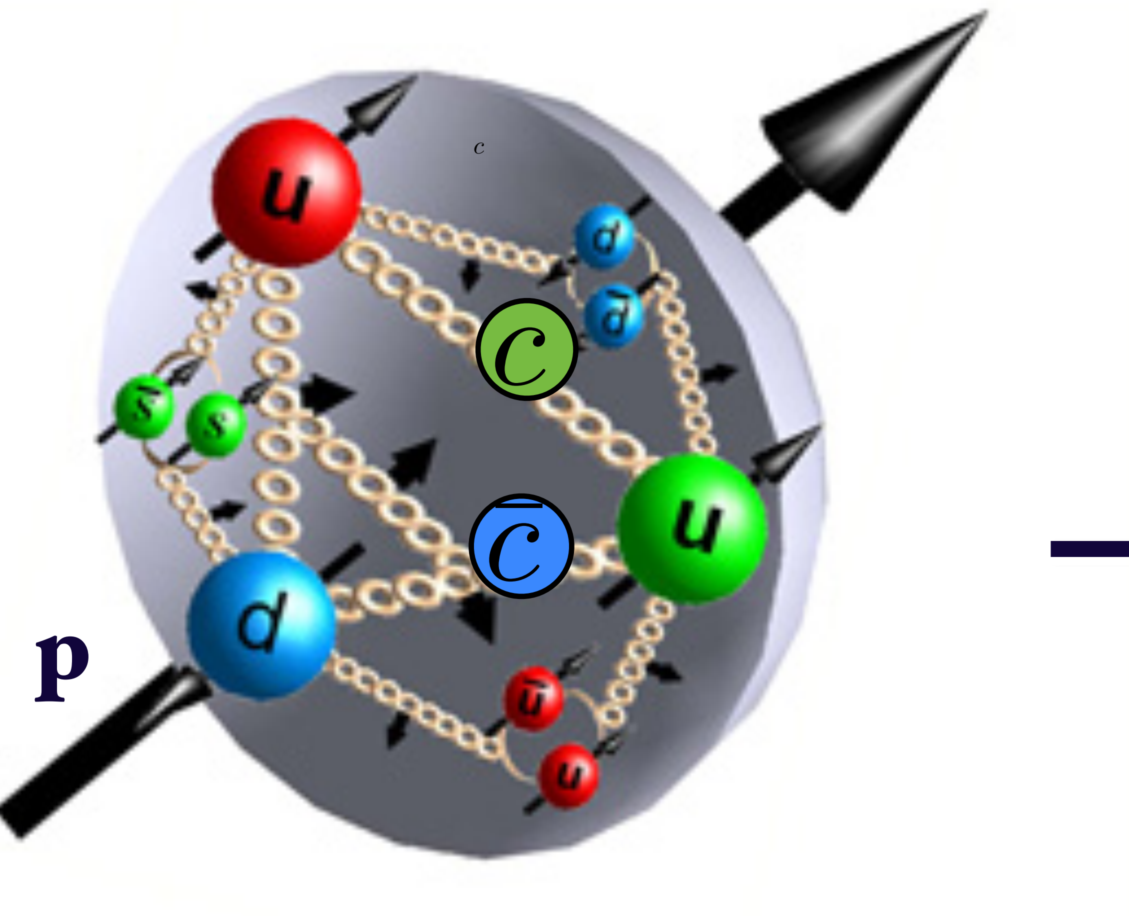
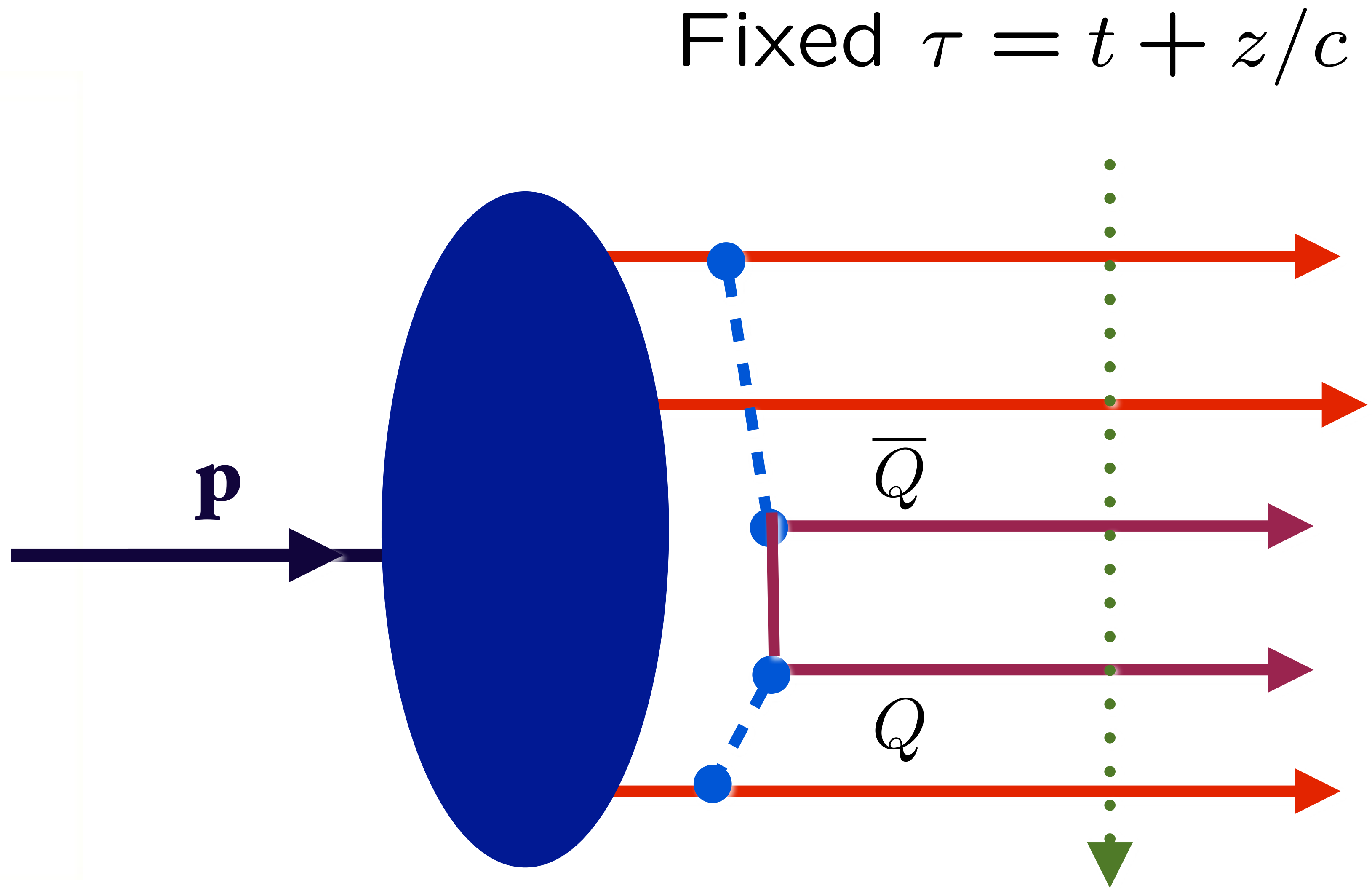
QCD, Heavy Flavors, and Higgs Production in the Very Forward Region





Workshop on Forward Physics and QCD at the LHC, the Future Electron Collider, and Cosmic Ray Physics

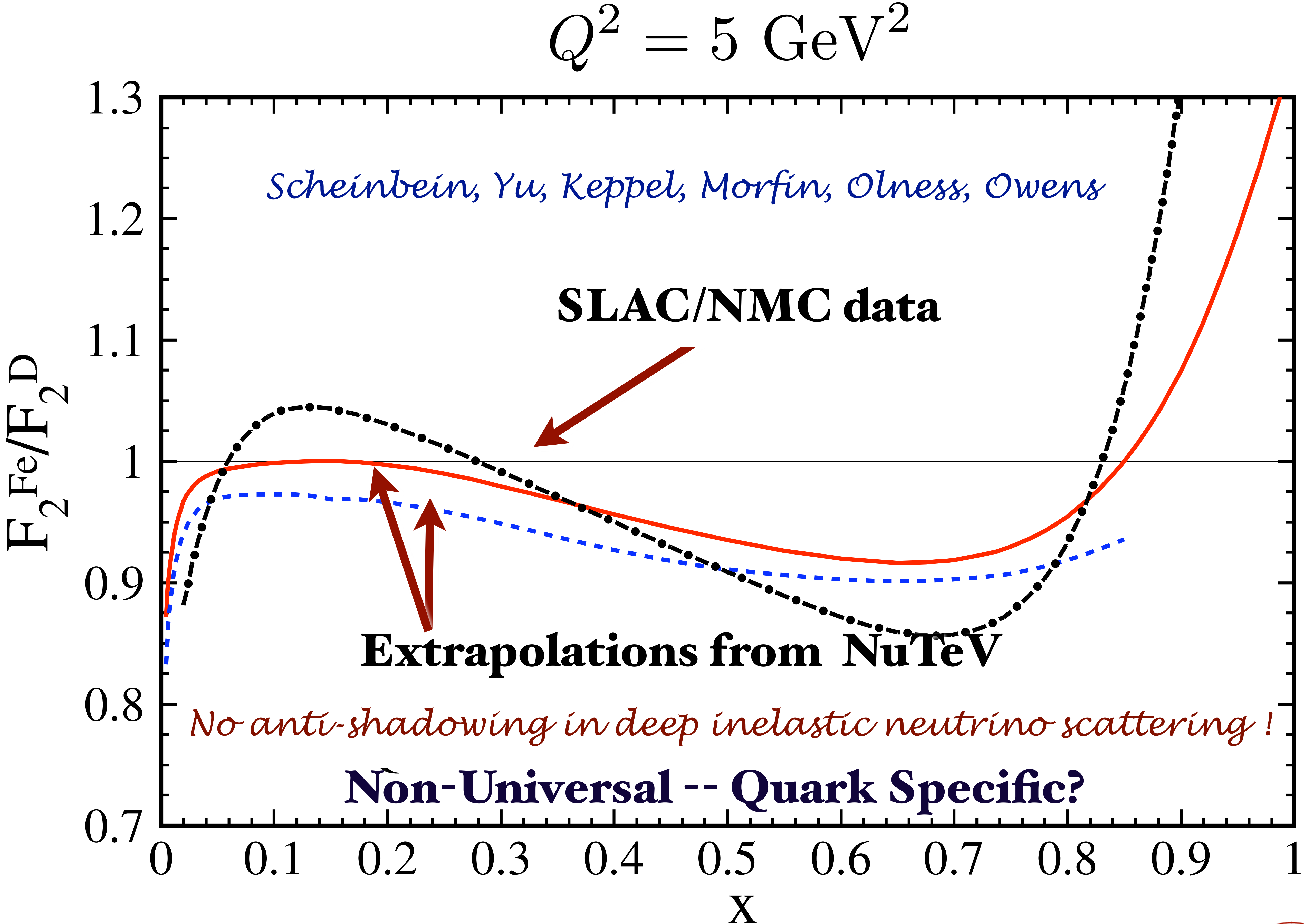
Hotel Guanajuato, Ciudad de Guanajuato, Mexico

November 18, 2019

Stan Brodsky

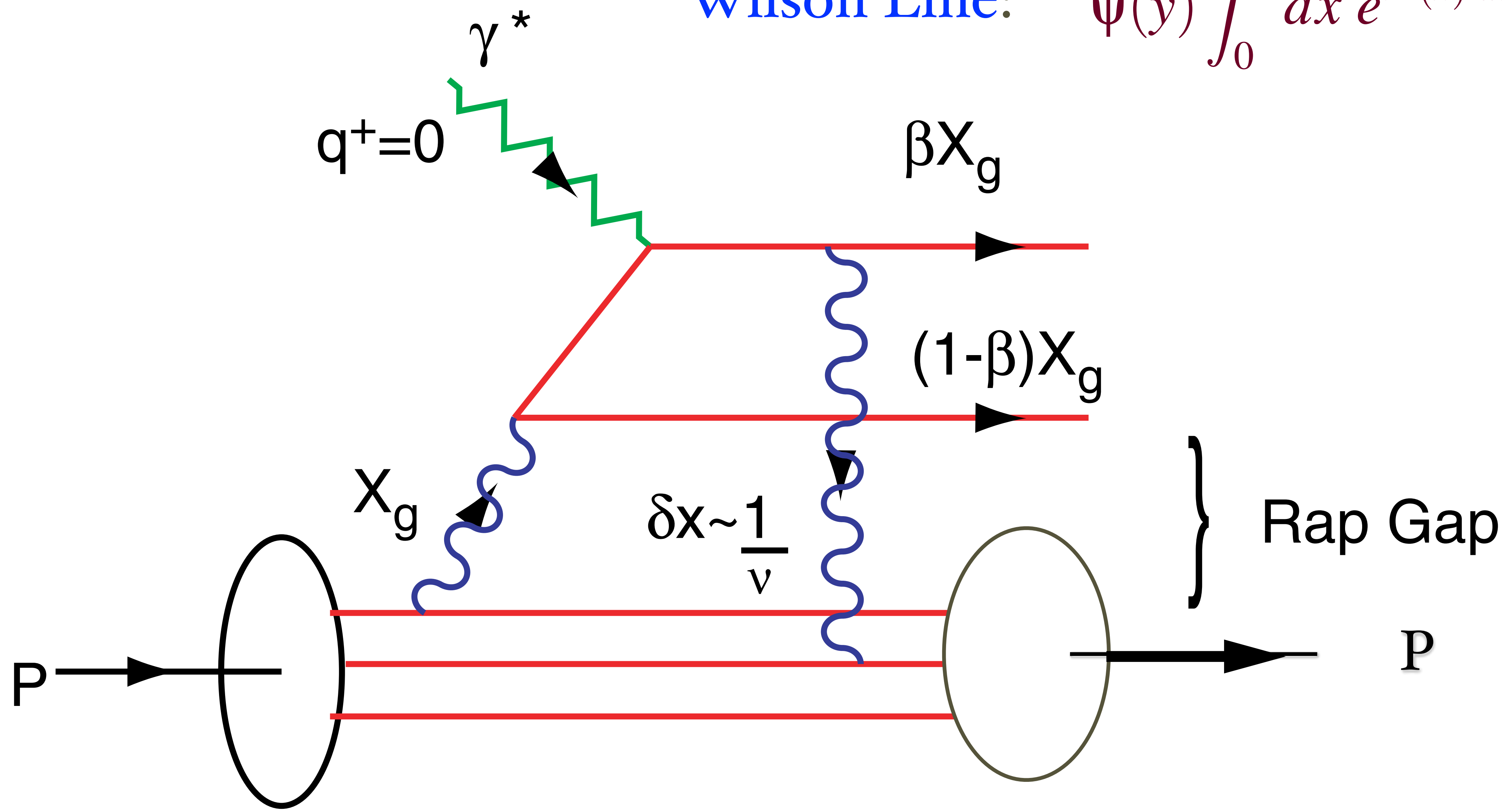
SLAC NATIONAL ACCELERATOR LABORATORY

LELAND STANFORD JUNIOR UNIVERSITY


$Q^2 = 5\ \mathrm{GeV}^2$
Scheinbein, Yu, Keppel, Morfin, Olness, Owens
SLAC/NMC data
Extrapolations from NuTeV
No anti-shadowing in deep inelastic neutrino scattering !
Non-Universal -- Quark Specific?
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

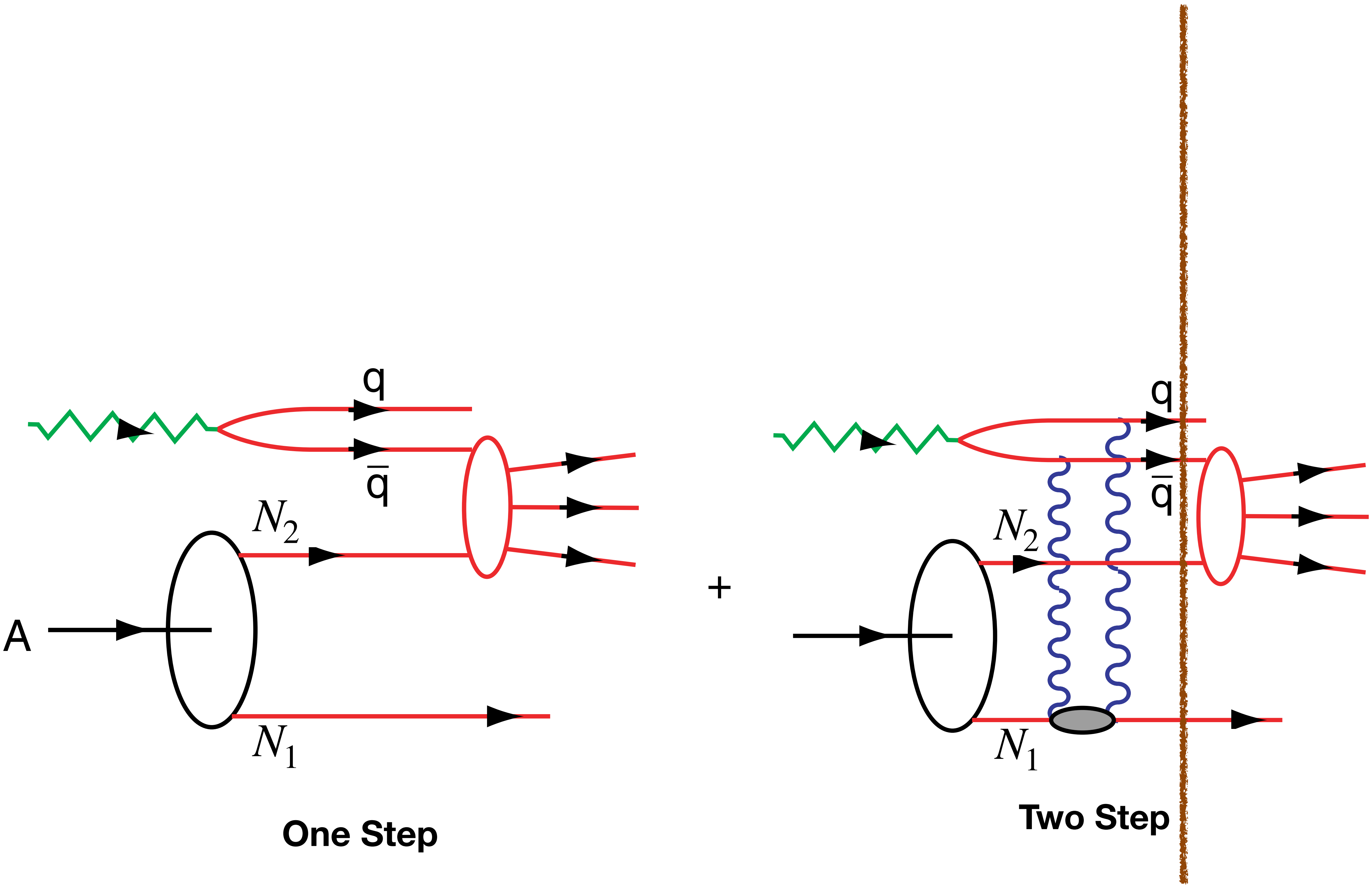
QCD Mechanism for Rapidity Gaps

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



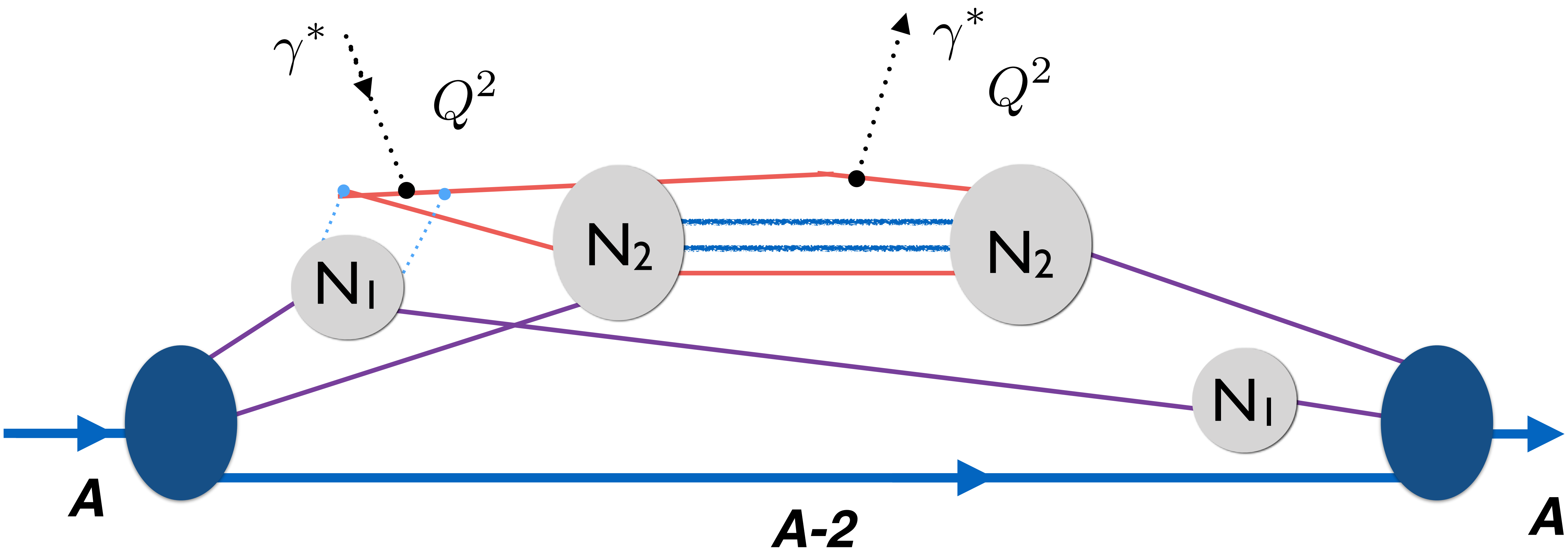
Reproduces lab-frame color dipole approach

DDIS: Input for leading twist nuclear shadowing



Glauber Cut:
On-Shell Propagation

Doubly Virtual Nuclear Compton Scattering $\gamma^*(q)A \to \gamma^*(q)A$



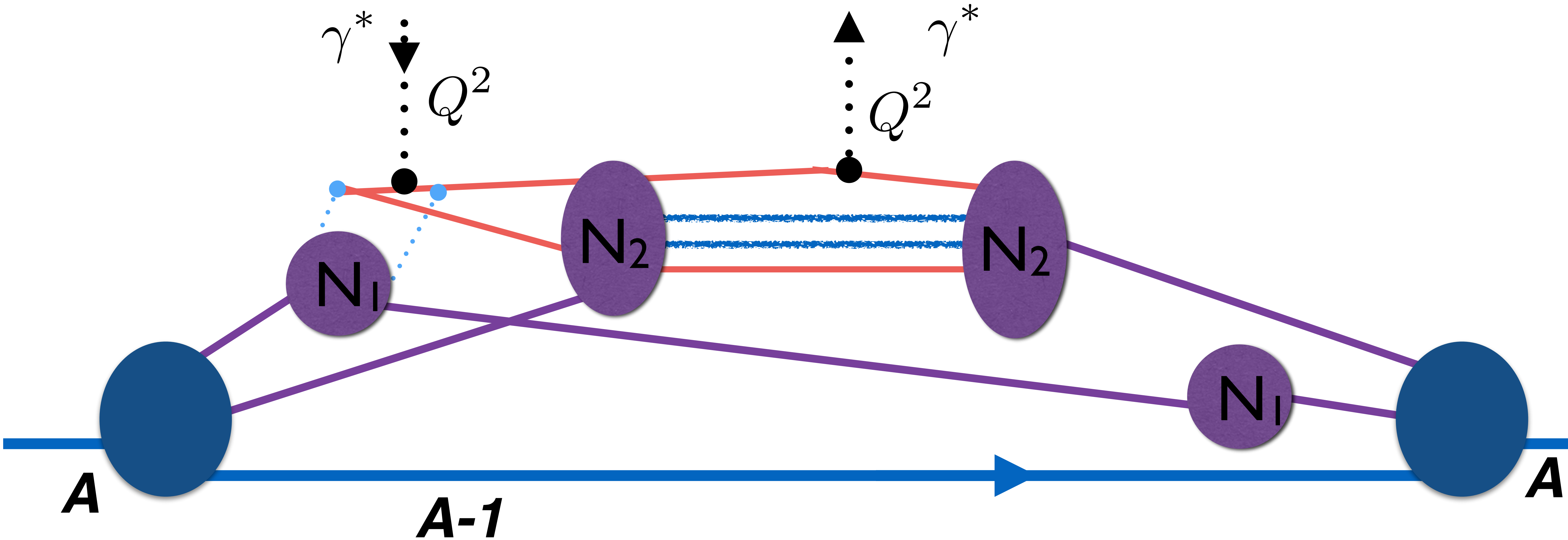
Front-Face Nucleon N_1 struck

Front-Face Nucleon N_1 not struck

Contribution from One-Step / Two-Step Interference

Illustrates the LF time sequence

$$q^+ = 0 \quad q_\perp^2 = Q^2 = -q^2$$



Front-Face Nucleon N_1 struck

Front-Face Nucleon N_1 not struck

One-Step / Two-Step Interference

Study Double Virtual Compton Scattering $\gamma^* A \to \gamma^* A$

Cannot reduce to matrix element of local operator! No Sum Rules!

Liuti, Schmidt sjb

S. Liuti, I. Schmidt, sjb

- Unlike shadowing, anti-shadowing from Reggeon exchange is flavor specific;
- Each quark and anti-quark will have distinctly different constructive interference patterns
- The flavor dependence of antishadowing explains why anti- shadowing is different for electron (neutral electro- magnetic current) vs. neutrino (charged weak current) DIS reactions.
- Test of the explanation of antishadowing: Bjorken-scaling leading-twist charge exchange DDIS reaction $\gamma^* p \to n X^+$ with a rapidity gap due to I=1 Reggeon exchang
- The finite path length due to the on-shell propagation of V^0 between N_1 and N_2 contributes a finite distance $(\Delta z)^2$ between the two virtual photons in the DVCS amplitude.

The usual "handbag" diagram where the two $J^\mu(x)$ and $J^\nu(0)$ currents acting on an uninterrupted quark propagator are replaced by a local operator $T^{\mu\nu}(0)$ as $Q^2 \to \infty$, is inapplicable in deeply virtual Compton scattering from a nucleus since the currents act on different nucleons.

