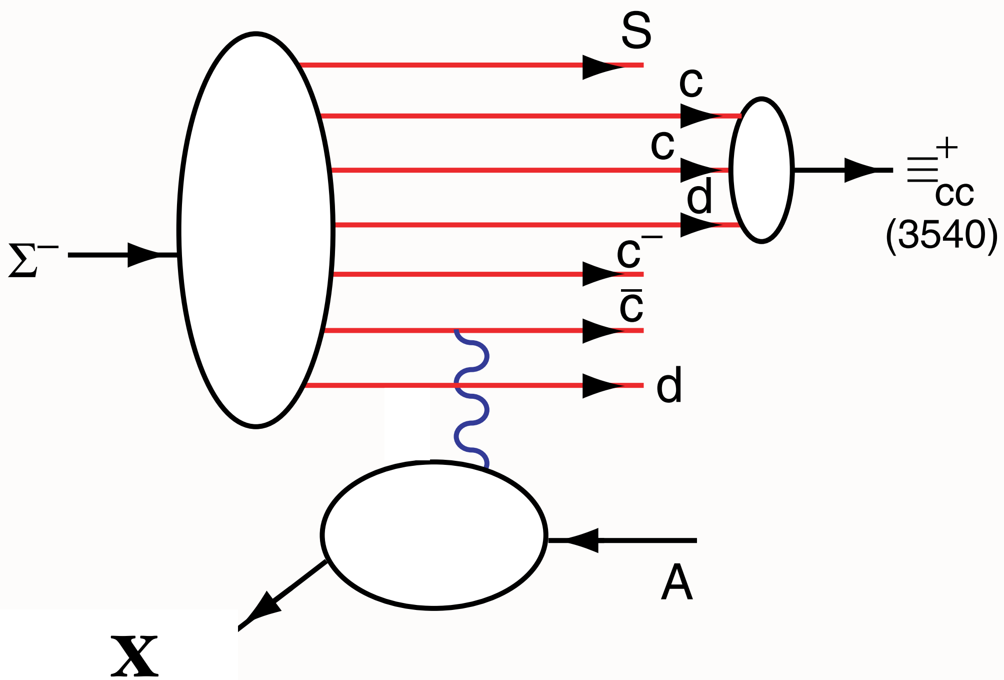
- High x_F $pp \to \Xi(ccd) X$ (SELEX)

C.H. Chang, J.P. Ma, C.F. Qiao and X.G.Wu, Hadronic production of the doubly charmed baryon Xi/cc with intrinsic charm," arXiv:hep-ph/0610205.

Leading Hadron Production from Intrinsic Charm



Coalescence of Comoving Charm and Valence Quarks Produce J/ψ, Λ_c and other Charm Hadrons at High x_F



Production of a Double-Charm Baryon

SELEX high x_F $< x_F >= 0.33$

Open and Hidden Charm Production Near Threshold

$$\bar{p}p \to J/\psi X$$

$$\bar{p}p \to D\bar{D}X$$

$$\bar{p}p \to \Lambda_c D X$$

- Several Mechanisms for Inclusive Production:

$$gg \to c\bar{c} \qquad q\bar{q} \to g \to c\bar{c}$$

$$c_I + g \to cg \qquad [c_I + \bar{c}_I] + g \to J/\psi$$

ISI and FSI, Schwinger Sommerfeld Threshold Corrections

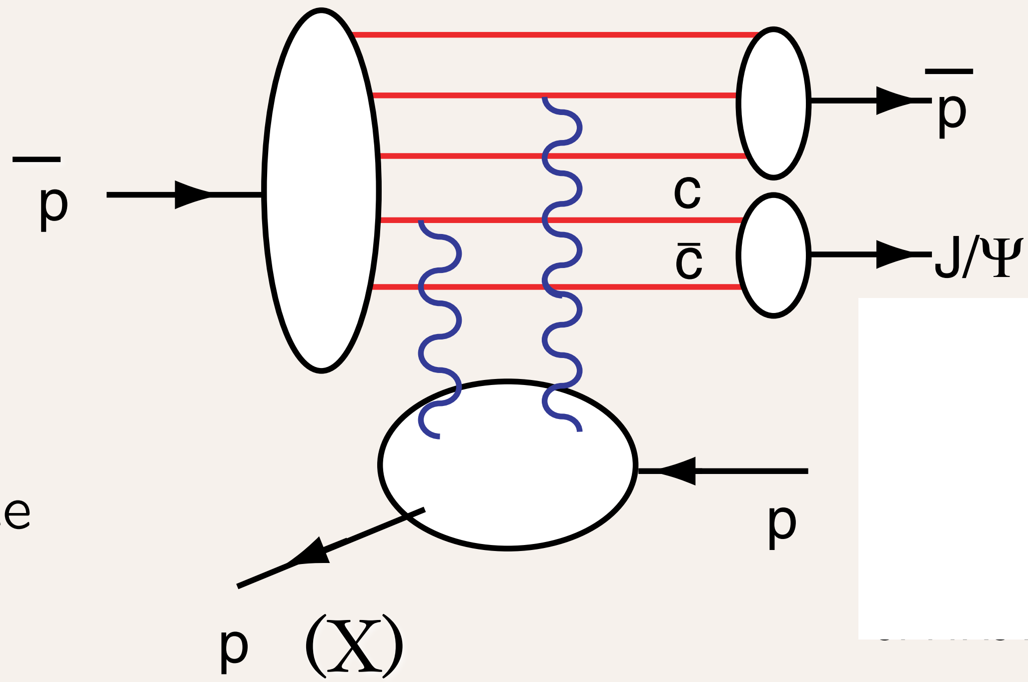
Key QCD Experiment at FAIR

Measure diffractive hidden charm production at forward x_F

Even close to threshold

$$\frac{d\sigma}{dt_1 dt_2 dx_F}(\overline{p}p \to \overline{p} + J/\psi + p)$$

$$\frac{d\sigma}{dt dx_F}(\overline{p}p \to \overline{p} + J/\psi + X)$$



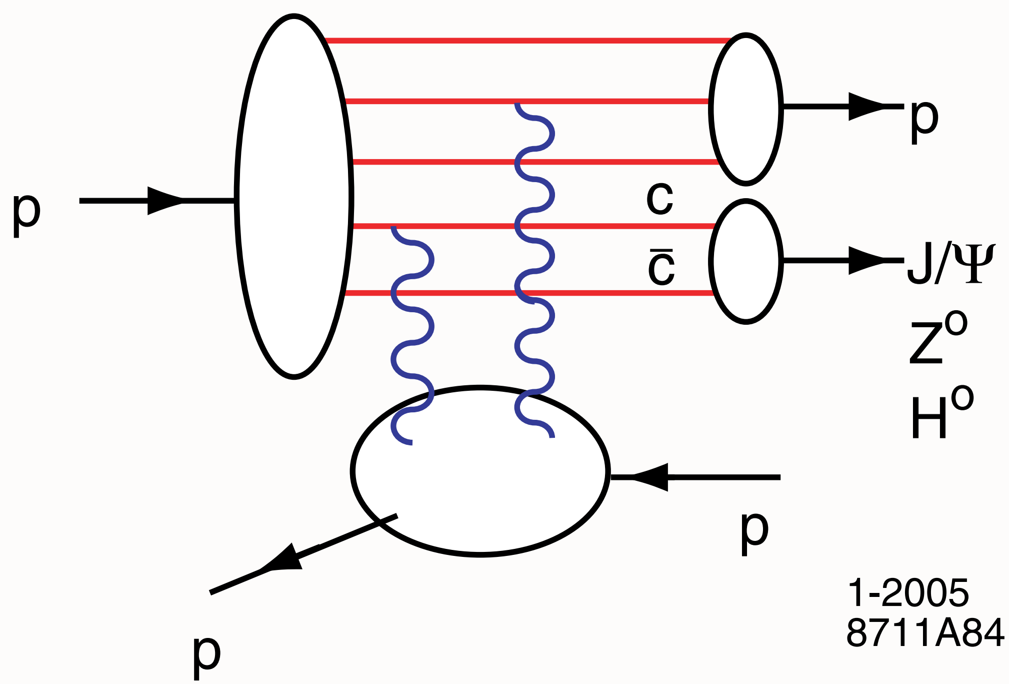
Anomalous nuclear dependence

$$\frac{d\sigma}{dx_F}(\overline{p}A \to J/\psi + X)$$

$A^{\alpha(x_2)}$ versus $A^{\alpha(x_F)}$

Important Tests of Intrinsic Charm

Intrinsic Charm Mechanism for Exclusive Diffraction Production



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

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

Exclusive Diffractive
High-X_F Higgs Production

Kopeliovitch, Schmidt, Soffer, sjb

Intrinsic $c\bar{c}$ pair formed in color octet 8_C in proton wavefunction   Large Color Dipole