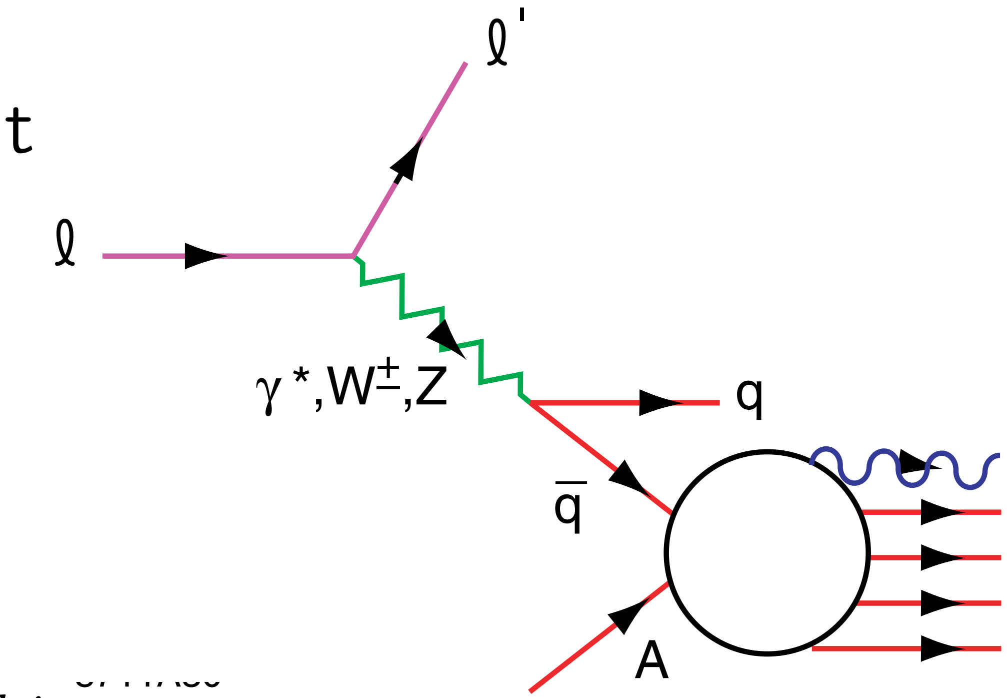
$$\Delta z^2 \text{ does not vanish as } \frac{1}{Q^2}.$$

OPE and Sum Rules invalid for nuclear pdfs

Origin of Regge Behavior of Deep Inelastic Structure Functions

$$F_{2p}(x) - F_{2n}(x) \propto x^{1/2}$$

Antiquark interacts with target nucleus at energy $\widehat{s} \propto \frac{1}{x_{bj}}$



Regge contribution: $\sigma_{\bar{q}N} \sim \widehat{s}^{\alpha_R - 1}$

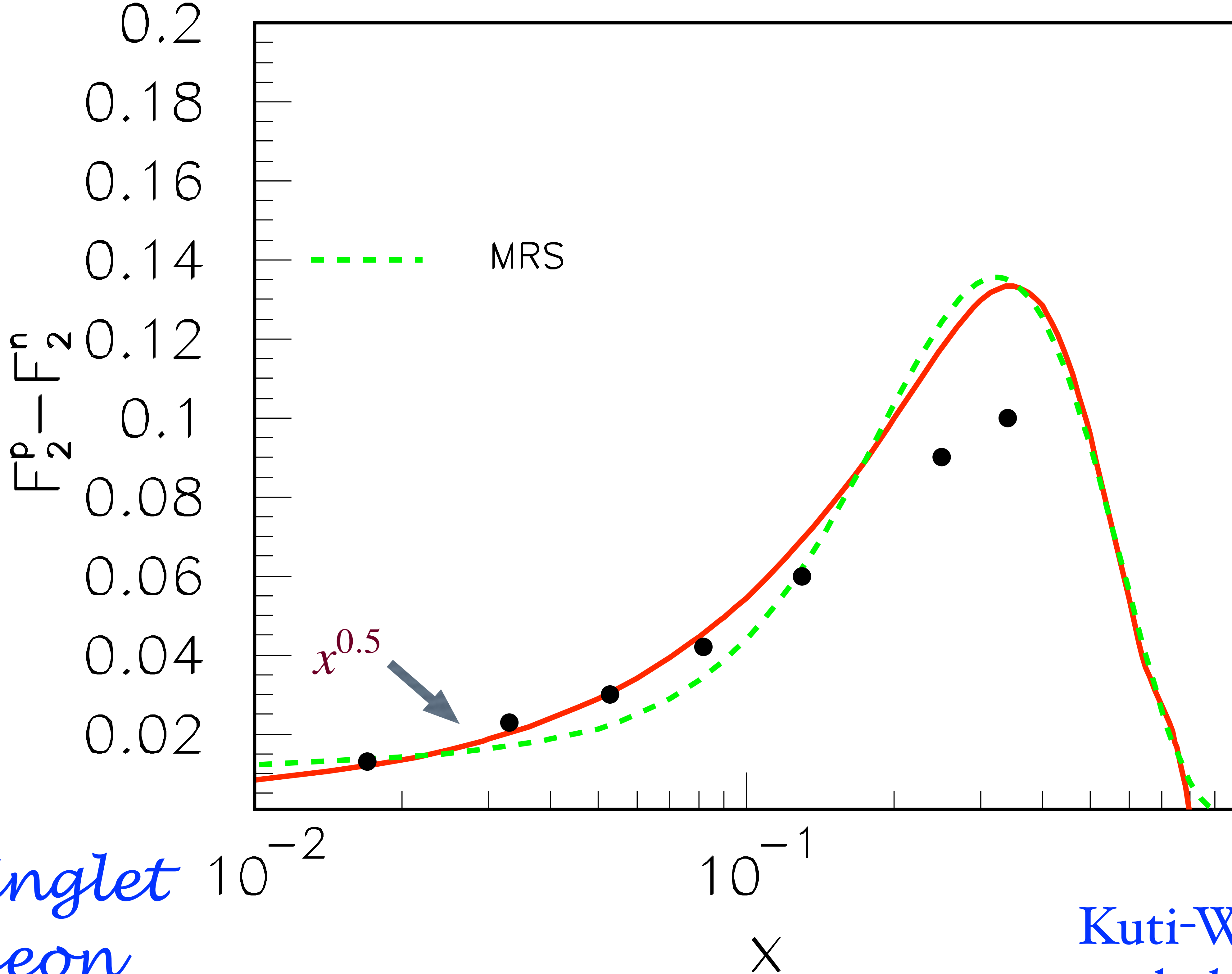
Nonsinglet Kuti-Weisskoff $F_{2p} - F_{2n} \propto \sqrt{x_{bj}}$ at small x_{bj}.

Shadowing of $\sigma_{\bar{q}M}$ produces shadowing of nuclear structure function.

Landshoff, Polkinghorne, Short

Close, Gunion, sjb

Schmidt, Yang, Lu, sjb



Non-singlet Reggeon Exchange

Kuti-Weisskopf behavior

Reggeon Exchange

Phase of two-step amplitude relative to one step:

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

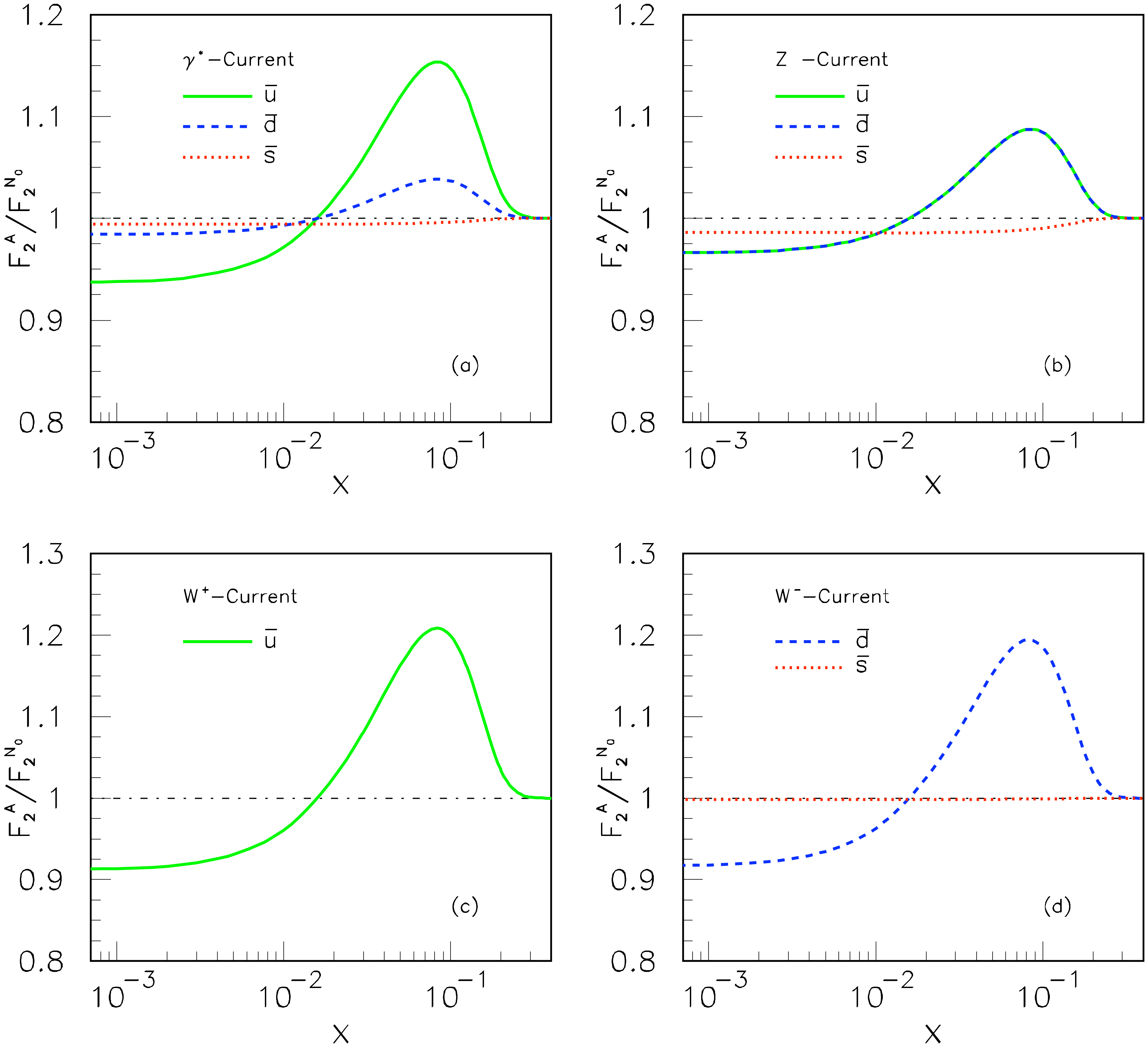
Constructive Interference

Depends on quark flavor!

Thus antishadowing is not universal

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

Critical tests: Tagged SIDIS, Drell-Yan



Schmidt, Yang; sjb

Modifies NuTeV extraction of

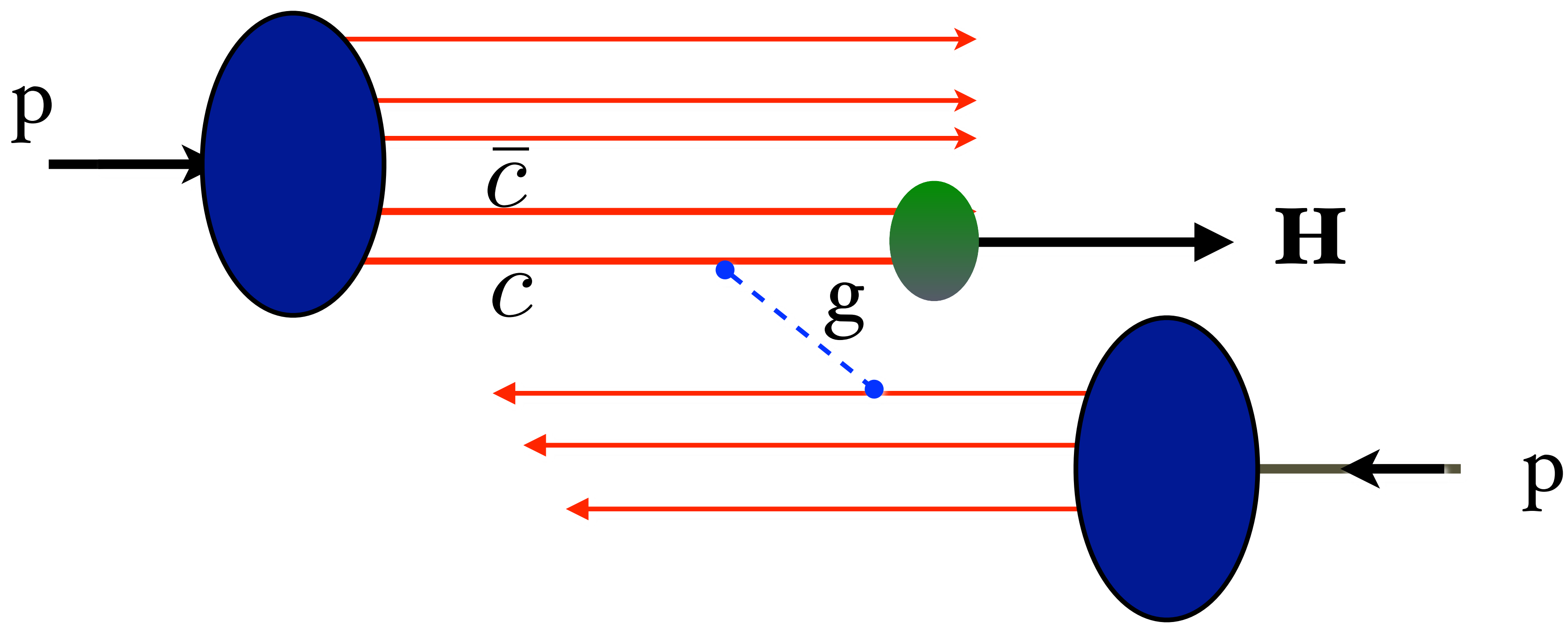
$$\sin^2 \theta_W$$

Test in flavor-tagged DIS at the EIC

Nuclear Antishadowing not universal !

Goldhaber, Kopeliovich, Schmidt, Soffer sjb

Intrinsic Charm Mechanism for Inclusive High-X_F Higgs Production



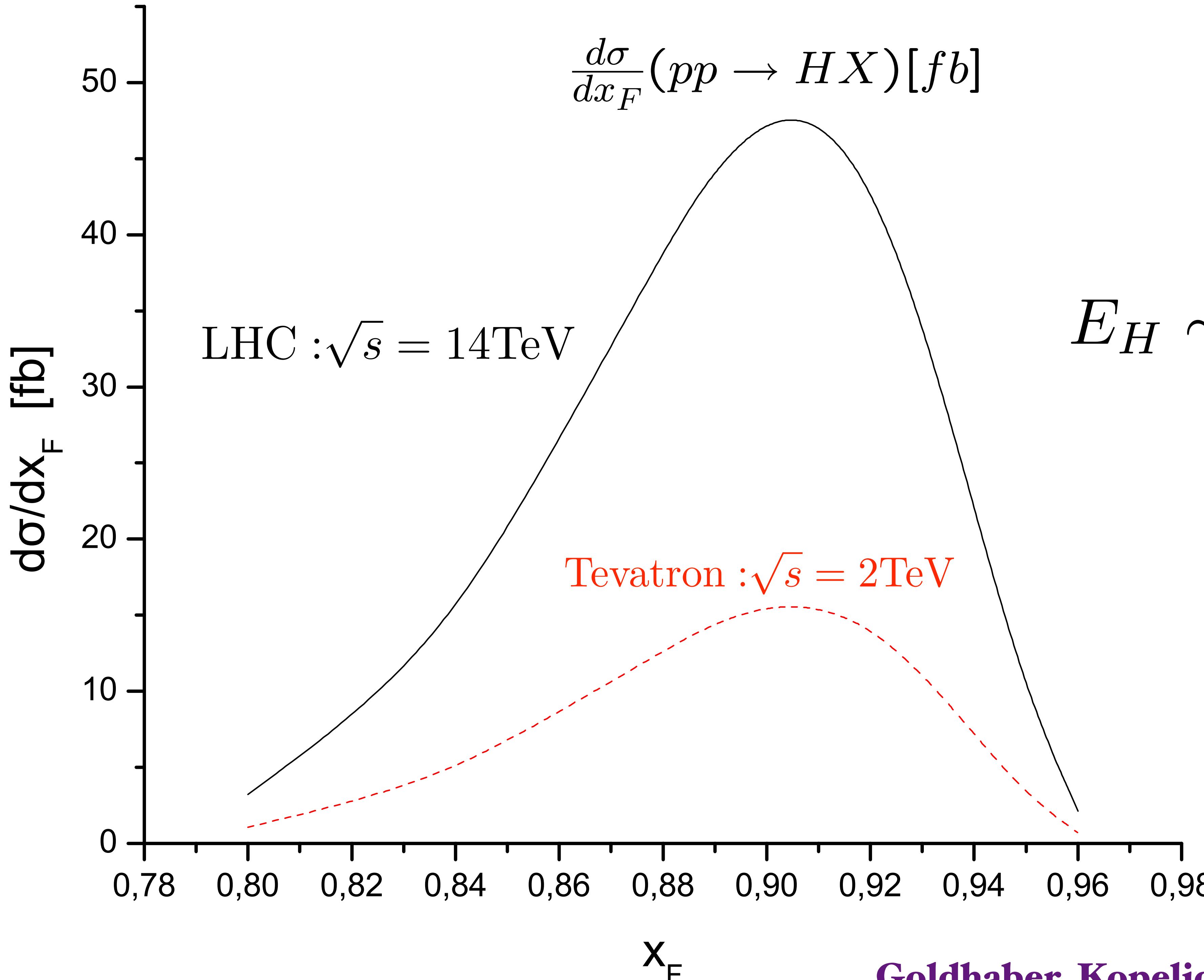
$$pp \to HX$$

Also: intrinsic strangeness, bottom, top

Higgs can have > 80% of Proton Momentum!

New production mechanism for Higgs

Intrinsic Heavy Quark Contribution to Inclusive Higgs Production



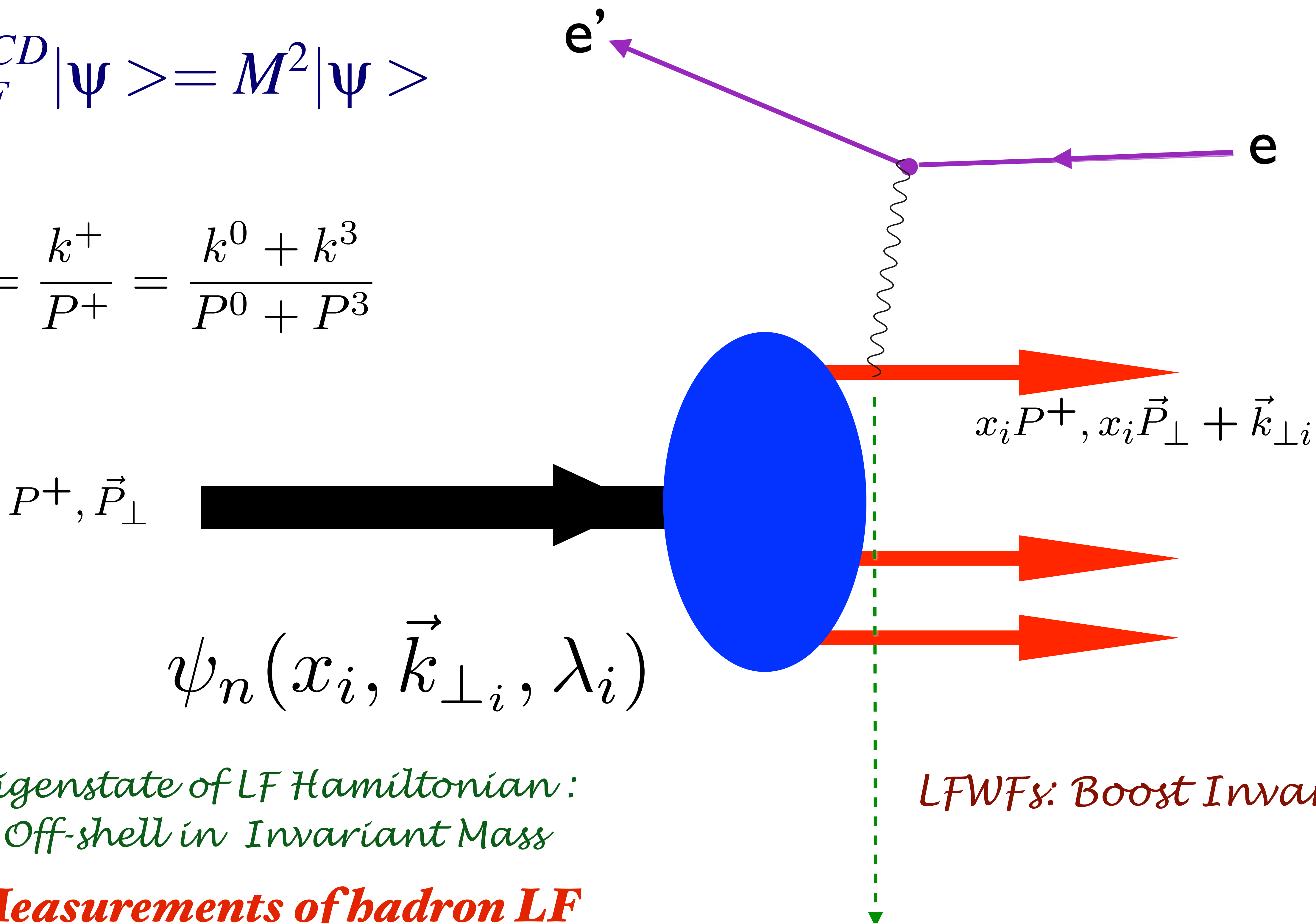
$$E_H \sim 0.9 E_p$$

Goldhaber, Kopeliovich, Schmidt, sjb

$$\text{Measure } H \to ZZ^* \to \mu^+\mu^-\mu^+\mu^-.$$

$$\mathrm{H}^{QCD}_{LF}|\psi> = M^2|\psi>$$

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



$$\psi_n(x_i, \vec{k}_{\perp_i}, \lambda_i)$$

Eigenstate of LF Hamiltonian :
Off-shell in Invariant Mass

LFWFs: Boost Invariant

Measurements of hadron LF wavefunction are at fixed LF time

Fixed $\tau = t + z/c$

Like a flash photograph

$$x_{bj} = x = \frac{k^+}{P^+}$$

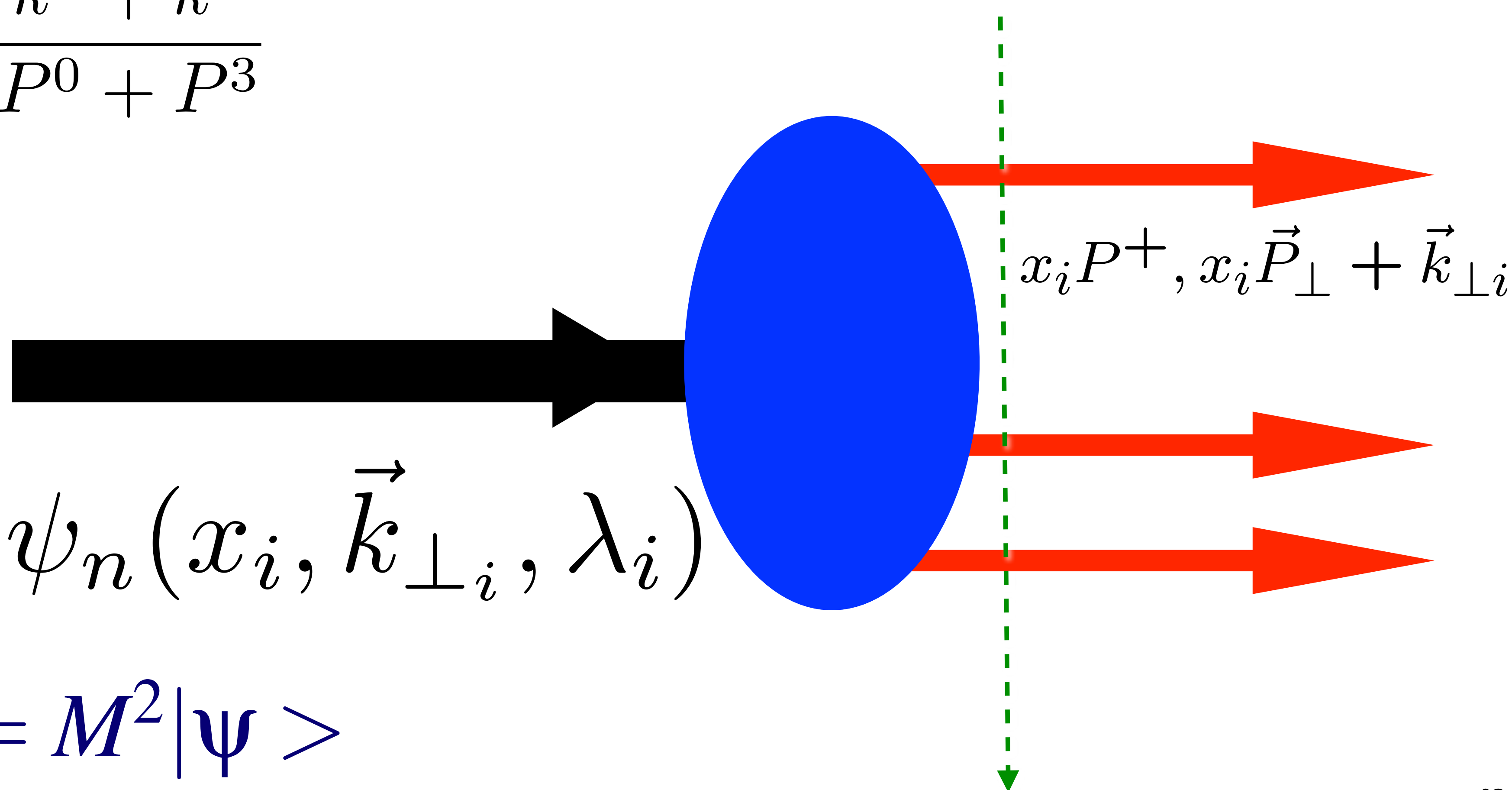
Light-Front Wavefunctions: rigorous representation of composite systems in quantum field theory

Eigenstate of LF Hamiltonian

Fixed $\tau = t + z/c$

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

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



$$\psi_n(x_i, \vec{k}_{\perp_i}, \lambda_i)$$

$$\mathrm{H}_{LF}^{QCD} |\psi> = M^2 |\psi>$$

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

$\sum_i^n x_i = 1$

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

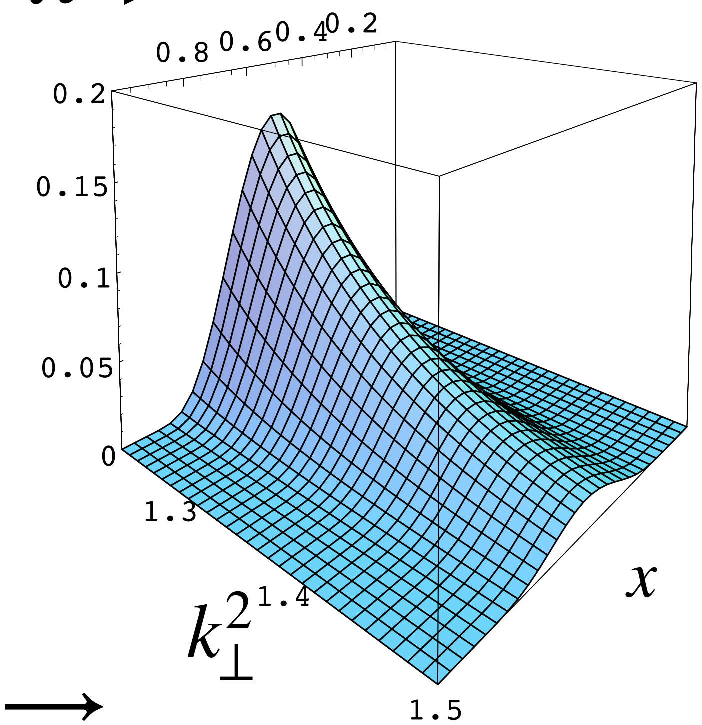
Invariant under boosts! Independent of P^μ

Causal, Frame-independent. Creation Operators on Simple Vacuum, Current Matrix Elements are Overlaps of LFWFS

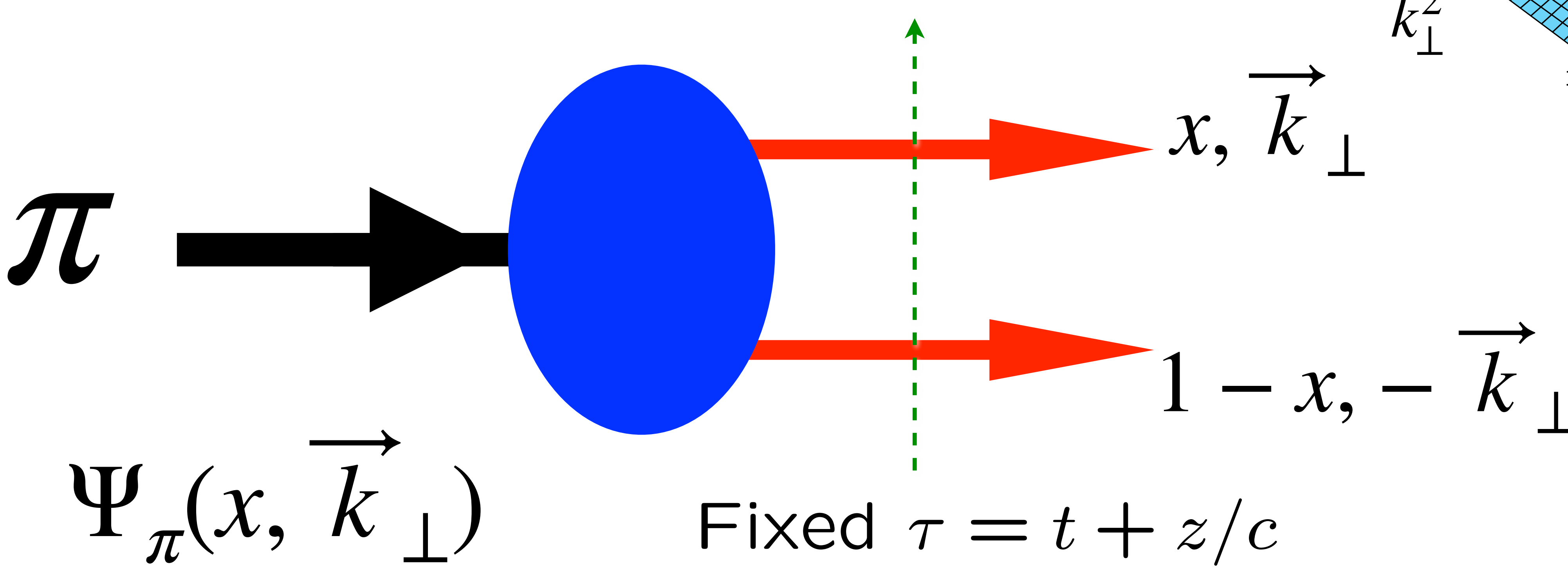
The Pion's Valence Light-Front Wavefunction

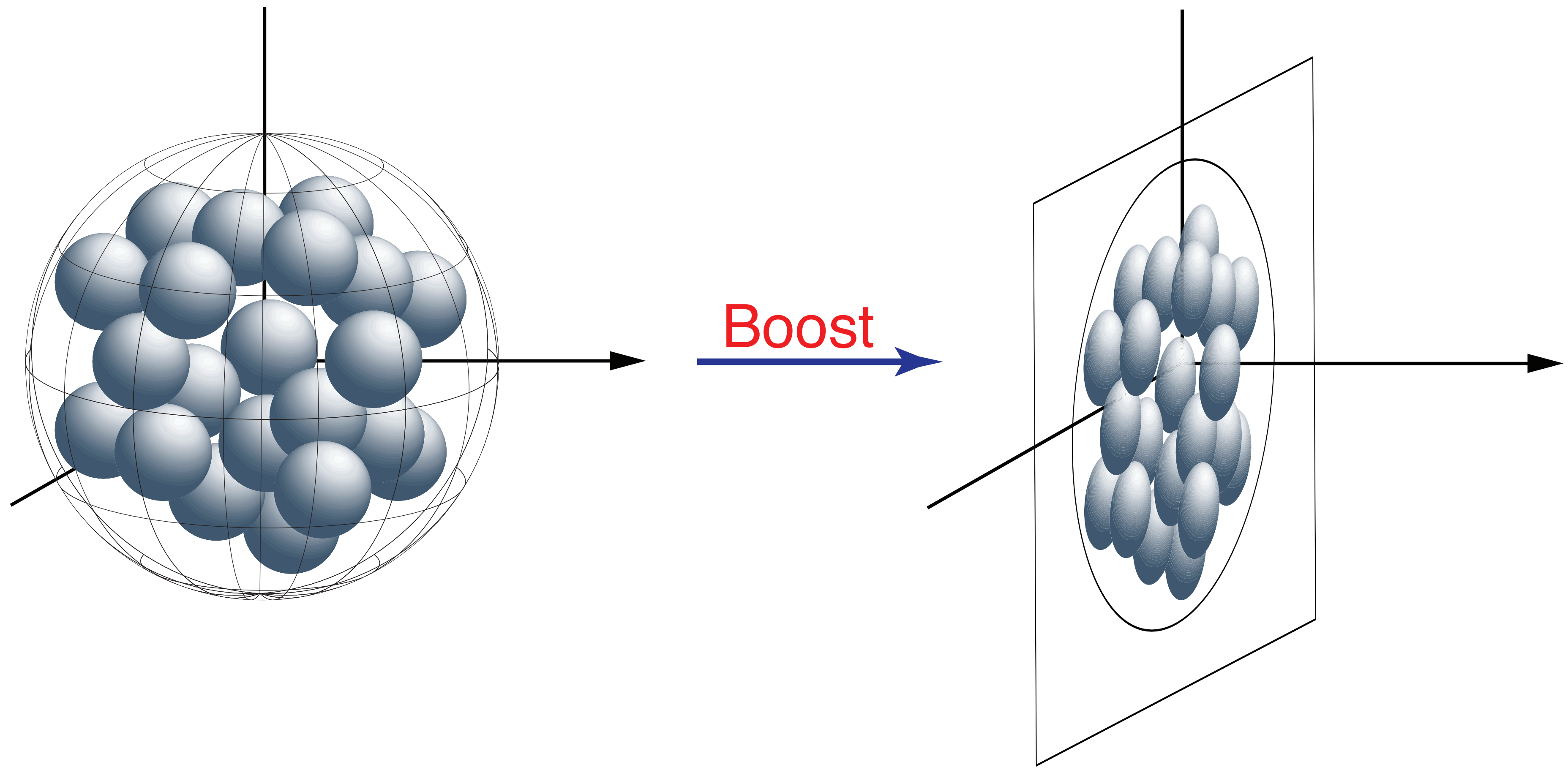
- Relativistic Quantum-Mechanical Wavefunction of the pion eigenstate $H_{LF}^{QCD}|\pi> = m_\pi^2|\pi>$

$$\Psi_\pi(x,\vec{k}_\perp) = <q(x,\vec{k}_\perp)\bar{q}(1-x,-\vec{k}_\perp)|\pi>$$



- Independent of the observer's or pion's motion
- No Lorentz contraction; causal
- ***Confined*** quark-antiquark bound state





large nucleus before and after an ultra-relativistic boost.

Is this really true? Will an electron-proton collider see different results than a fixed target experiment such as SLAC because the nucleus is squashed to a pancake?

Light-Front: No length contraction — no pancakes!

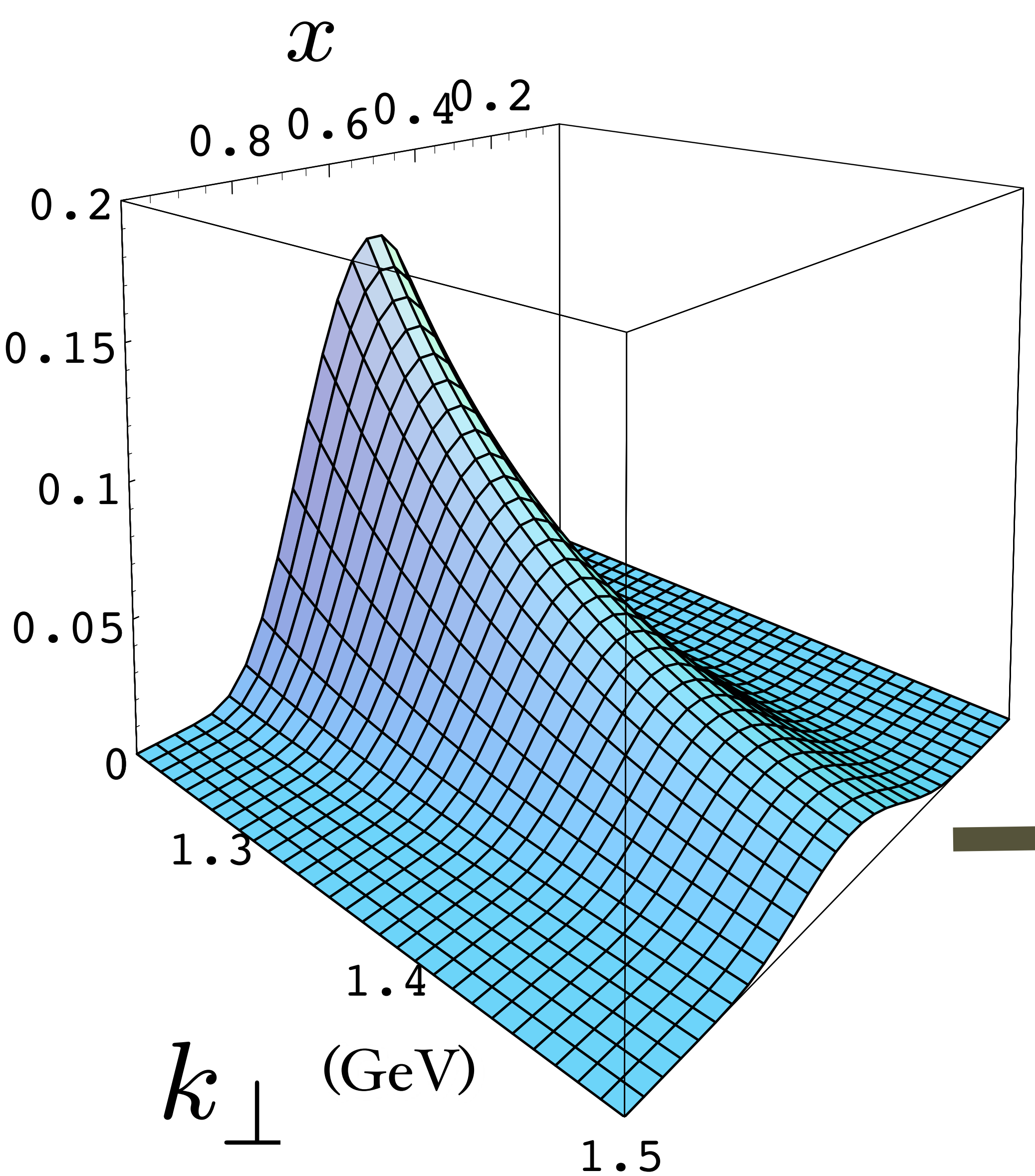
Penrose
Terrell
Weiskopf

We do not make observations at one time t!

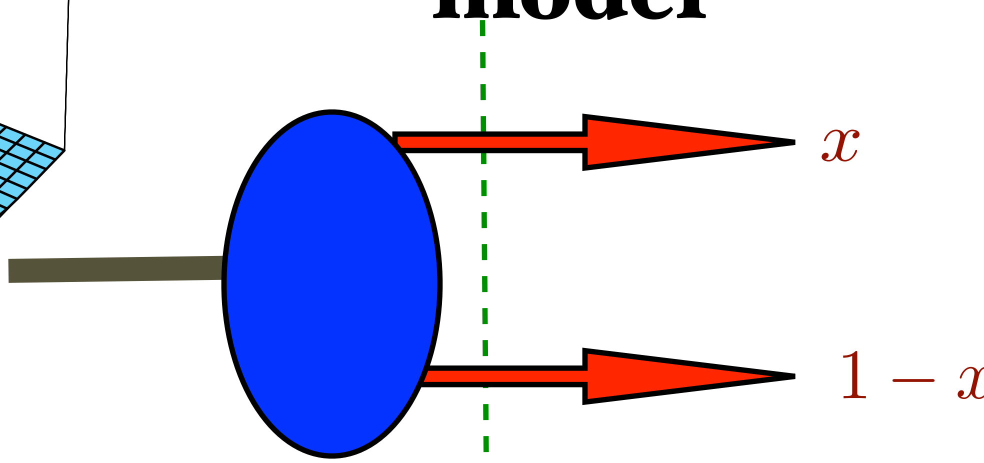
Prediction from AdS/QCD: Meson LFWF

de Teramond, Cao, sjb

$\psi_M(x, k_\perp^2)$



"Soft Wall" model



massless quarks

Note coupling

$k_\perp^2, x$

$$\psi_M(x, k_\perp) = \frac{4\pi}{\kappa\sqrt{x(1-x)}} e^{-\frac{k_\perp^2}{2\kappa^2 x(1-x)}}$$

$$\boxed{\phi_\pi(x) = \frac{4}{\sqrt{3}\pi} f_\pi \sqrt{x(1-x)}}$$

$$f_\pi = \sqrt{P_{q\bar{q}}}\frac{\sqrt{3}}{8}\kappa = 92.4 \text{ MeV}$$

Provides Connection of Confinement to Hadron Structure

$$\psi_n(\vec{k}_{\perp i}, x_i) \propto \frac{1}{\kappa^{n-1}} \; e^{-\mathcal{M}_n^2/2\kappa^2} \; \Pi_{j=1}^{n} \frac{1}{\sqrt{x_j}}$$

Properties of Color-Confining LFWF

- minimal $\quad \mathcal{M}_n^2 = \sum_{i=1}^{n} (\frac{k_\perp^2 + m^2}{x})_i$
- Maximum when $\quad x_i = \propto \; m_{\perp i} = \sqrt{m_i^2 + k_{\perp i}^2}$
- Maximum overlap at matching rapidity

$$y = \frac{1}{2} \log \frac{k^+}{k^-} = \log \frac{x P^+}{m_\perp}$$

Frame independent $\quad \Delta y = y_a - y_b = \log \frac{x_a}{m_{\perp a}} - \log \frac{x_b}{m_{\perp b}}$

Relative to proton $\quad \Delta y = y_H - y_p = \log \frac{x_H}{m_{\perp H}/m_p}$

Feynman: Correlations with proton $\Delta y < 2$

$|\pi^+ >= |u\bar{d} >$

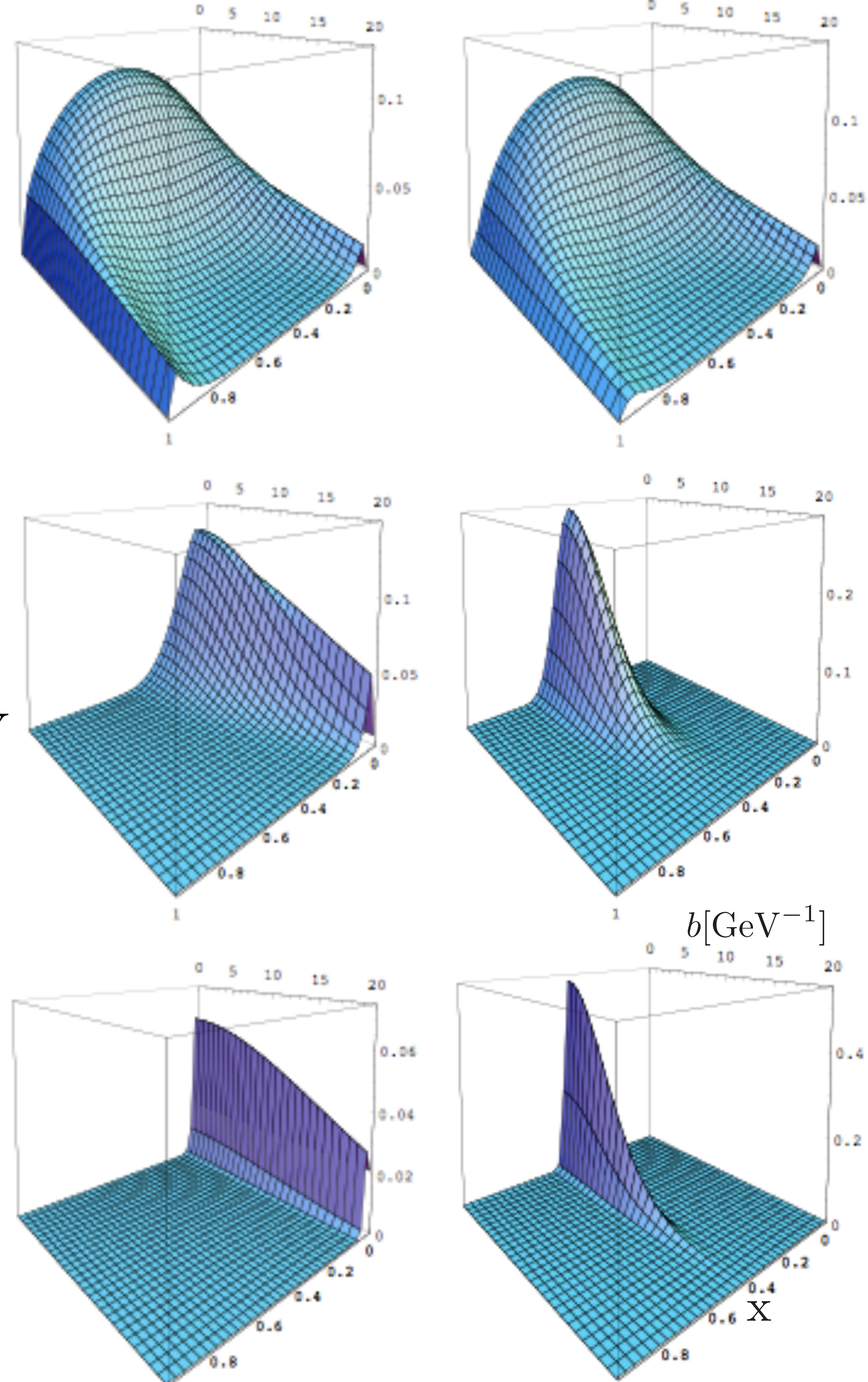
$m_u = 2\ MeV$
$m_d = 5\ MeV$

$|D^+ >= |c\bar{d} >$

$m_c = 1.25\ GeV$

$|B^+ >= |u\bar{b} >$

$m_b = 4.2\ GeV$



$|K^+ >= |u\bar{s} >$

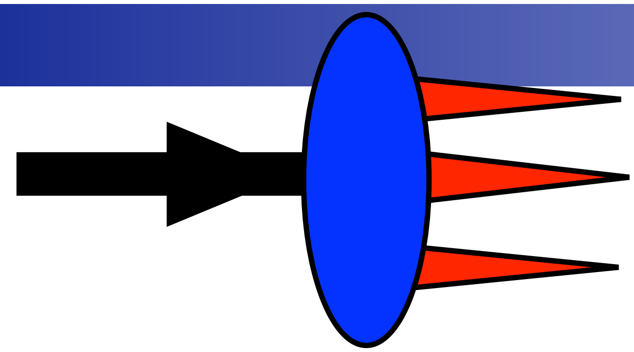
$m_s = 95\ MeV$

$|\eta_c >= |c\bar{c} >$

$|\eta_b >= |b\bar{b} >$

$\kappa = 375\ MeV$

- *Light Front Wavefunctions:*



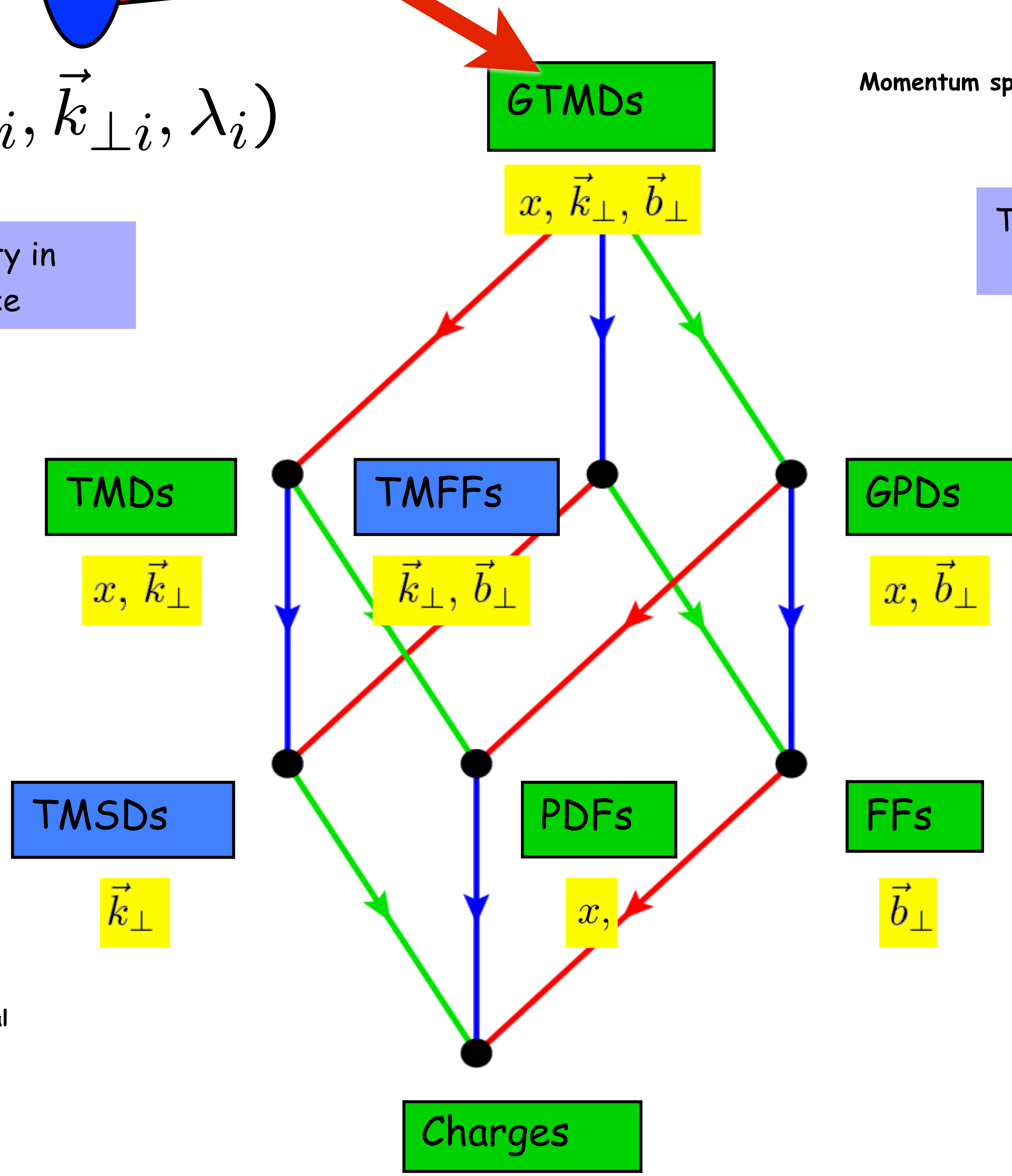
$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

Transverse density in momentum space

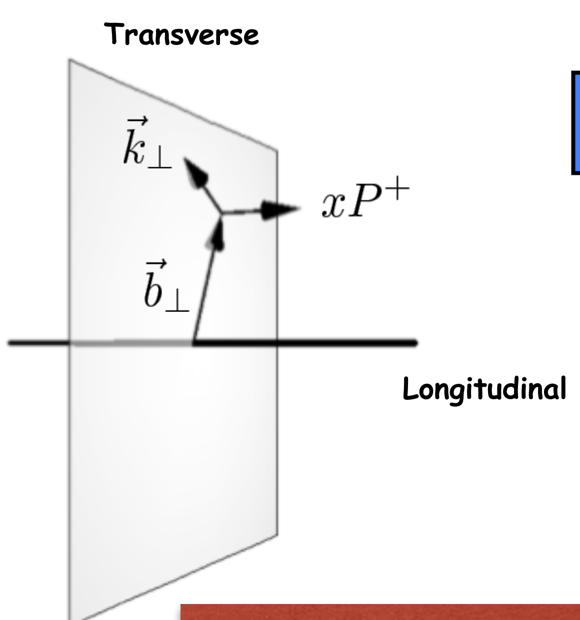
Momentum space $\vec{k}_\perp \leftrightarrow \vec{z}_\perp$ **Position space**

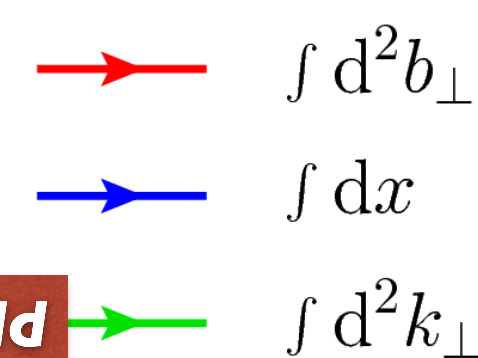
$\vec{\Delta}_\perp \leftrightarrow \vec{b}_\perp$