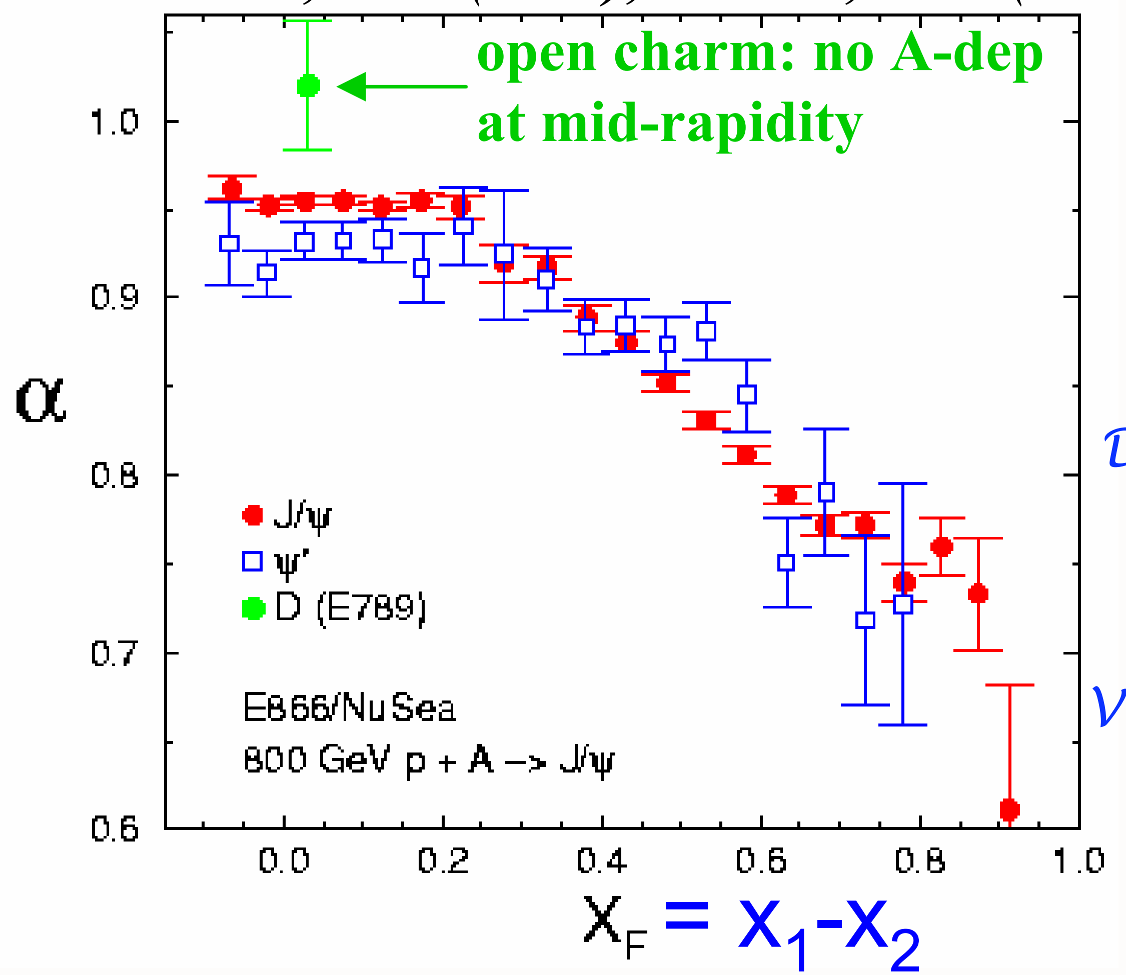
Collision produces color-singlet J/ψ through color exchange

RHIC Experiment

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