Transverse density in position space



Lorce, Pasquini





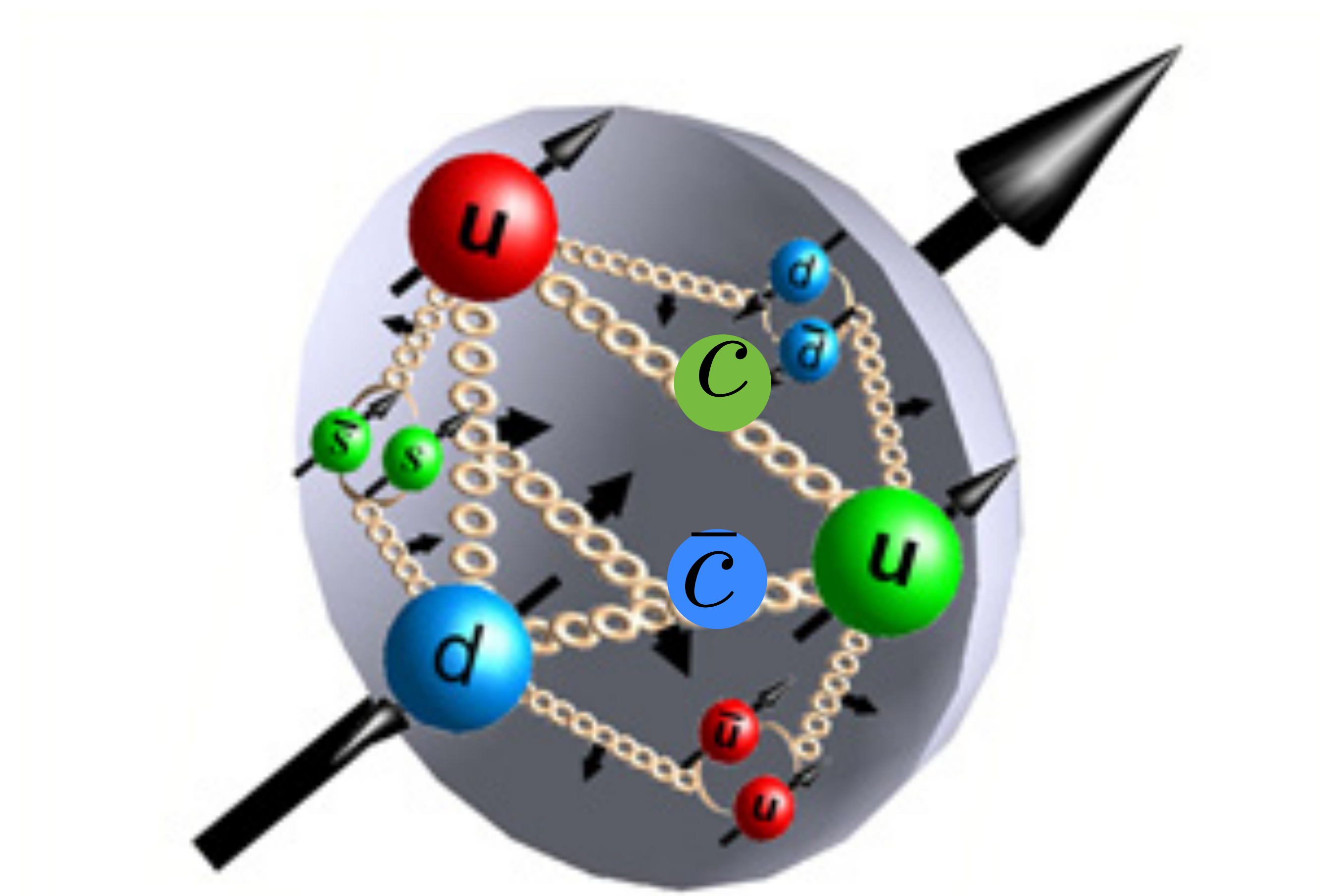
+ *Factorization-Breaking Lensing Corrections: Sivers, T-odd*

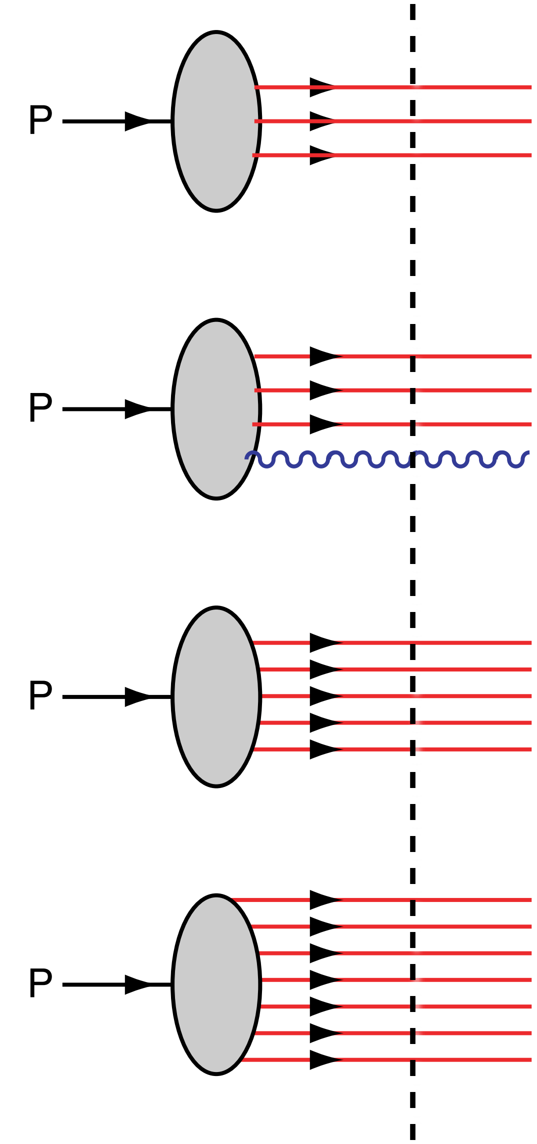
Wavefunction at fixed LF time: Arbitrarily Off-Shell in Invariant Mass

$$H_{LF}^{QCD}|\psi> = M^2|\psi>$$

Higher Fock States of the Proton:

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





Fixed LF time

Eigenstate of LF Hamiltonian : all Fock states contribute

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

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

The Light Front Fock State Wavefunctions

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

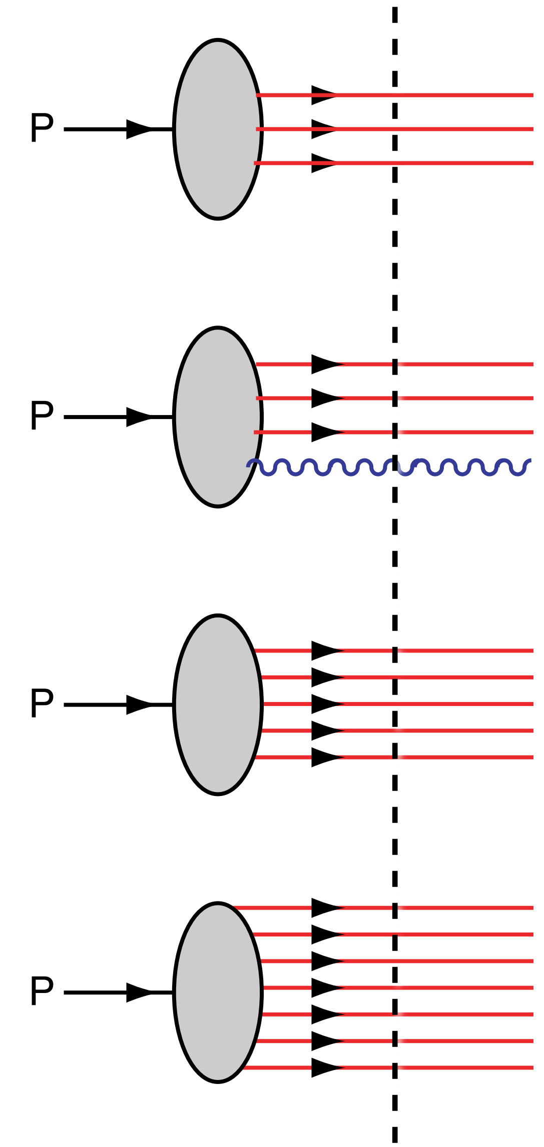
are boost invariant; they are independent of the hadron's energy and momentum P^μ.

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.

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



Intrinsic heavy quarks

s(x), c(x), b(x) at high x !

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

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

Fixed LF time

$\tau = t + z/c$

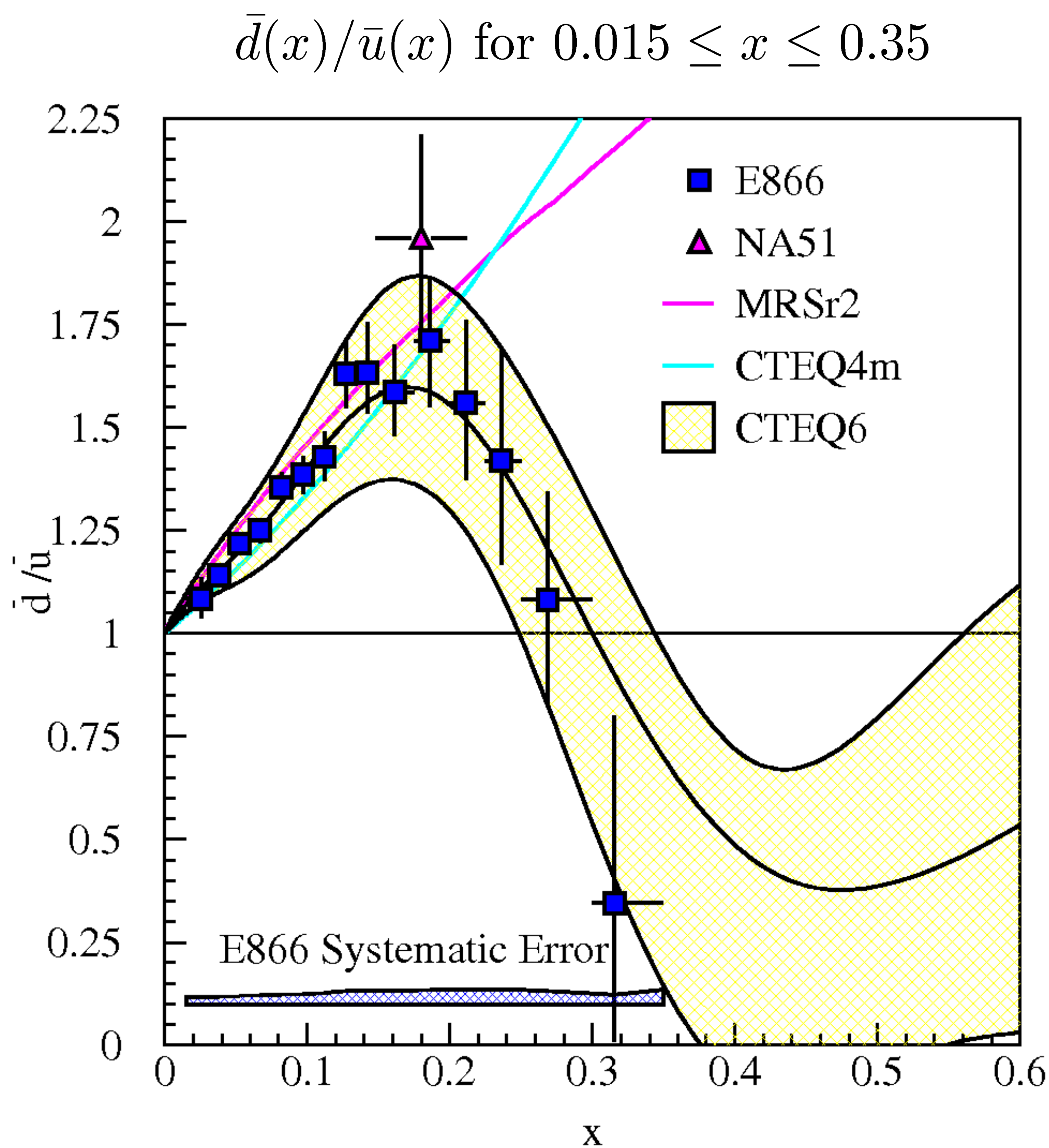
Deuteron: Hidden Color

- E866/NuSea (Drell-Yan)

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

Interactions of quarks at same rapidity in 5-quark Fock state

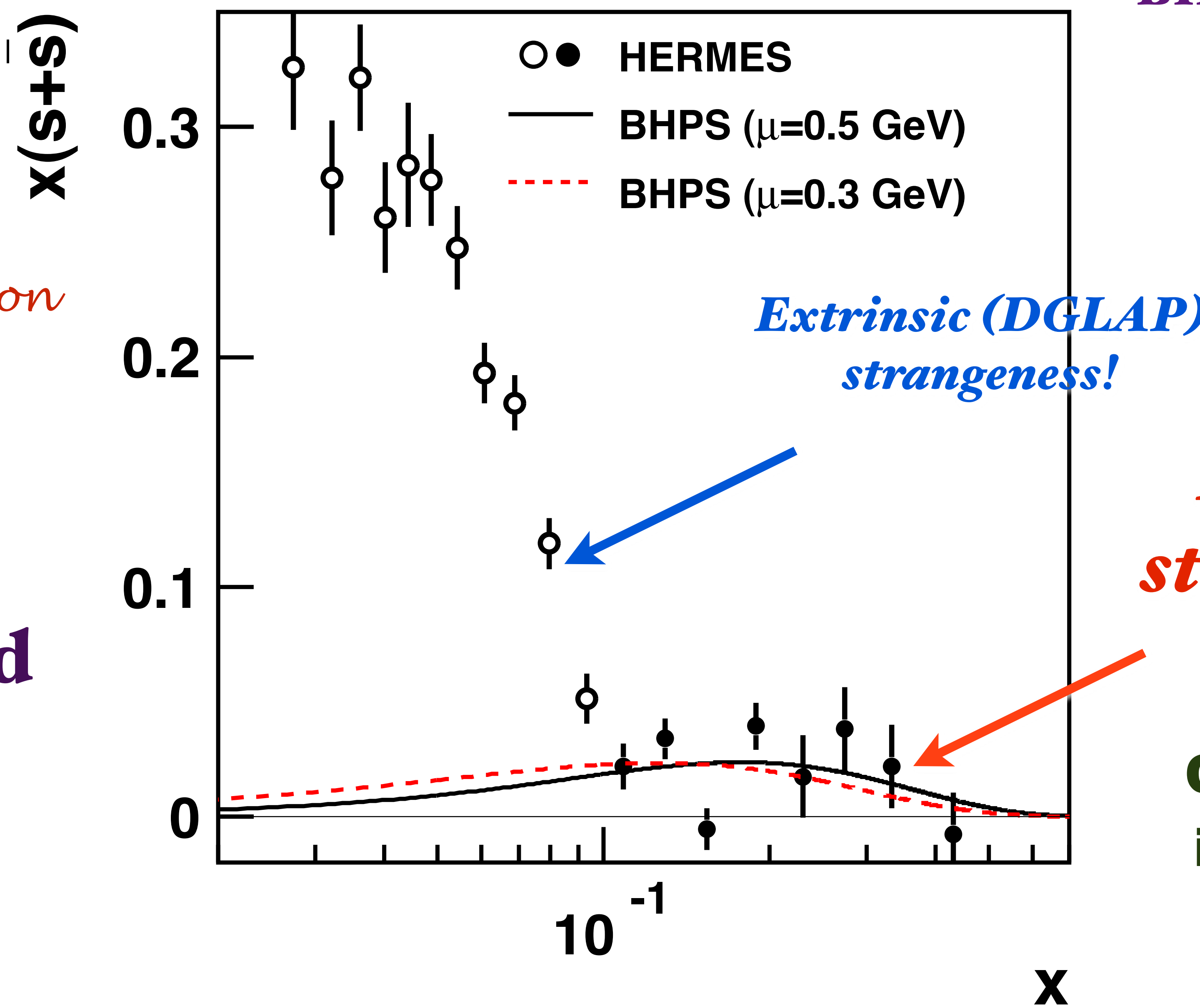
Intrinsic sea quarks



HERMES: Two components to s(x,Q²)!

BHPS: Hoyer, Sakai, Peterson, sjb

Sensitive to Fragmentation Function



W. C. Chang and J.-C. Peng

arXiv:1105.2381

Consistent with intrinsic charm data

QCD: $\frac{1}{M_Q^2}$ scaling

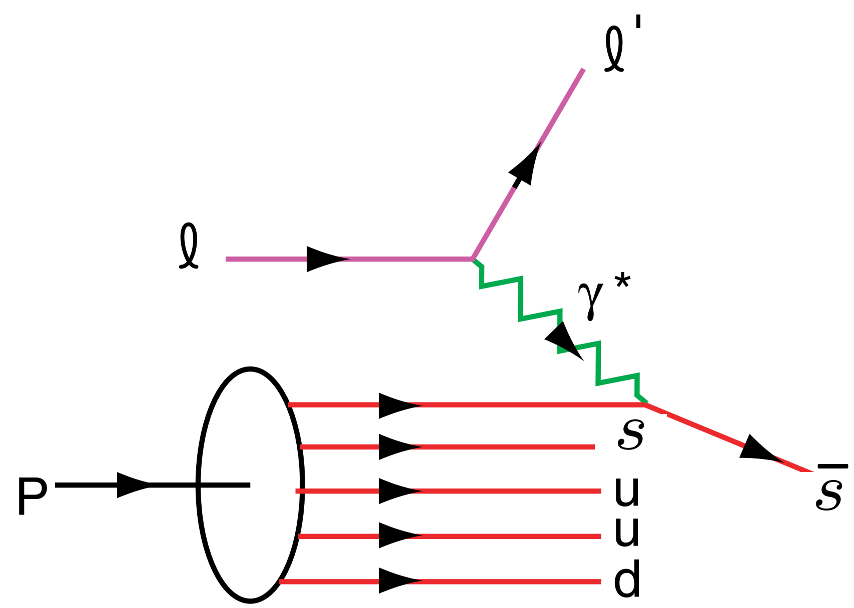
Comparison of the HERMES $x(s(x)+\bar{s}(x))$ data with the calculations based on the BHPS model. The solid and dashed curves are obtained by evolving the BHPS result to $Q^2 = 2.5$ GeV^2 using $\mu = 0.5$ GeV and $\mu = 0.3$ GeV, respectively. The normalizations of the calculations are adjusted to fit the data at $x > 0.1$ with statistical errors only, denoted by solid circles.

$$s(x, Q^2) = s(x, Q^2)_{\text{extrinsic}} + s(x, Q^2)_{\text{intrinsic}}$$

Measure strangeness distribution in Semi-Inclusive DIS at JLab

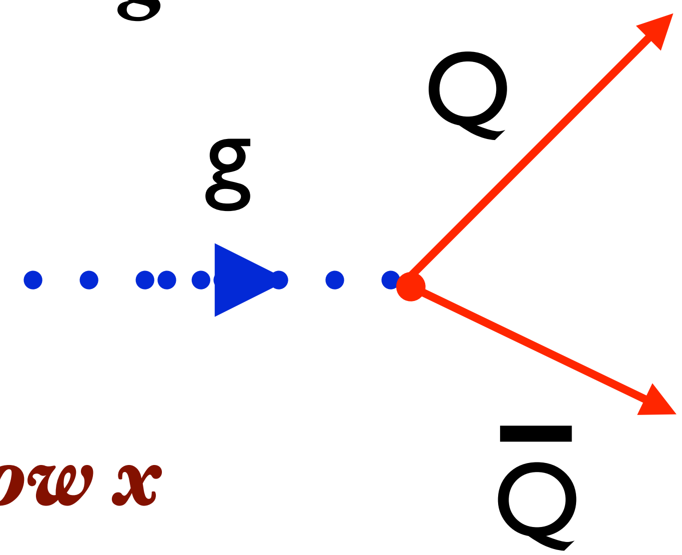
$$\text{Is } s(x) = \bar{s}(x)?$$

- **Non-symmetric strange and antistrange sea?**
- **Non-perturbative physics; e.g** $|uuds\bar{s}> \simeq |\Lambda(uds)K^+(\bar{s}u)>$
- **Important for interpreting NuTeV anomaly** **B. Q. Ma, sjb**



Tag struck quark flavor in semi-inclusive DIS $ep \to e'K^+X$

Do heavy quarks exist in the proton at high x?



Conventional wisdom: gluon splitting

Heavy quarks generated only at low x via DGLAP evolution from gluon splitting

Maximally off-shell - requires low x, high W^2

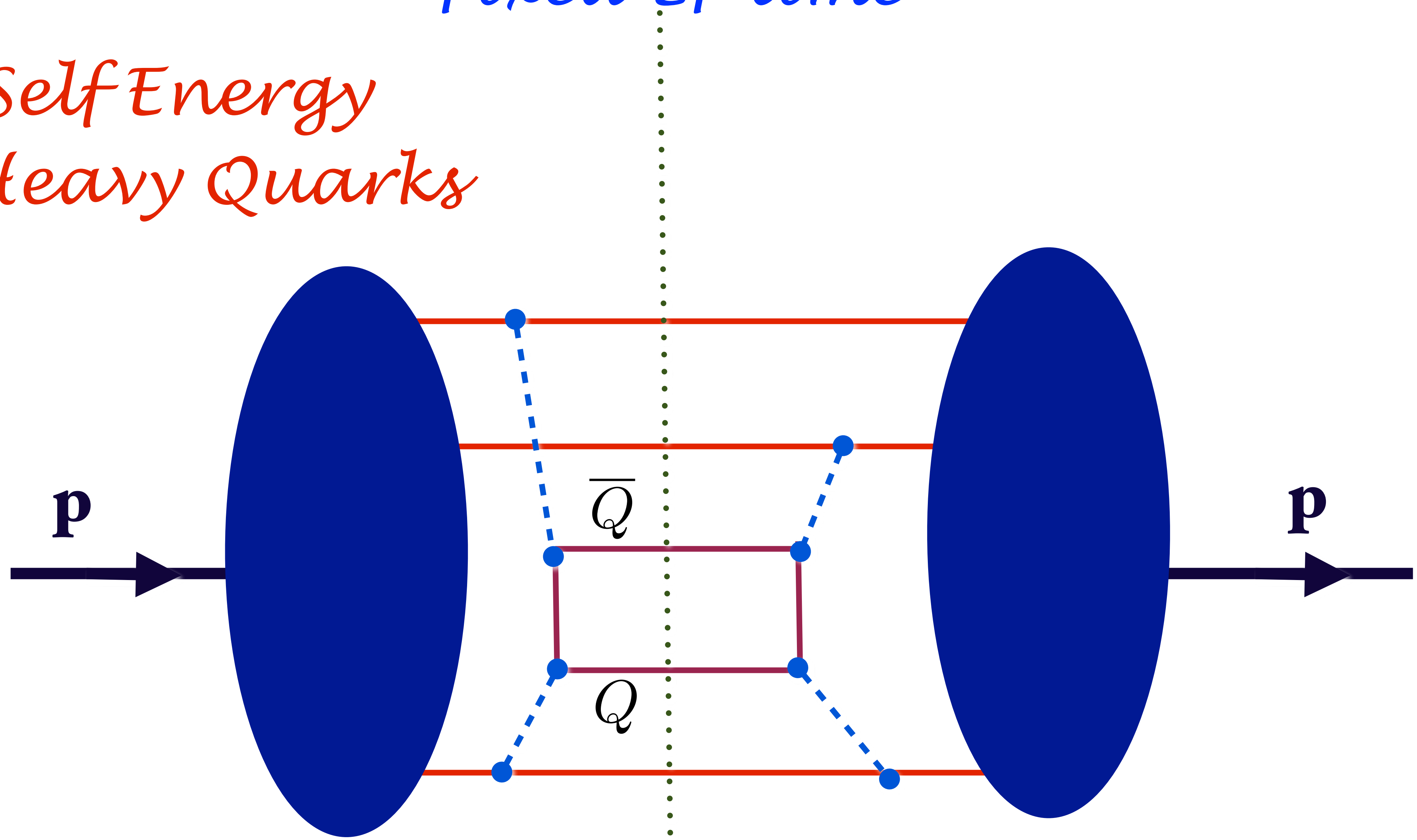
$$s(x,\mu_F^2) = c(x,\mu_F^2) = b(x,\mu_F^2) \equiv 0$$

$$\text{at starting scale } Q_0^2 = \mu_F^2$$

Conventional wisdom is wrong even in QED!

Fixed LF time

Proton Self Energy
Intrinsic Heavy Quarks

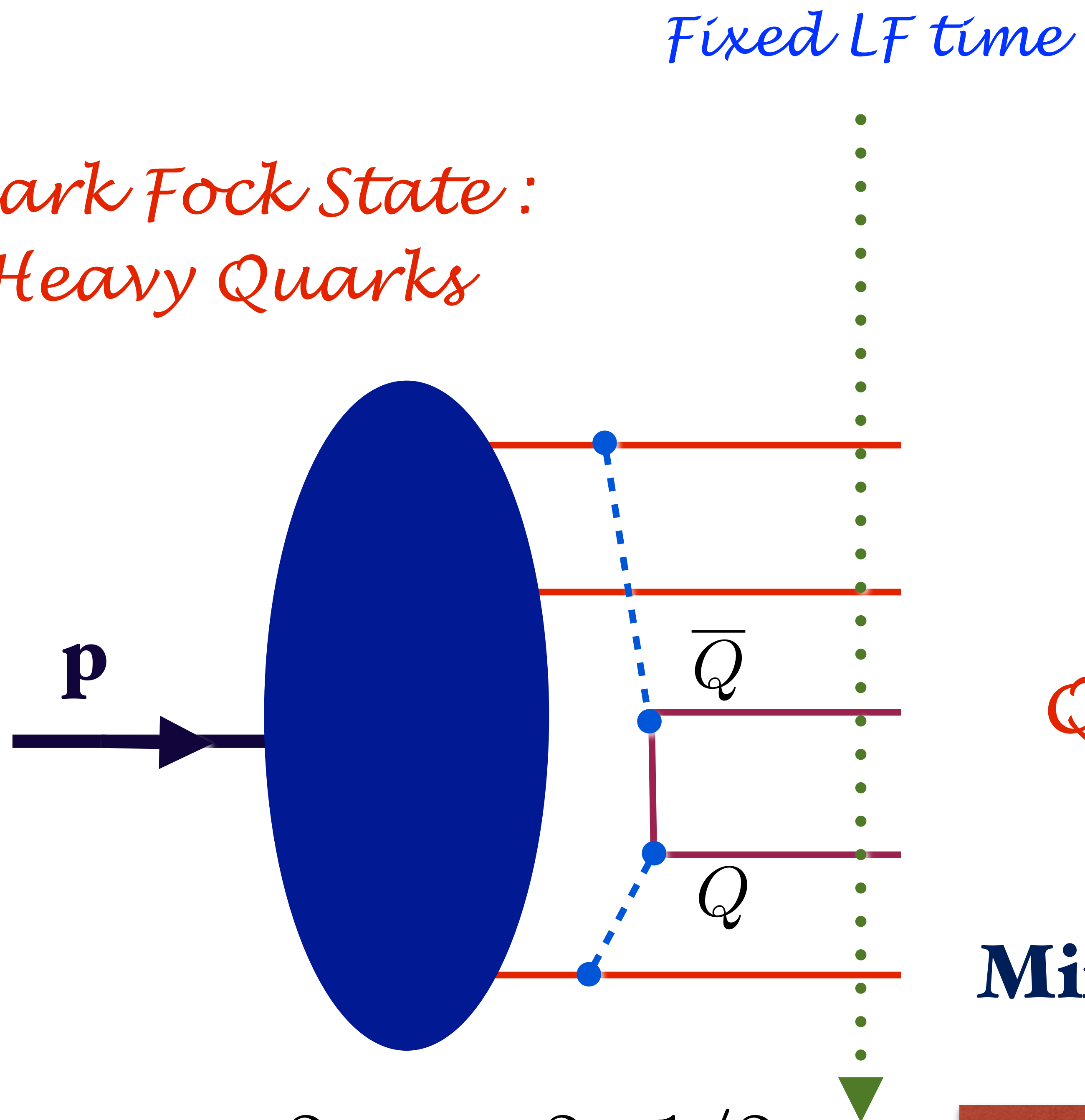


$$\text{Probability (QED)} \propto \frac{1}{M_\ell^4} \qquad \text{Probability (QCD)} \propto \frac{1}{M_Q^2}$$

Rigorous OPE Analysis

Collins, Ellis, Gunion, Mueller, sjb
M. Polyakov, et al.

Proton 5-quark Fock State :
Intrinsic Heavy Quarks



QCD predicts Intrinsic Heavy Quarks at high x!

Minimal off-shellness

Maximum at Equal rapidity!

$$x_Q \propto (m_Q^2 + k_\perp^2)^{1/2}$$

$$\text{Probability (QED)} \propto \frac{1}{M_\ell^4} \qquad \text{Probability (QCD)} \propto \frac{1}{M_Q^2}$$

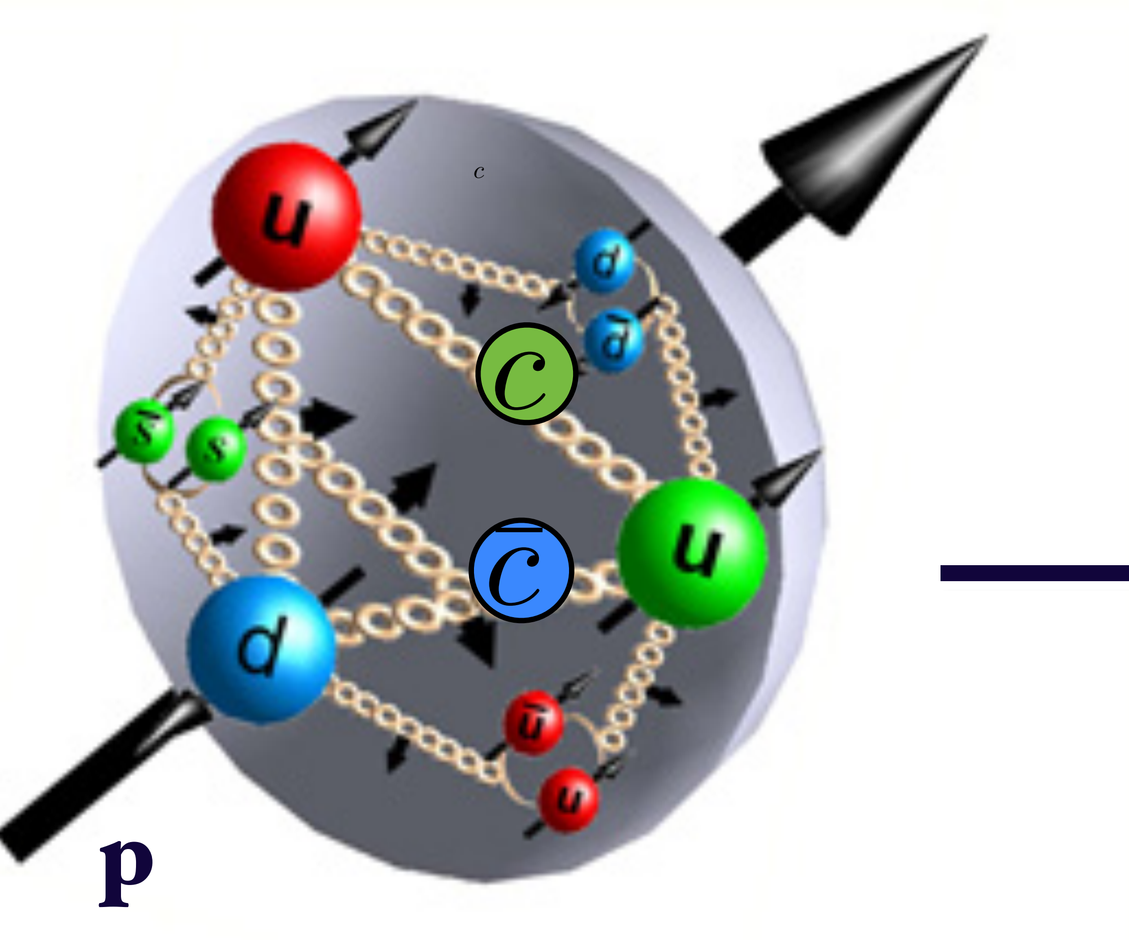
Rigorous OPE Analysis

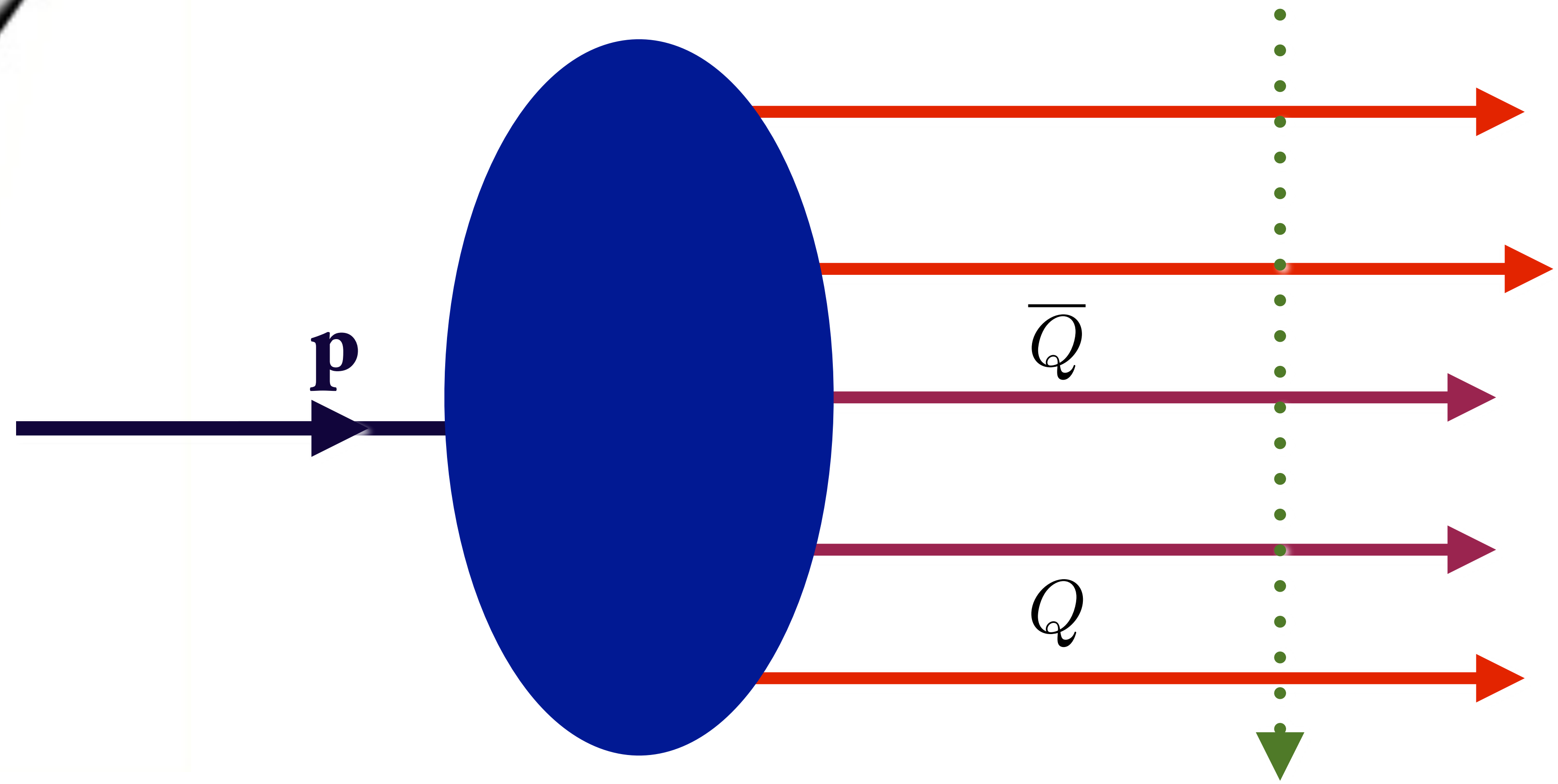
Collins, Ellis, Gunion, Mueller, sjb
Polyakov, et al.

Color confinement potential from AdS/QCD

$$U(\zeta^2) = \kappa^4 \zeta^2 = b_\perp^2 x(1-x)$$

Fixed $\tau = t + z/c$





$$\psi_n(\vec{k}_{\perp i}, x_i) \propto \frac{1}{\kappa^{n-1}}\; e^{-\mathcal{M}_n^2/2\kappa^2}\; \Pi_{j=1}^{n} \frac{1}{\sqrt{x_j}}$$

$$\mathcal{M}_n^2 = \sum_{i=1}^{n} \left(\frac{k_\perp^2 + m^2}{x}\right)_i$$

$$\psi_n(\vec{k}_{\perp i}, x_i) \propto \frac{1}{\kappa^{n-1}} \; e^{-\mathcal{M}_n^2/2\kappa^2} \; \Pi_{j=1}^{n} \frac{1}{\sqrt{x_j}}$$

Properties of Color-Confining LFWF

- minimal $\mathcal{M}_n^2 = \sum_{i=1}^{n} (\frac{k_\perp^2 + m^2}{x})_i$
- Maximum when $x_i = \propto \; m_{\perp i} = \sqrt{m_i^2 + k_{\perp i}^2}$
- Maximum overlap at matching rapidity

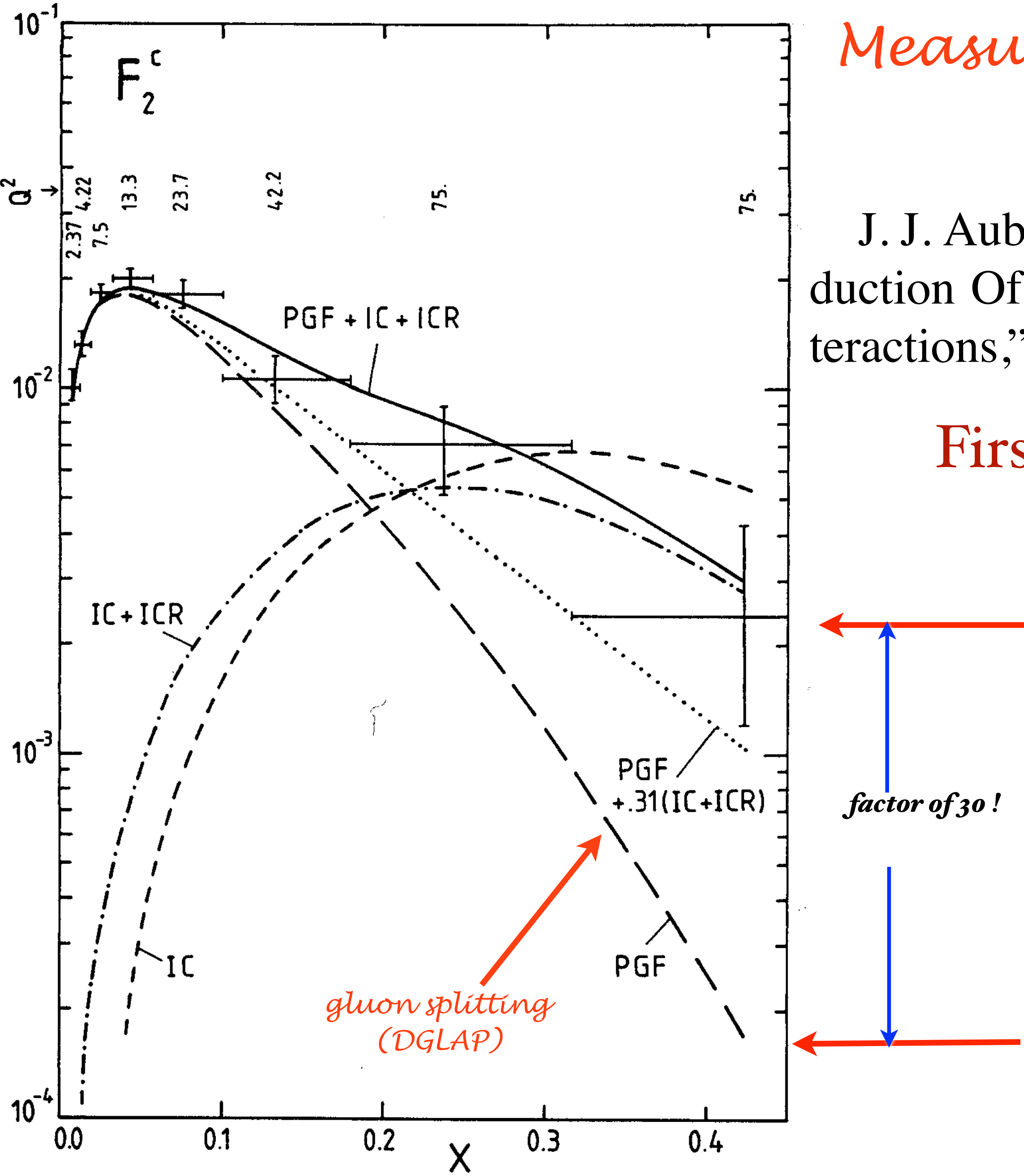
$$y = \frac{1}{2} \log \frac{k^+}{k^-} = \log \frac{x P^+}{m_\perp}$$

Frame independent $\Delta y = y_a - y_b = \log \frac{x_a}{m_{\perp a}} - \log \frac{x_b}{m_{\perp b}}$

Relative to proton $\Delta y = y_H - y_p = \log \frac{x_H}{m_{\perp H}/m_p}$

Feynman: Correlations with parent proton $\Delta y < 2$

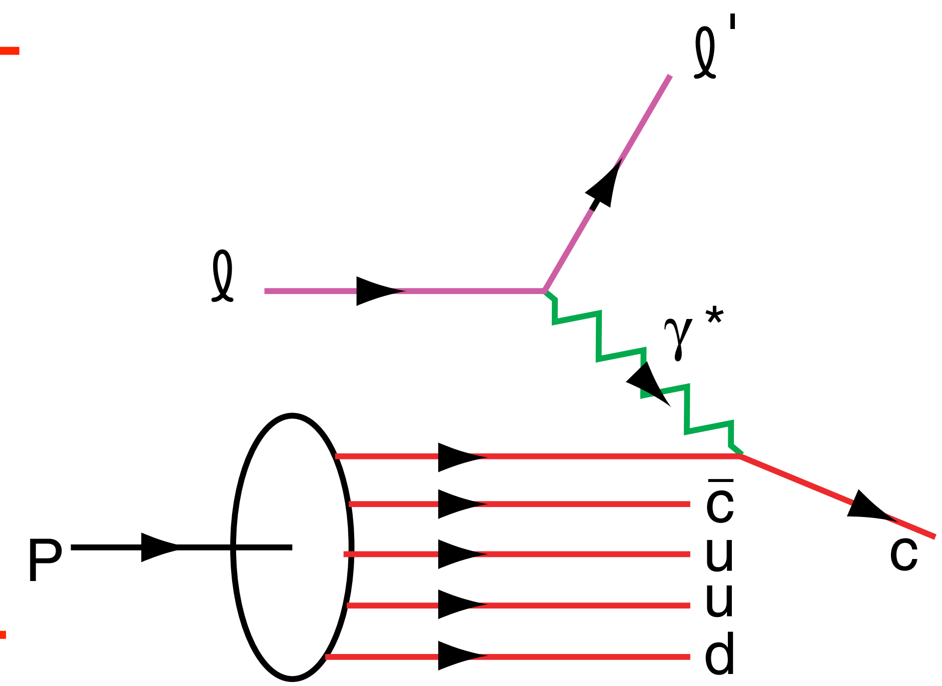
Measurement of Charm Structure Function!



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

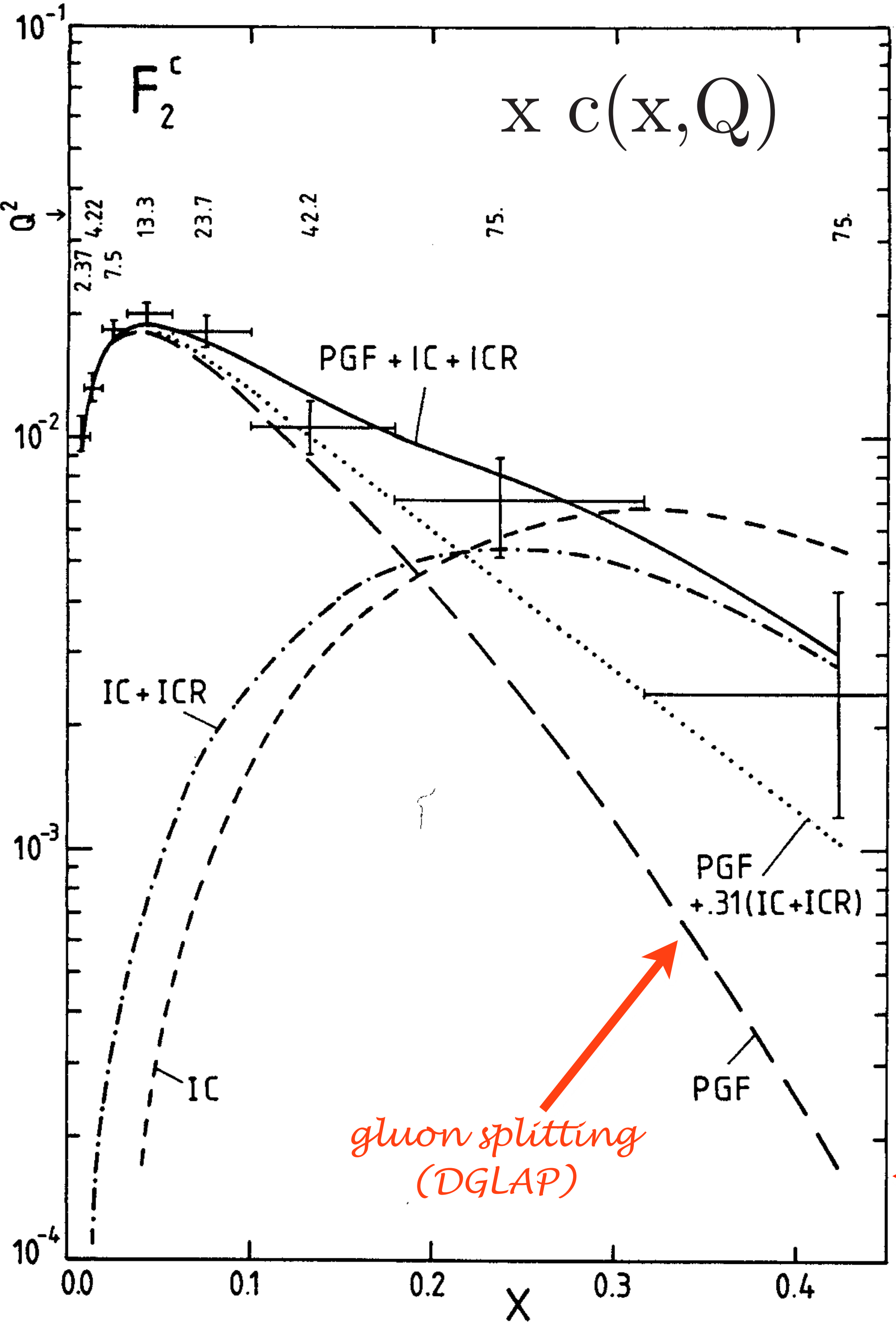
Hoyer, Peterson, Sakai, sjb



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

Two Components (separate evolution):

$$c(x, Q^2) = c(x, Q^2)_{\mathrm{extrinsic}} + c(x, Q^2)_{\mathrm{intrinsic}}$$



Measurement of Charm Structure Function!

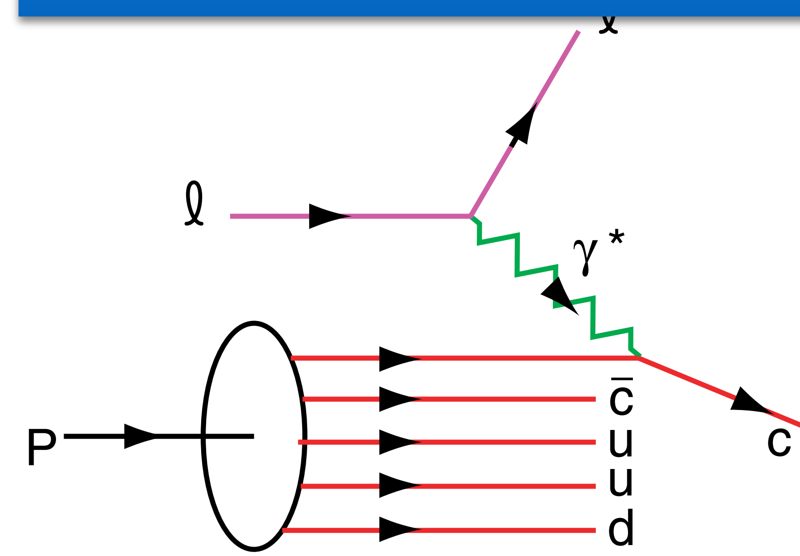
J. J. Aubert et al. [European Muon Collaboration], "Production Of Charmed Particles In 250-Gev Mu+ - Iron Interactions," Nucl. Phys. B 213, 31 (1983).

Evidence for Intrinsic Charm

$$< x_{c\bar{c}} >_p \simeq 1\%$$

New Analysis:
R.D. Ball, et al. [NNPDF Collaboration],
"A Determination of the Charm Content of the Proton,"
arXiv:1605.06515 [hep-ph].

factor of 30 !



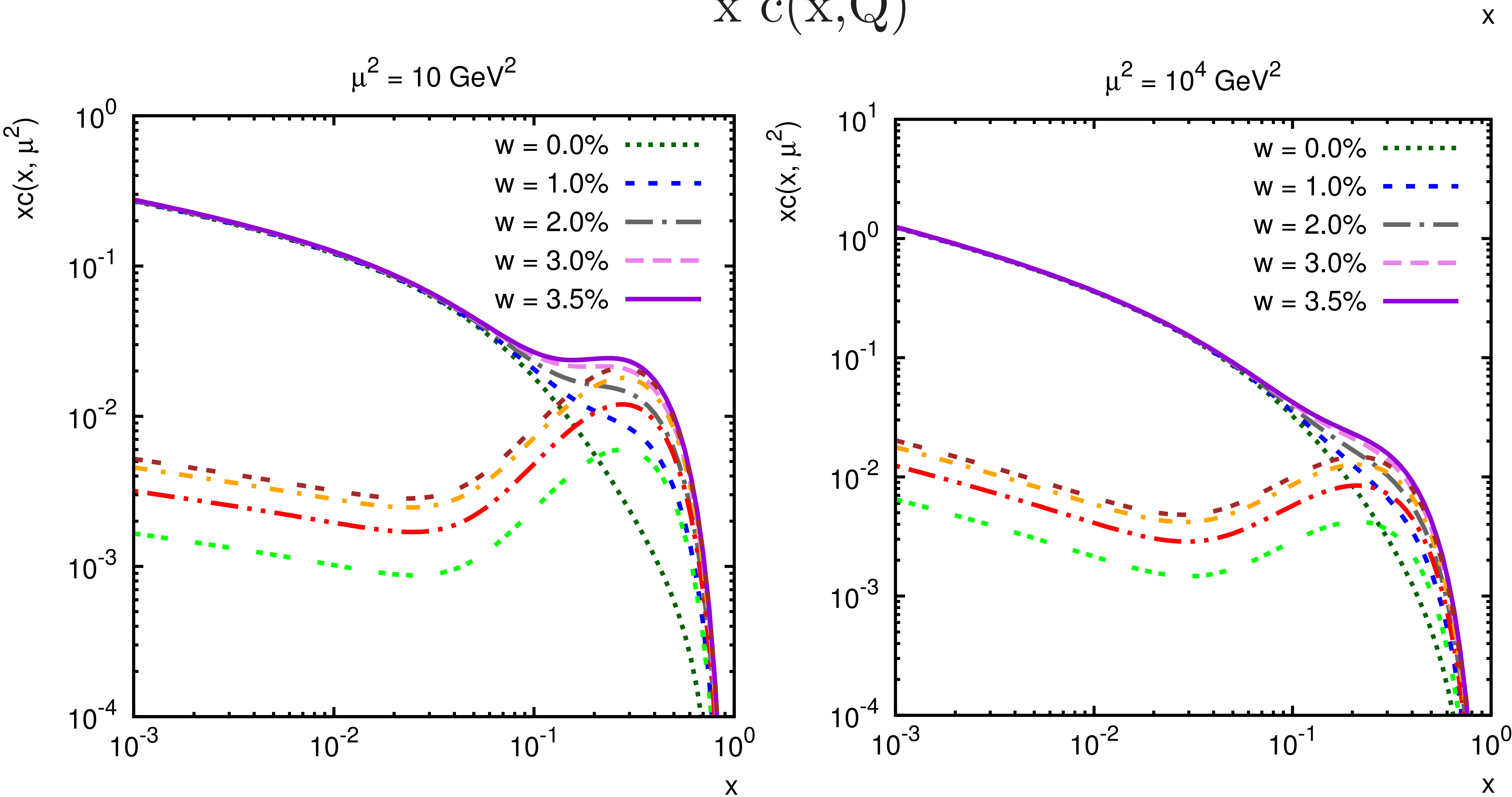
DGLAP / Photon-Gluon Fusion: factor of 30 too small

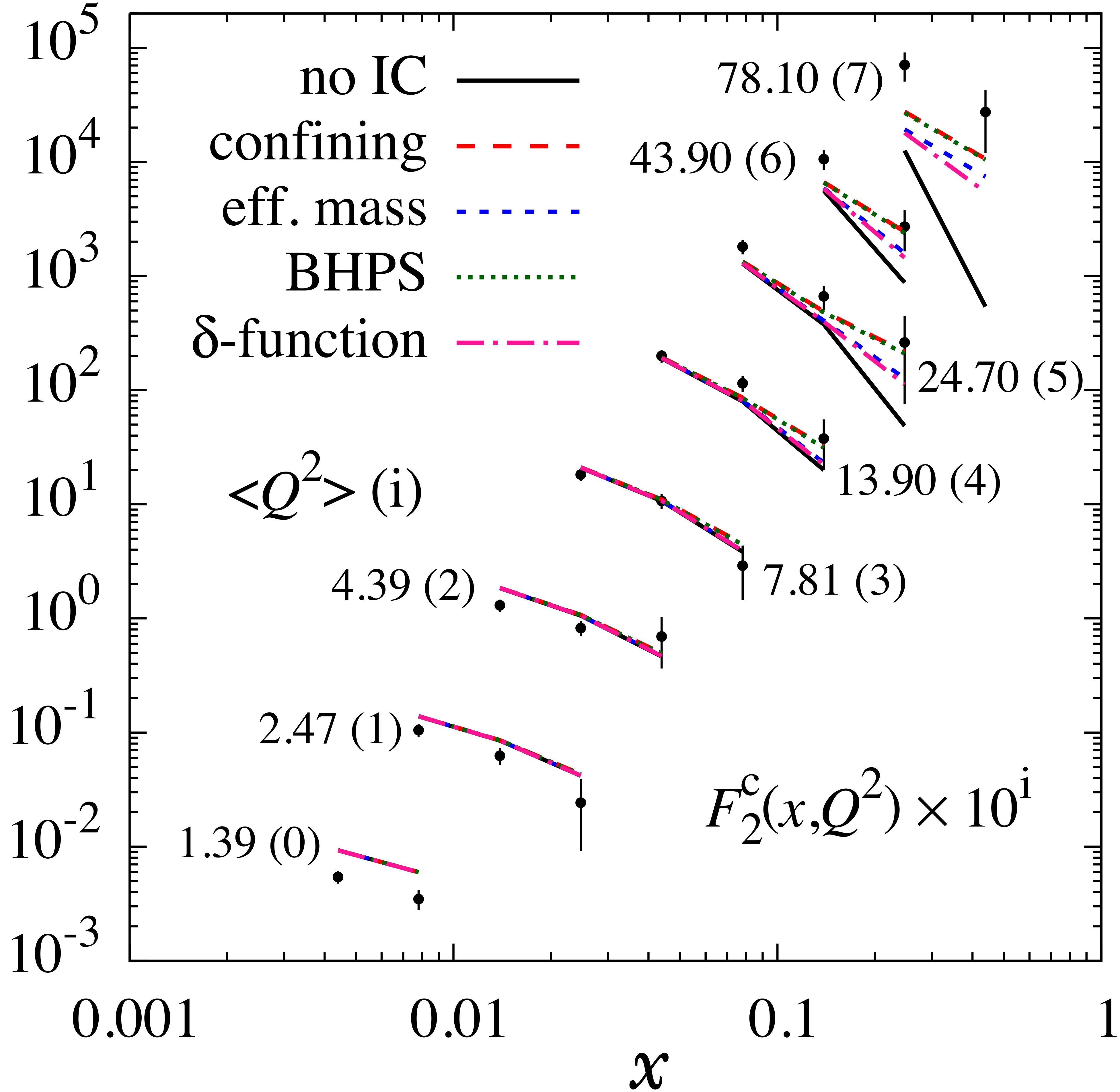
Two Components (separate evolution):

$$c(x, Q^2) = c(x, Q^2)_{\text{extrinsic}} + c(x, Q^2)_{\text{intrinsic}}$$

Bednyakov, Lykasov, Smiesko, Tokar, sjb

$\mathrm{x\ c(x,Q)}$

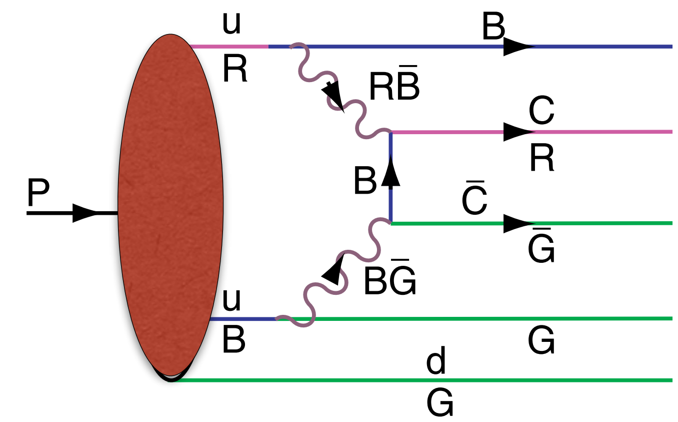




no IC
confining
eff. mass
BHPS
δ-function
$<Q^2>$ (i)
78.10 (7)
43.90 (6)
24.70 (5)
13.90 (4)
7.81 (3)
4.39 (2)
2.47 (1)
1.39 (0)
$F_2^c(x,Q^2) \times 10^i$
10⁵
10⁴
10³
10²
10¹
10⁰
10⁻¹
10⁻²
10⁻³
0.001
0.01
0.1
1
x

Hoyer, Peterson, Sakai, sjb

Intrinsic Heavy-Quark Fock



- **Rigorous prediction of QCD, OPE**
- **Color-Octet Color-Octet Fock State**
- **Probability**

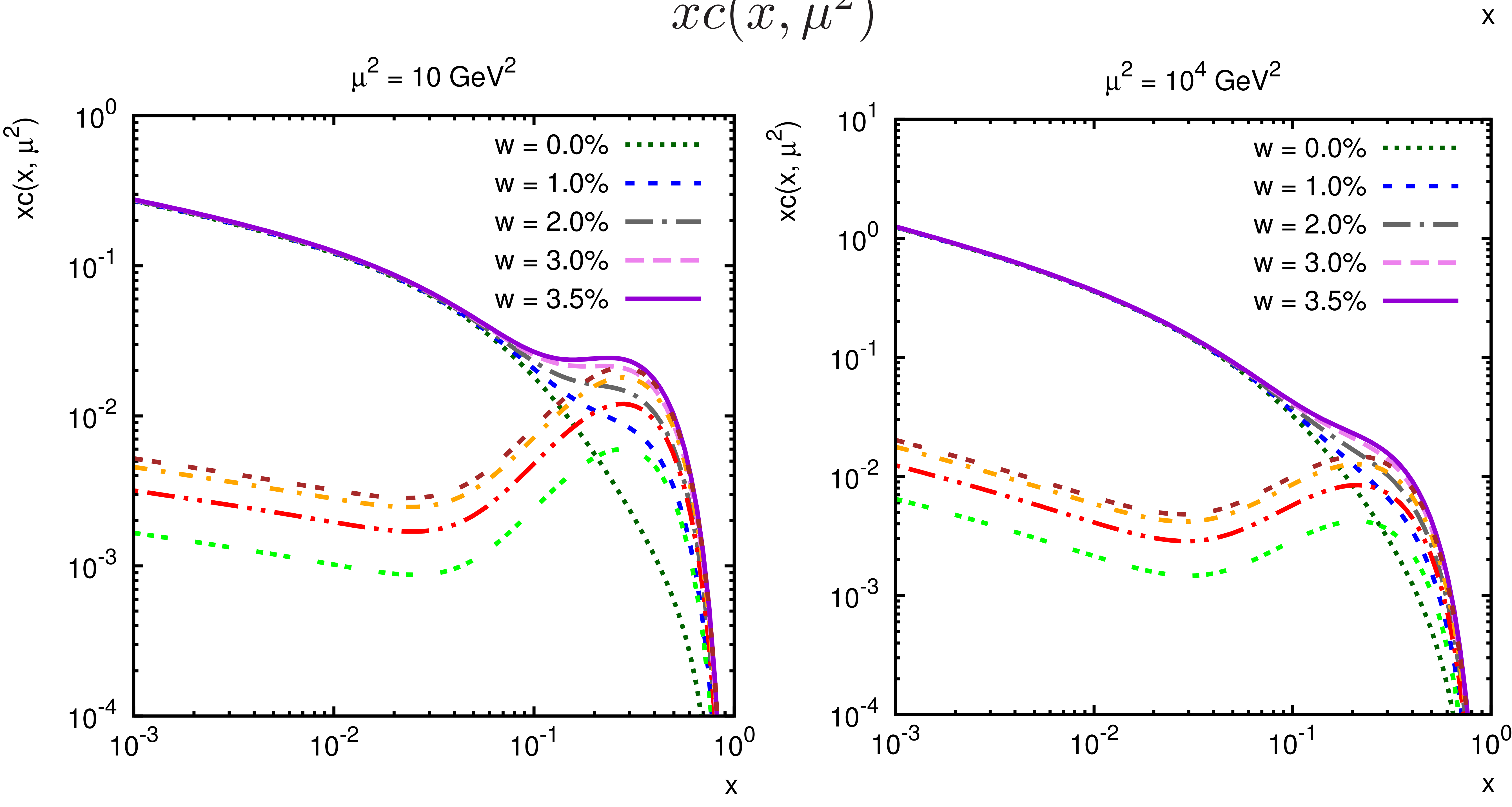
$$P_{Q\bar{Q}} \propto \frac{1}{M_Q^2} \qquad P_{Q\bar{Q}Q\bar{Q}} \sim \alpha_s^2 P_{Q\bar{Q}} \qquad P_{c\bar{c}/p} \simeq 1\%$$

- **Large Effect at high x**
- **Greatly increases kinematics of colliders such as Higgs production (Kopeliovich, Schmidt, Soffer, sjb)**
- **Underestimated in conventional parameterizations of heavy quark distributions (Pumplin, Tung)**
- **Many EIC tests**

OPE: Collins, S. Ellis, Gunion, Mueller, sjb
Franz, Goecke, M. Polyakov,

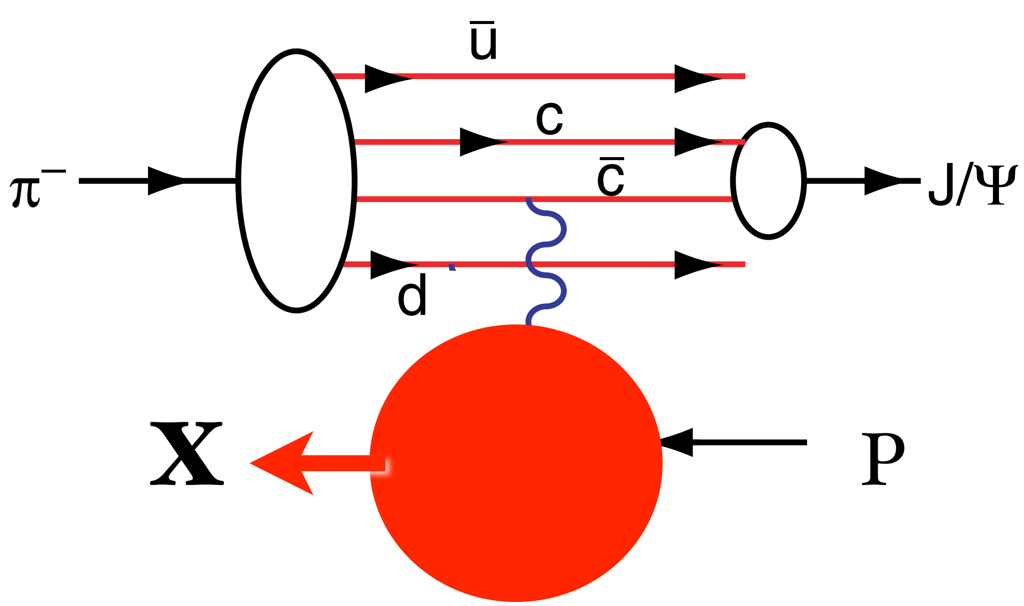
Bednyakov, Lykasov, Smiesko, Tokar, sjb

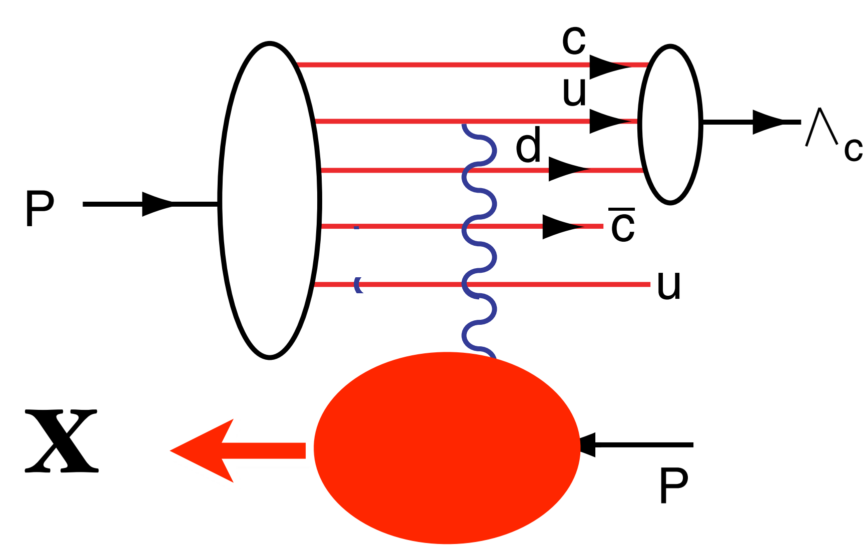
$$xc(x, \mu^2)$$



$$w = P_{c\bar{c}}^{intrinsic}$$

Coalescence of comovers produces high x_F heavy hadrons





Spectator counting rules

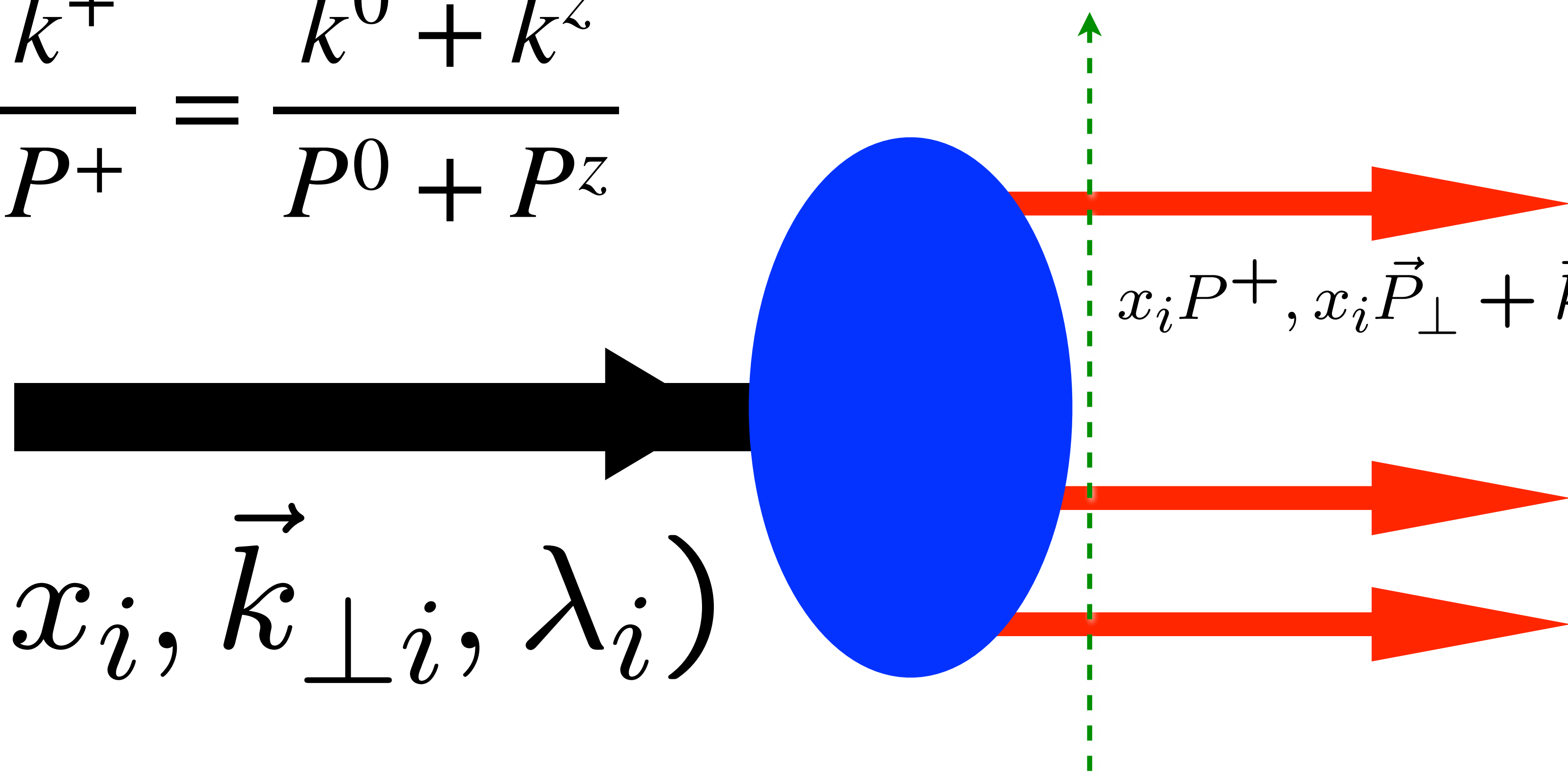
$$\frac{dN}{dx_F} \propto (1-x_F)^{2n_{spect}-1}$$

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

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

Fixed $\tau = t + z/c$

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



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

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

$\sum_i^n x_i = 1$

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

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

Invariant under boosts! Independent of P^μ

Light-Front Wavefunctions: Off-Shell in Invariant Mass

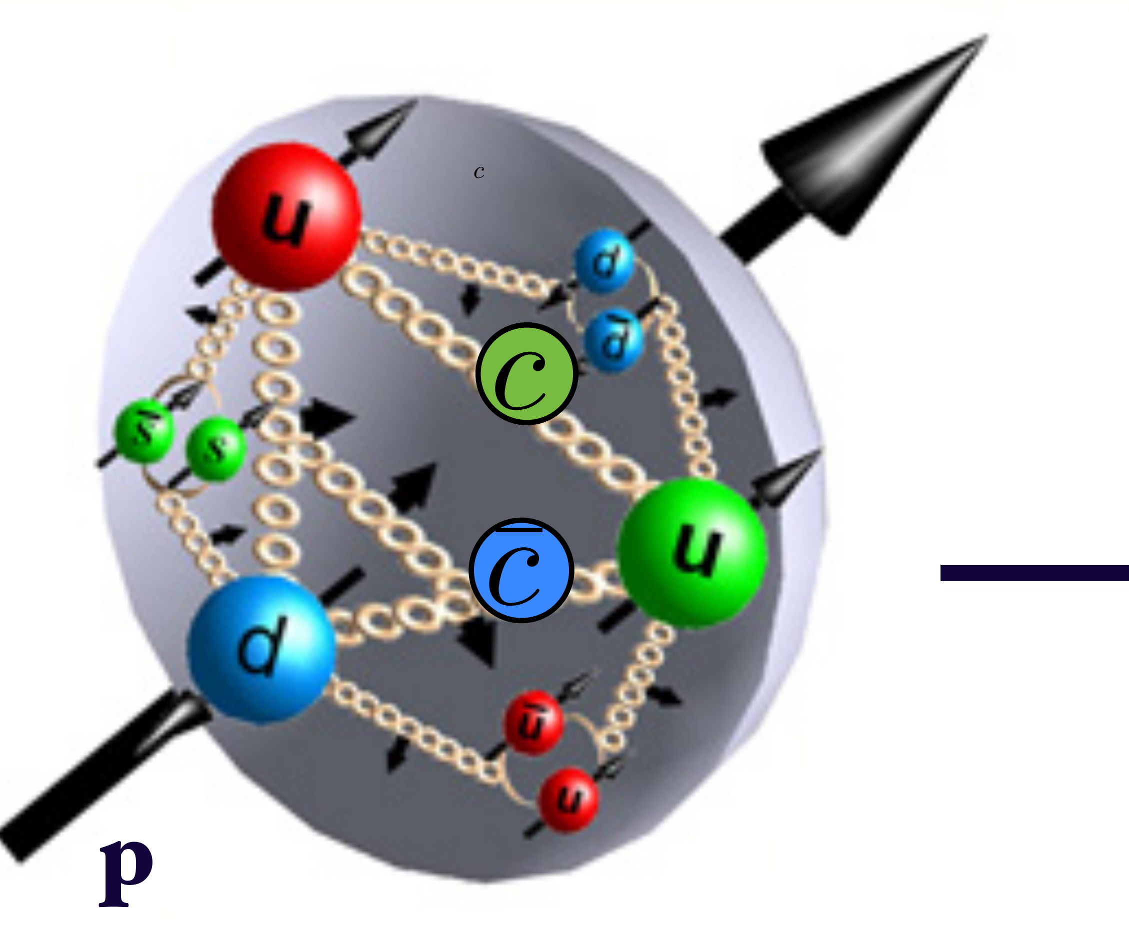
$$\mathcal{M}_n^2 = (\sum_{i=1}^n k^\mu)^2 = \sum_{i=1}^n \frac{k_{\perp i}^2 + m_i^2}{x_i}$$

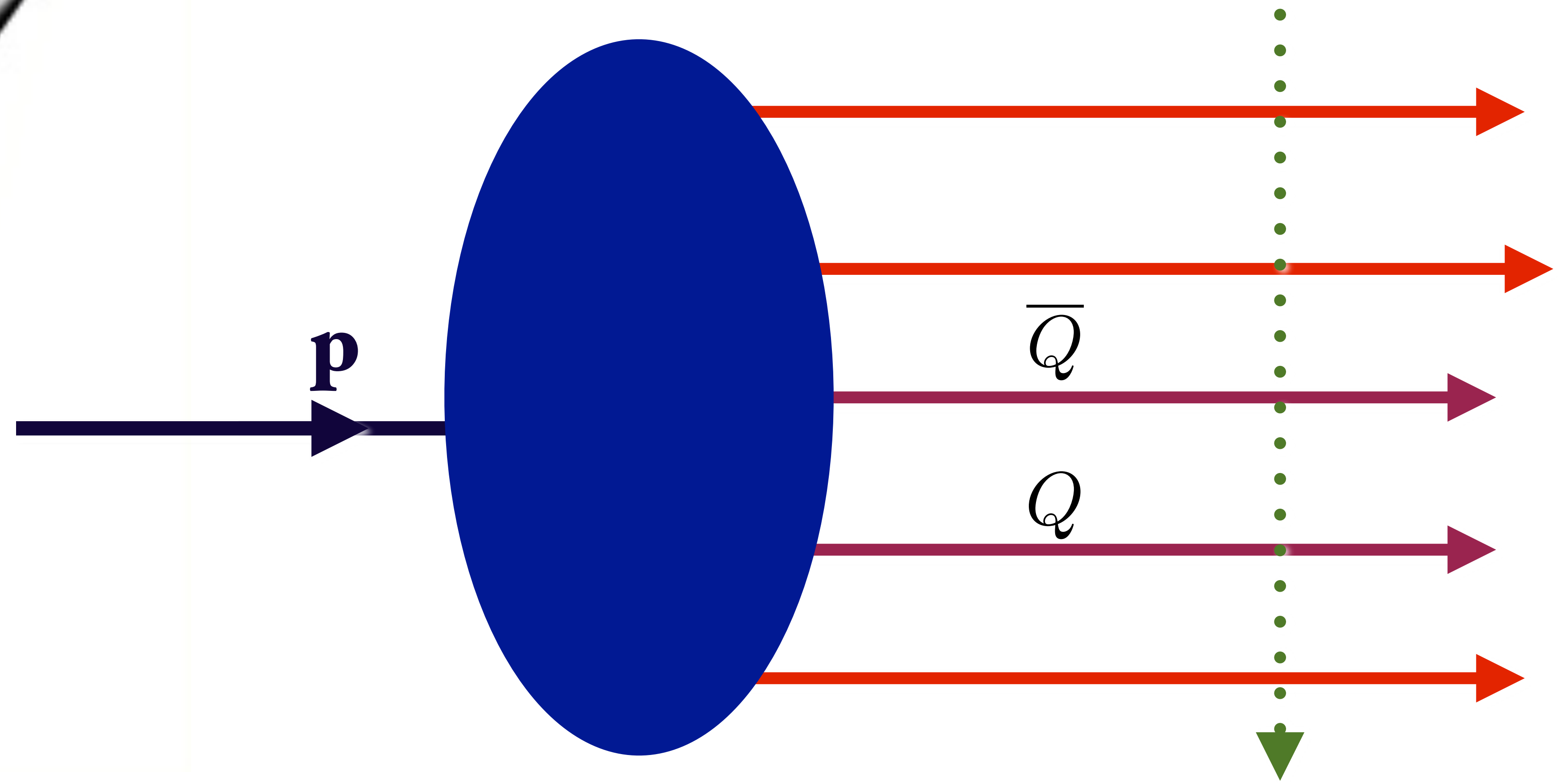
$$M^2 - \mathcal{M}_n^2 < 0$$

Color confinement potential from AdS/QCD

$$U(\zeta^2) = \kappa^4 \zeta^2 = \kappa^4 b_\perp^2 x(1-x)$$

Fixed $\tau = t + z/c$





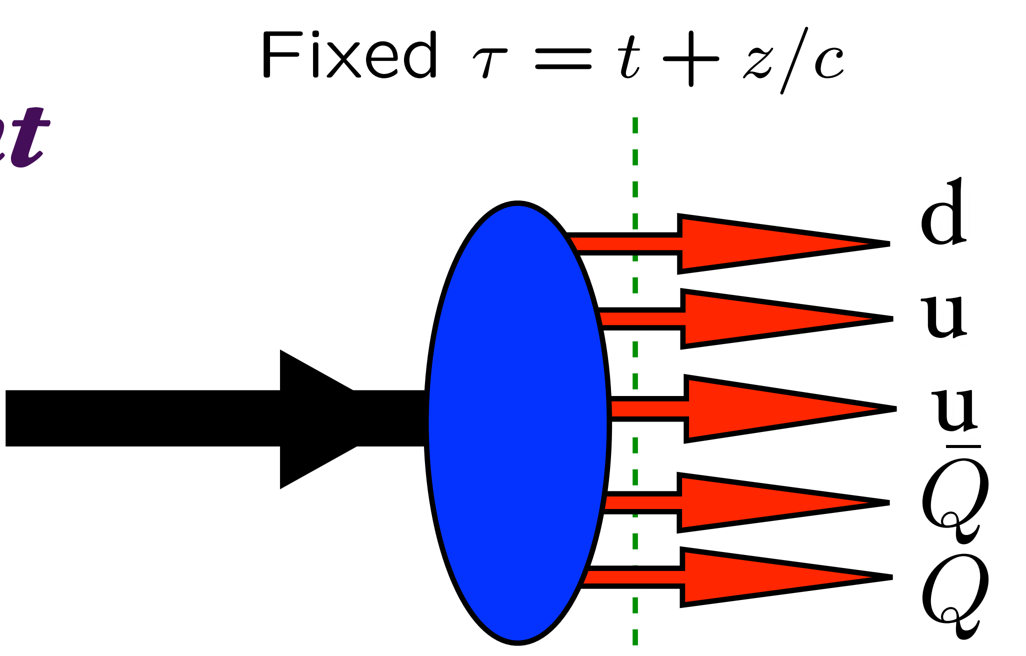
$$\psi_n(\vec{k}_{\perp i}, x_i) \propto \frac{1}{\kappa^{n-1}} \, e^{-\mathcal{M}_n^2/2\kappa^2} \, \Pi_{j=1}^{n} \frac{1}{\sqrt{x_j}}$$

$$\mathcal{M}_n^2 = \sum_{i=1}^{n} \left(\frac{k_\perp^2 + m^2}{x}\right)_i$$

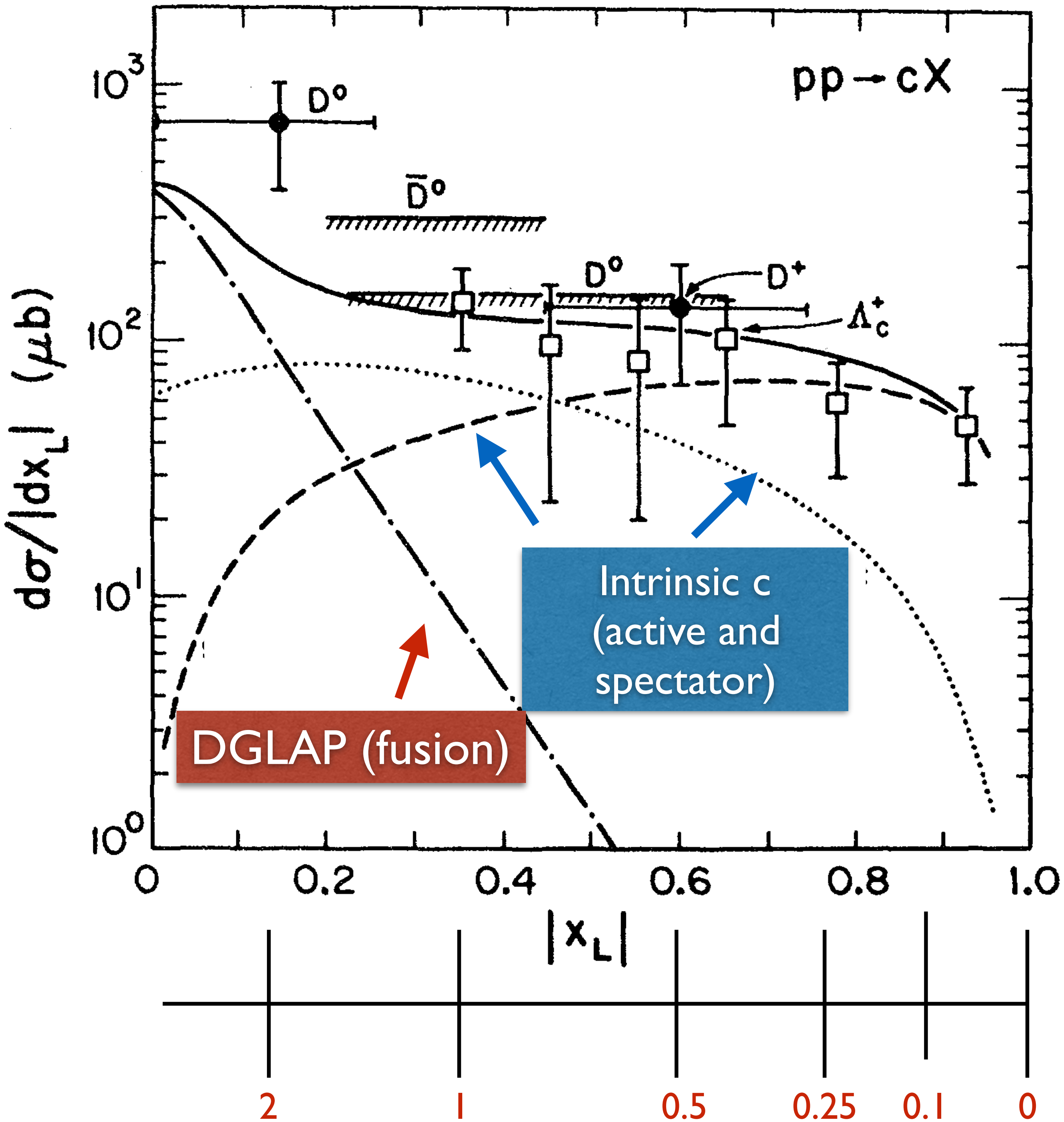
Minimally Off-Shell

Properties of Non-Perturbative Five-Quark Fock-State

- ***Dominant configuration: same rapidity***
- ***Heavy quarks have most momentum***
- ***Correlated with proton quantum numbers***
- ***Duality with meson-baryon channels***
- ***strangeness asymmetry at x > 0.1***
- ***Maximally energy efficient***



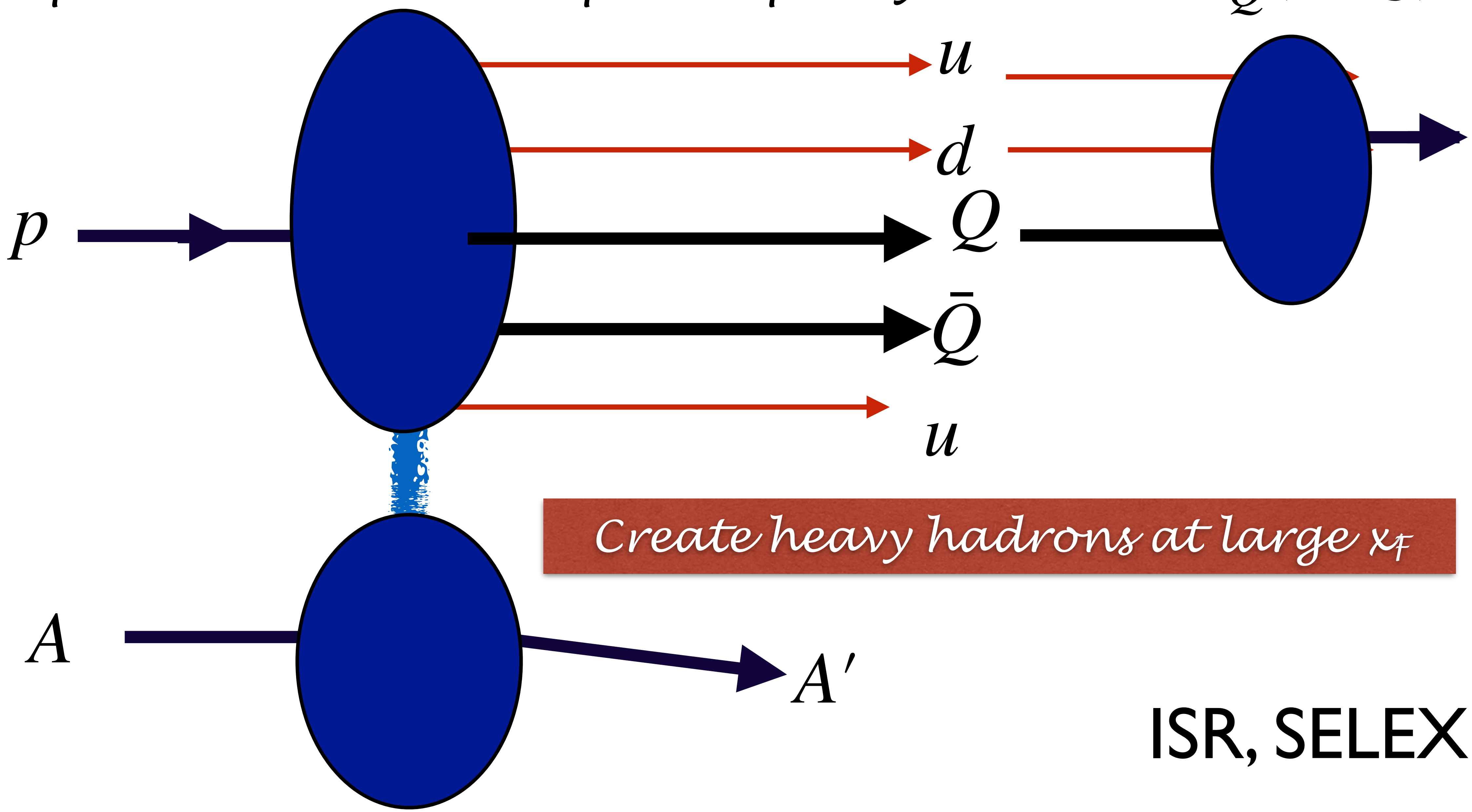
Barger, Halzen, Keung
PRD 25 (1981)



$\Delta y = \log x$

Novel Effects Derived from Light-Front Wavefunctions

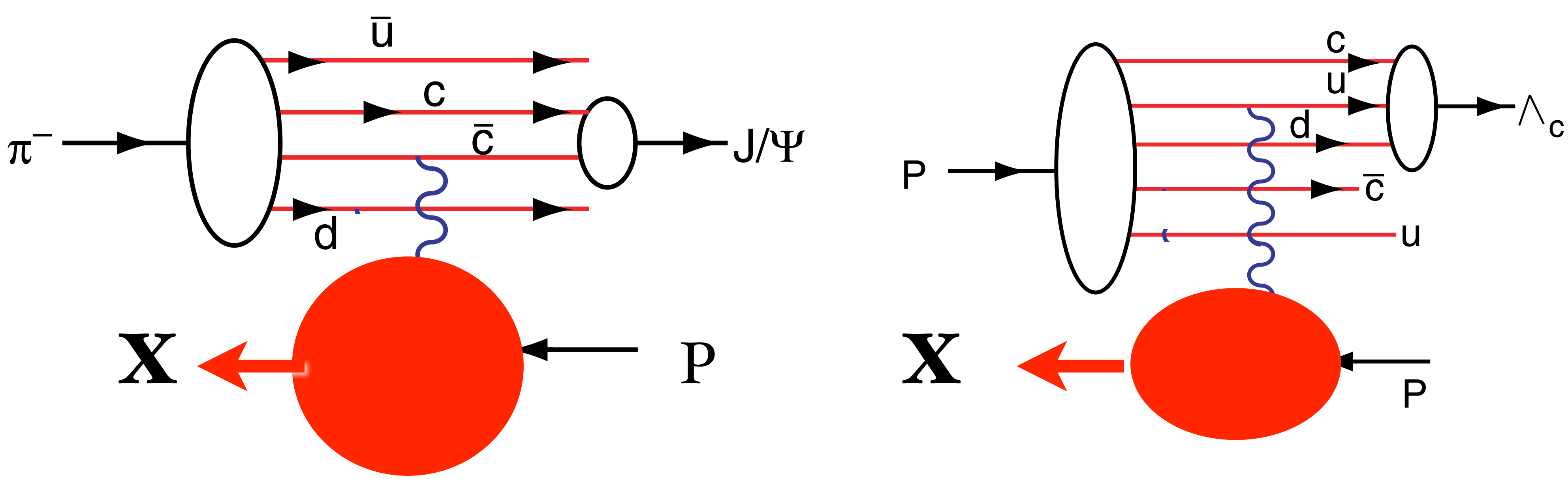
Intrinsic quarks coalesce at equal rapidity to make $\Lambda_Q(udQ)$



Create heavy hadrons at large x_F

ISR, SELEX

Coalescence of comovers produces high-x_F heavy hadrons



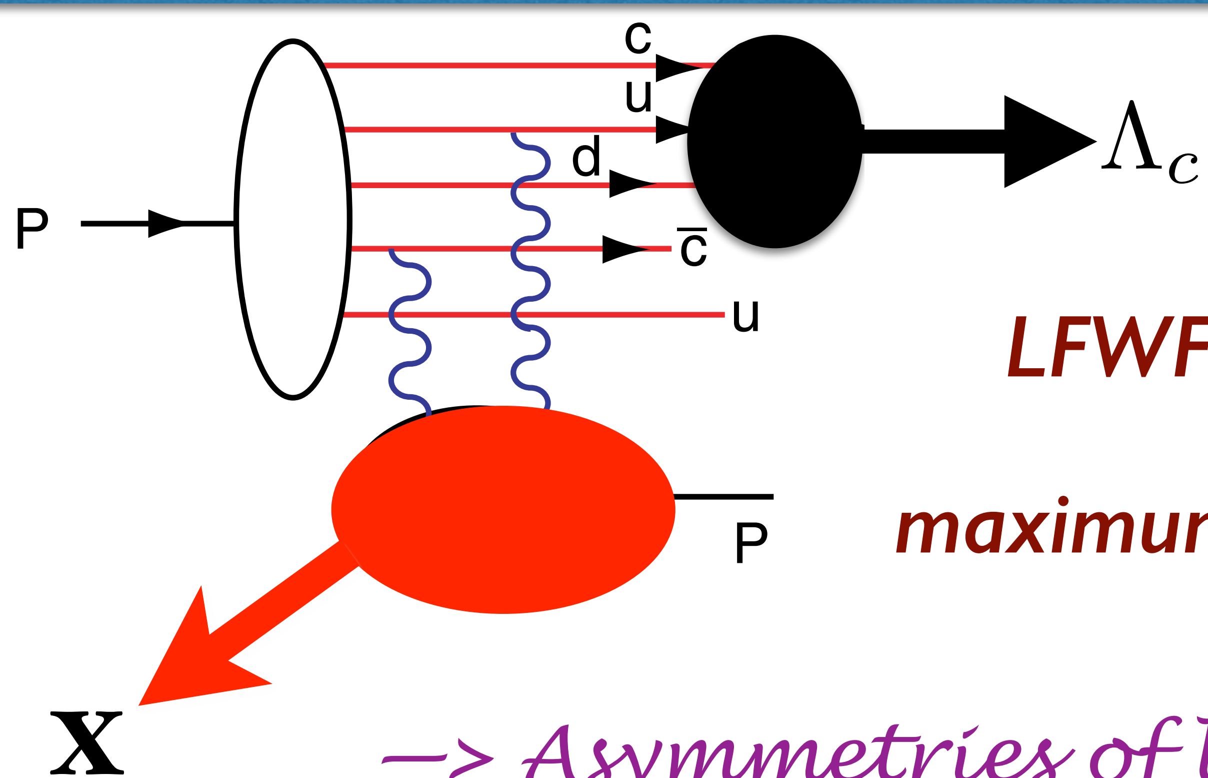
Spectator counting rules

$$\frac{dN}{dx_F} \propto (1 - x_F)^{2n_{spect}-1}$$

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

Coalesece of comovers produces high x_F heavy hadrons

High x_F hadrons combine most of the comovers, fewest spectators



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

LFWF maximum at equal rapidity

maximum at minimal invariant mass

—> Asymmetries of leading hadrons

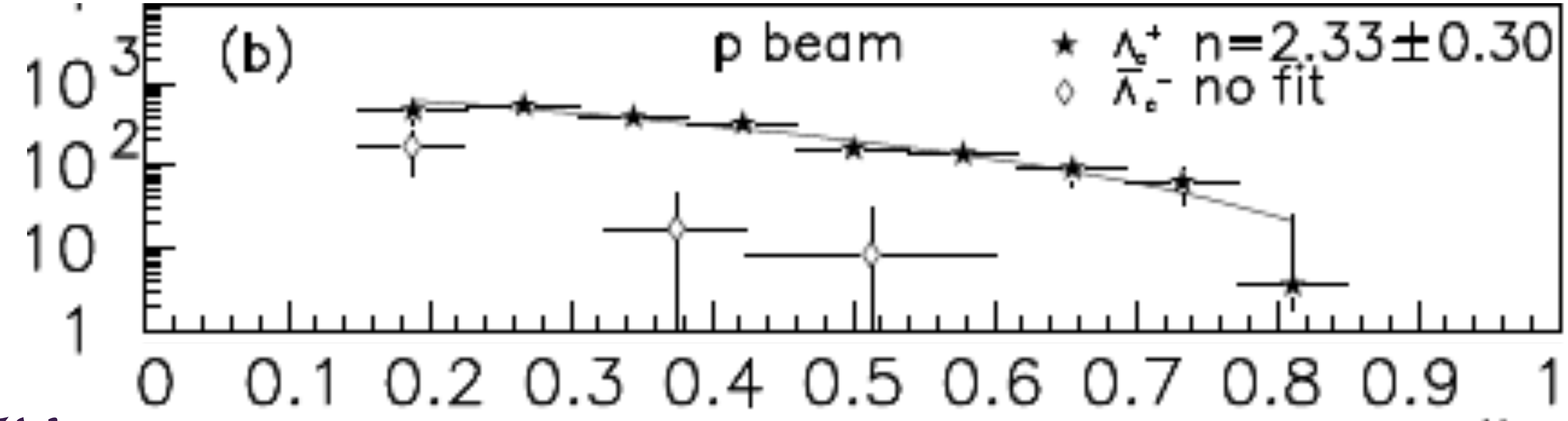
Spectator counting rules

$$\frac{dN}{dx_F} \propto (1 - x_F)^{2n_{spect}-1}$$

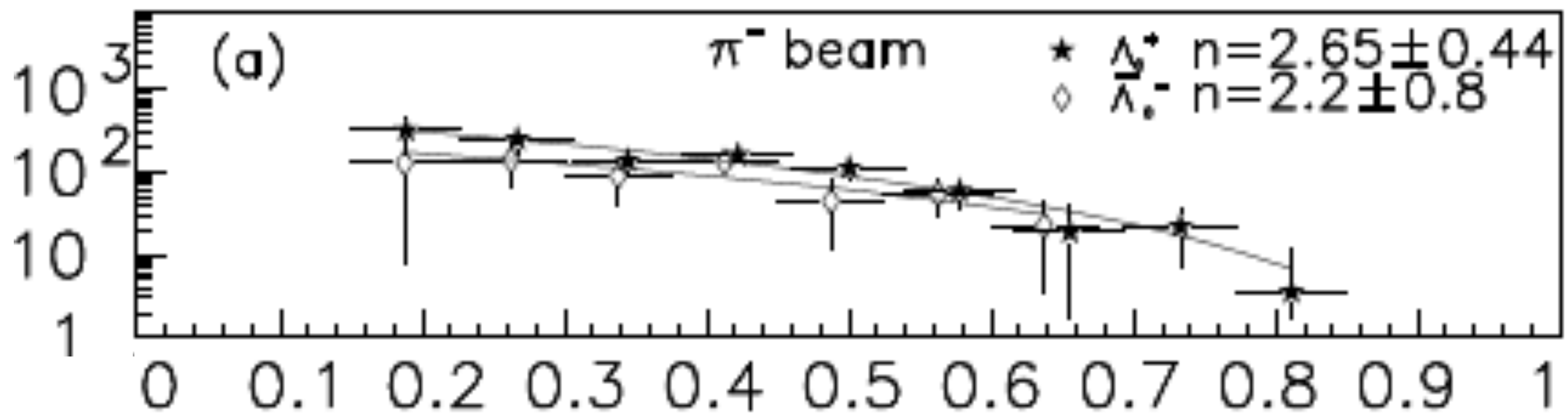
Coalescence of Comoving Charm and Valence Quarks
Produce J/ψ, Λ_c and other Charm Hadrons at High x_F

Vogt, sjb

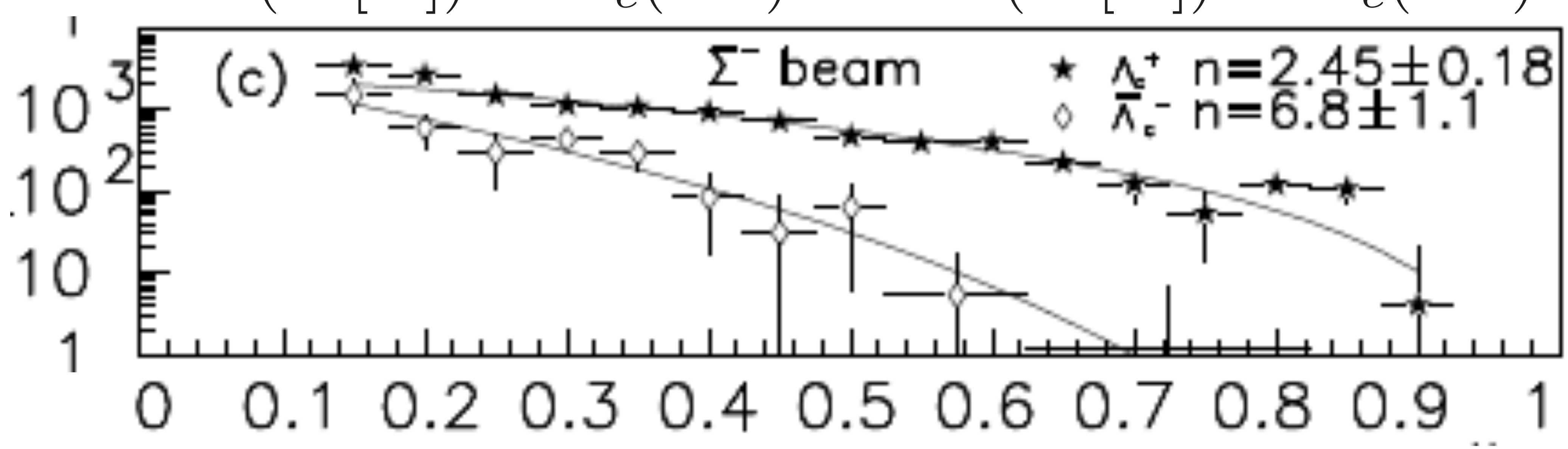
SELEX



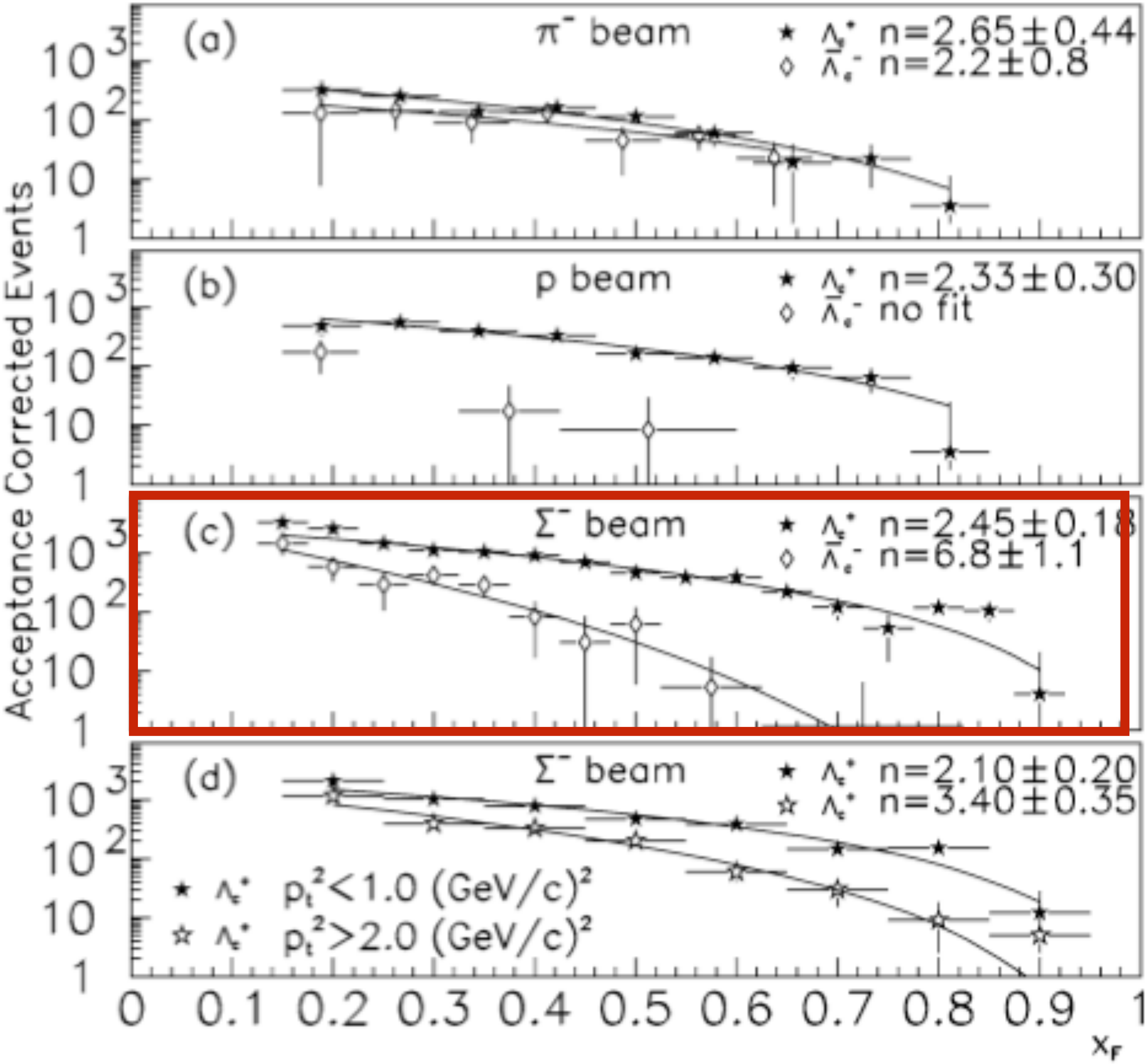
$p(uud[c\bar{c}]) \to \Lambda_c(udc)$ vs. $p(uud[c\bar{c}]) \to \bar{\Lambda}_c(\bar{u}\bar{d}\bar{c})$



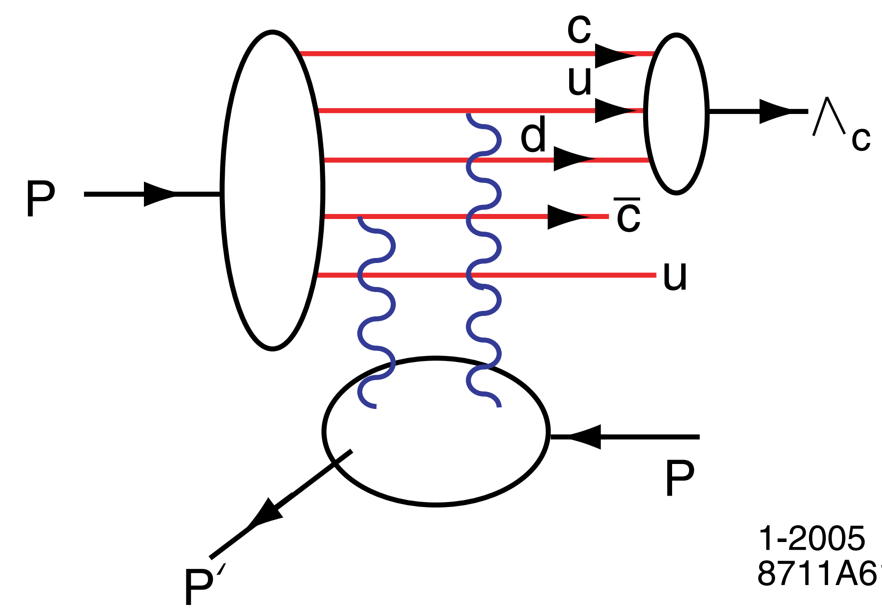
$\pi^-(\bar{u}d[c\bar{c}]) \to \Lambda_c(udc)$ vs. $\pi^-(\bar{u}d[c\bar{c}]) \to \bar{\Lambda}_c(\bar{u}\bar{d}\bar{c})$



$\Sigma^-(uds[c\bar{c}]) \to \Lambda_c(udc)$ vs. $\Sigma^-(uds[c\bar{c}]) \to \bar{\Lambda}_c(\bar{u}\bar{d}\bar{c})$



SELEX



$p(uudc\bar{c})$

$\rightarrow \Lambda_c(cud)$

$n_s = 2$

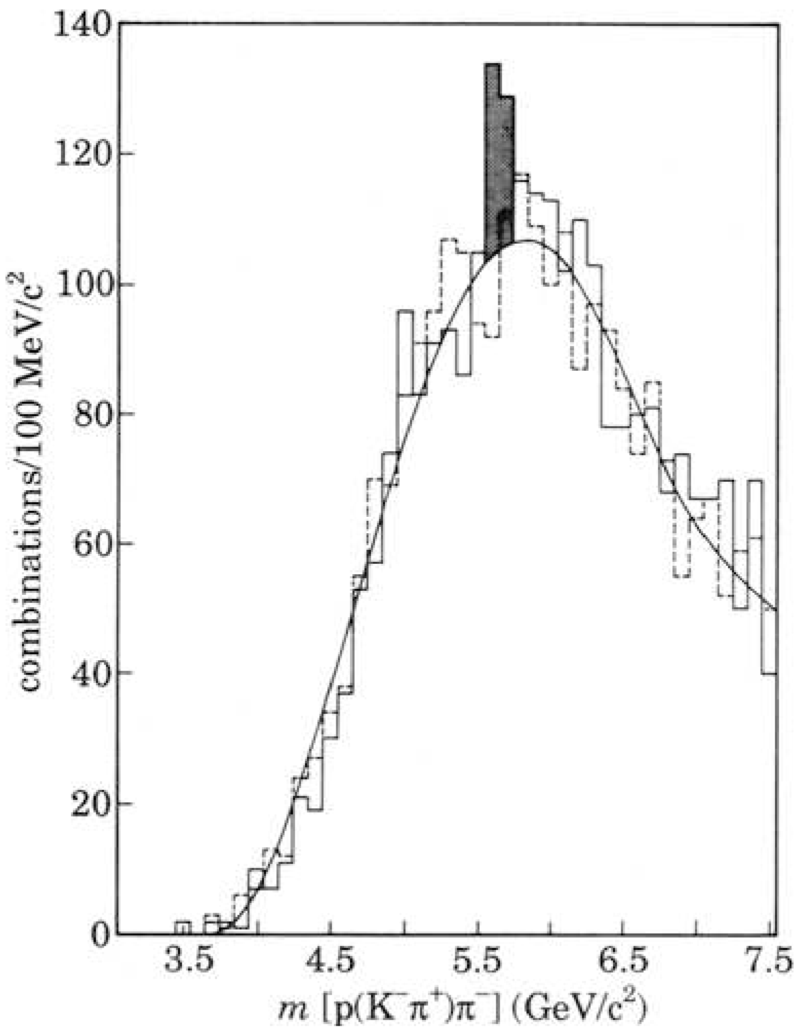
Phase space gives minimum power p

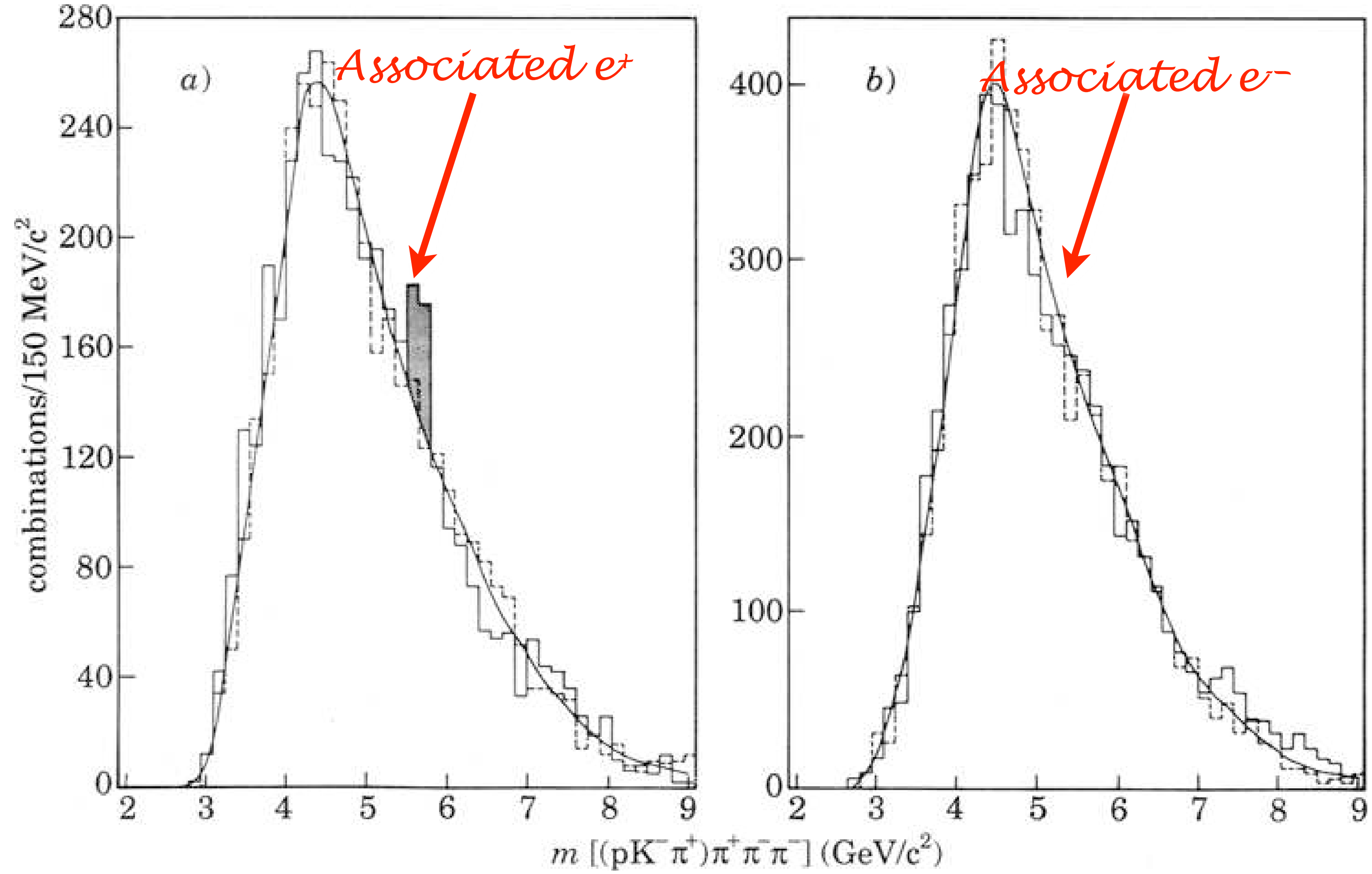
$(1 - x_F)^p, p = n_s - 1$

$\Sigma^-(sddc\bar{c})A \to \Lambda_c(cdu)X$ vs. $\Sigma^-(sddc\bar{c})A \to \bar{\Lambda}_c(\bar{c}\bar{d}\bar{u})X$

$pp \rightarrow \Lambda_b(bud) B(\bar{b}q) X$ at large x_F $\sqrt{s} = 63\ GeV$

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





$\Lambda_b^0 \rightarrow pD^0\pi^-$ $\Lambda_b^0 \rightarrow \Lambda_c^+\pi^+\pi^-\pi^-$

Il Nuovo Cimento 104, 1787

Discovery of Λ_b; Associated Production; Evidence for Intrinsic $b\bar{b}$

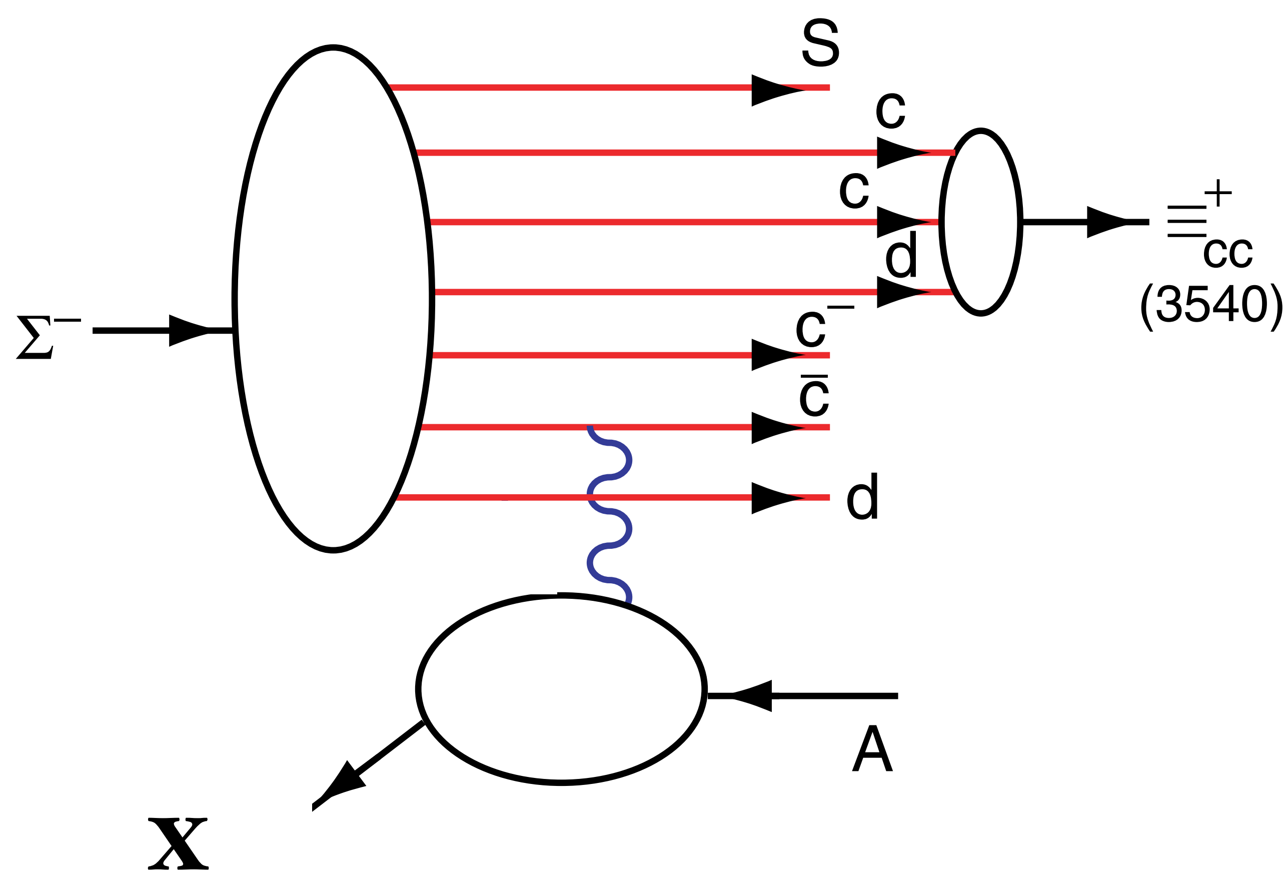
Create Λ_b at rest at LHCb at $\sqrt{s} = \sqrt{13000} = 115\ GeV$

Λ_b^0 MASS

$m_{\Lambda_b^0}$

INSPI

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
5619.51 ± 0.23	**OUR AVERAGE**				
5619.30 ± 0.34		[1] AAIJ	2014AA	LHCB	$p\,p$ at 7 TeV
$5620.15 \pm 0.31 \pm 0.47$		[2] AALTONEN	2014B	CDF	$p\,\overline{p}$ at 1.96 TeV
$5619.7 \pm 0.7 \pm 1.1$		[2] AAD	2013U	ATLS	$p\,p$ at 7 TeV
$5619.44 \pm 0.13 \pm 0.38$		[2] AAIJ	2013AV	LHCB	$p\,p$ at 7 TeV
$5621 \pm 4 \pm 3$		[3] ABE	1997B	CDF	$p\,\overline{p}$ at 1.8 TeV
$5668 \pm 16 \pm 8$	4	[4] ABREU	1996N	DLPH	$e^+ e^- \to Z$
$5614 \pm 21 \pm 4$	4	[4] BUSKULIC	1996L	ALEP	$e^+ e^- \to Z$
*** We do not use the following data for averages, fits, limits, etc ***					
$5619.19 \pm 0.70 \pm 0.30$		[2] AAIJ	2012E	LHCB	Repl. by AAIJ 2013AV
$5619.7 \pm 1.2 \pm 1.2$		[5] ACOSTA	2006	CDF	Repl. by AALTONEN 2014B
not seen		[6] ABE	1993B	CDF	Repl. by ABE 1997B
$5640 \pm 50 \pm 30$	16	[7] ALBAJAR	1991E	UA1	$p\,\overline{p}$ 630 GeV
5640^{+100}_{-210}	52	BARI	1991	SFM	$\Lambda_b^0 \to pD^0\pi^-$
5650^{+150}_{-200}	90	BARI	1991	SFM	$\Lambda_b^0 \to \Lambda_c^+\pi^+\pi^-\pi^-$



Production of a Double-Charm Baryon

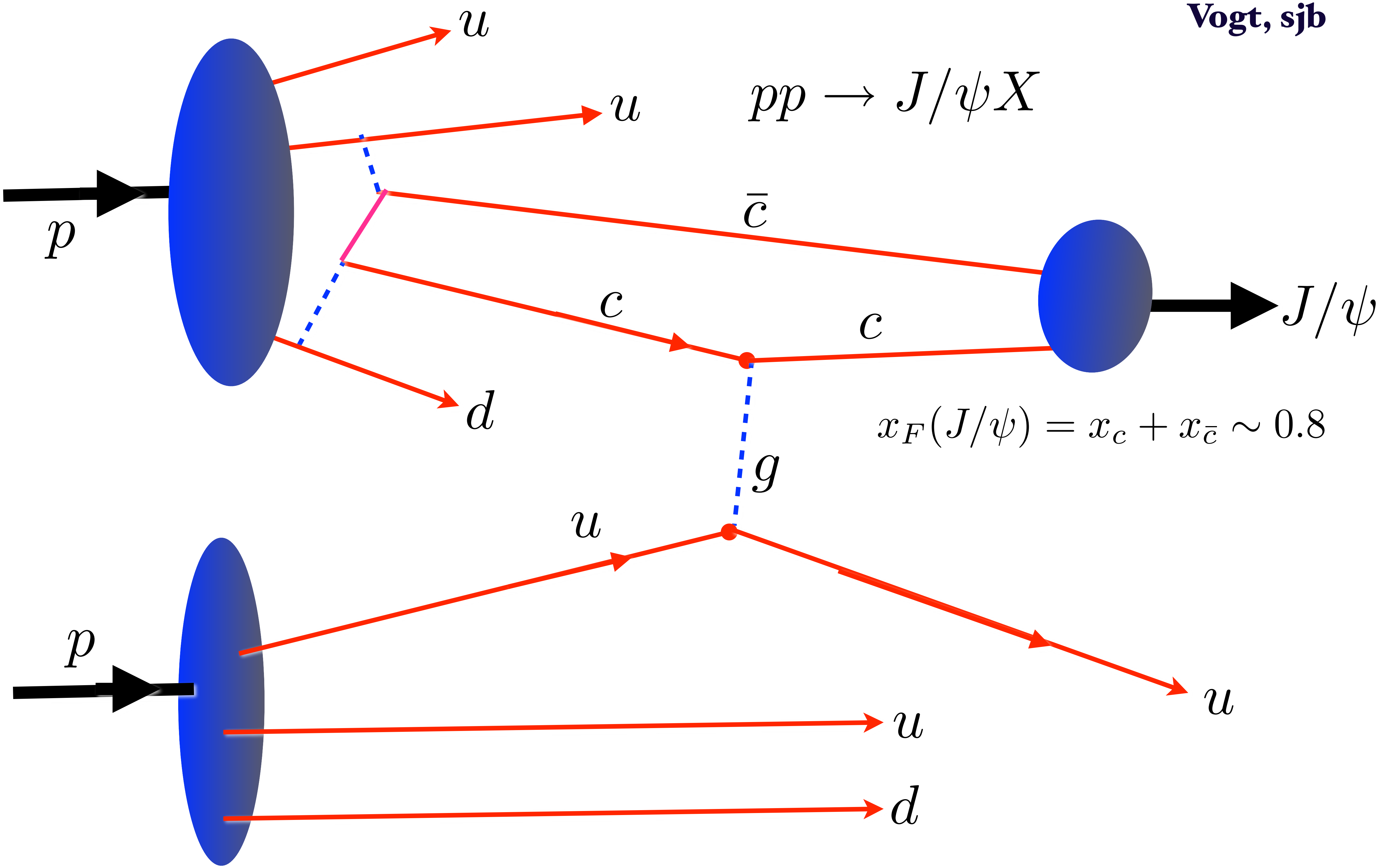
SELEX high x_F $\quad < x_F >= 0.33$

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

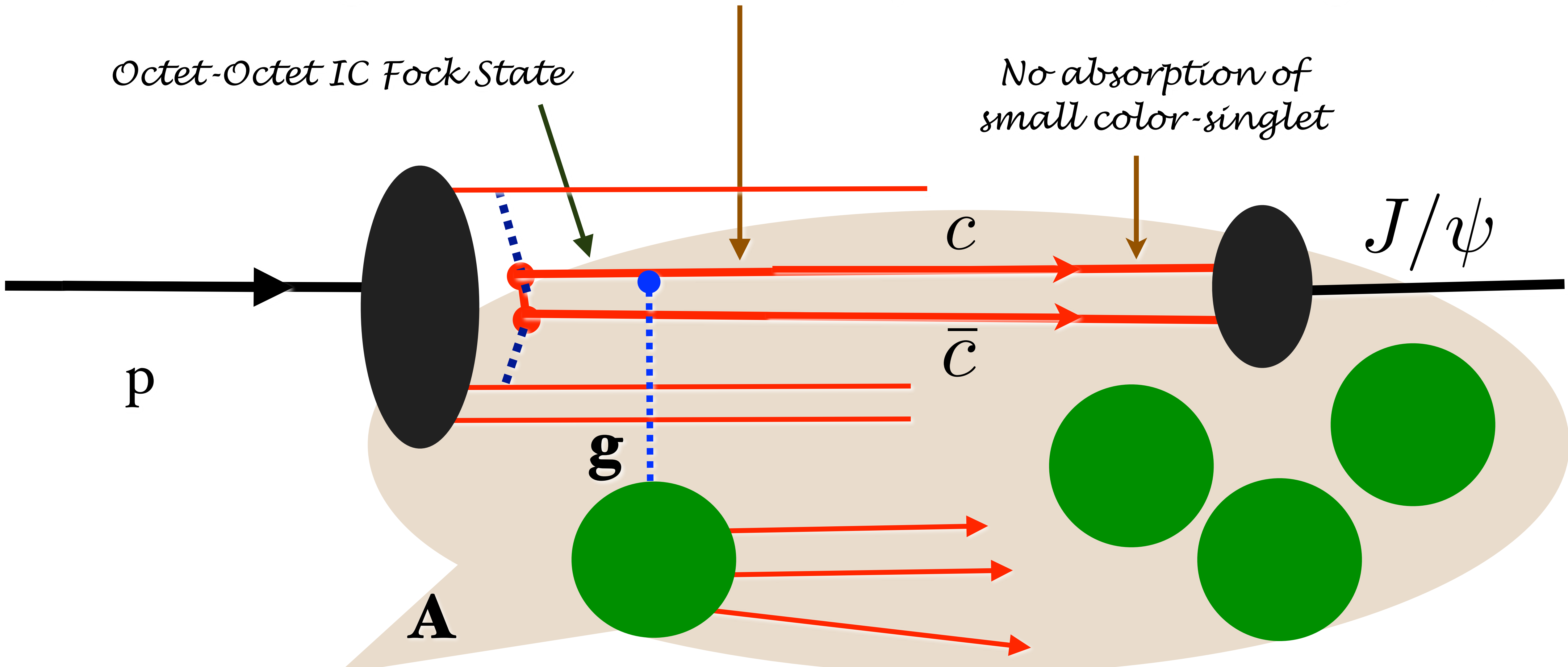
$$x_i \propto \frac{m_{\perp i}}{\sum_j m_{\perp j}}$$

High x_F

Color-Opaque IC Fock state interacts on nuclear front surface

Kopeliovich, Schmidt, Soffer, sjb

Scattering on front-face nucleon produces color-singlet $c\bar{c}$ pair

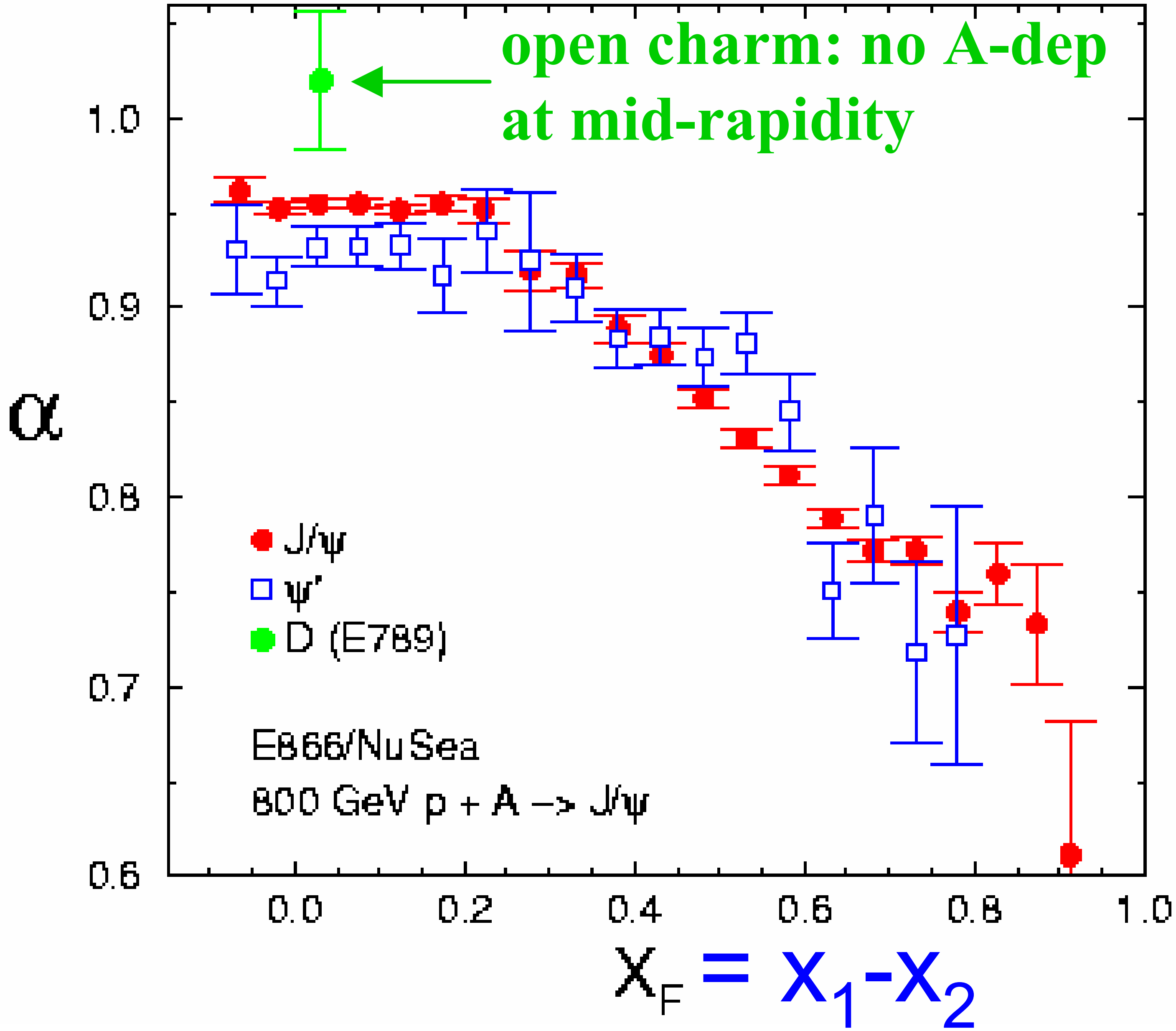


$$\frac{d\sigma}{dx_F}(pA \to J/\psi X) = A^{2/3} \times \frac{d\sigma}{dx_F}(pN \to J/\psi X)$$

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.

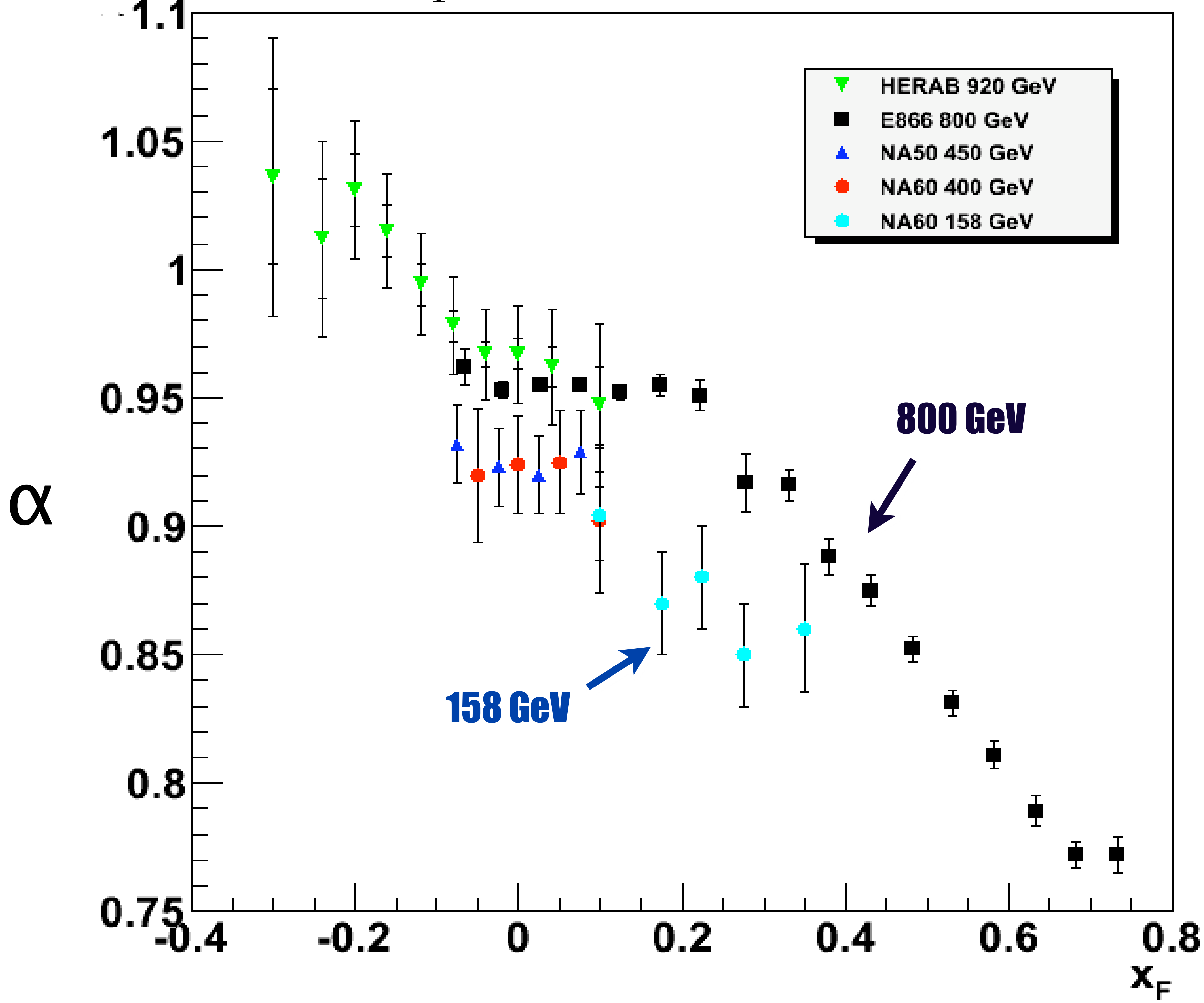
P. Hoyer, **M. Vanttinen** (**Helsinki U.**) , **U. Sukhatme** (**Illinois U., Chicago**) . **HU-TFT-90-14, May 1990. 7pp.**

Published in Phys.Lett.B246:217-220,1990

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

NA60 pA data @ 158GeV

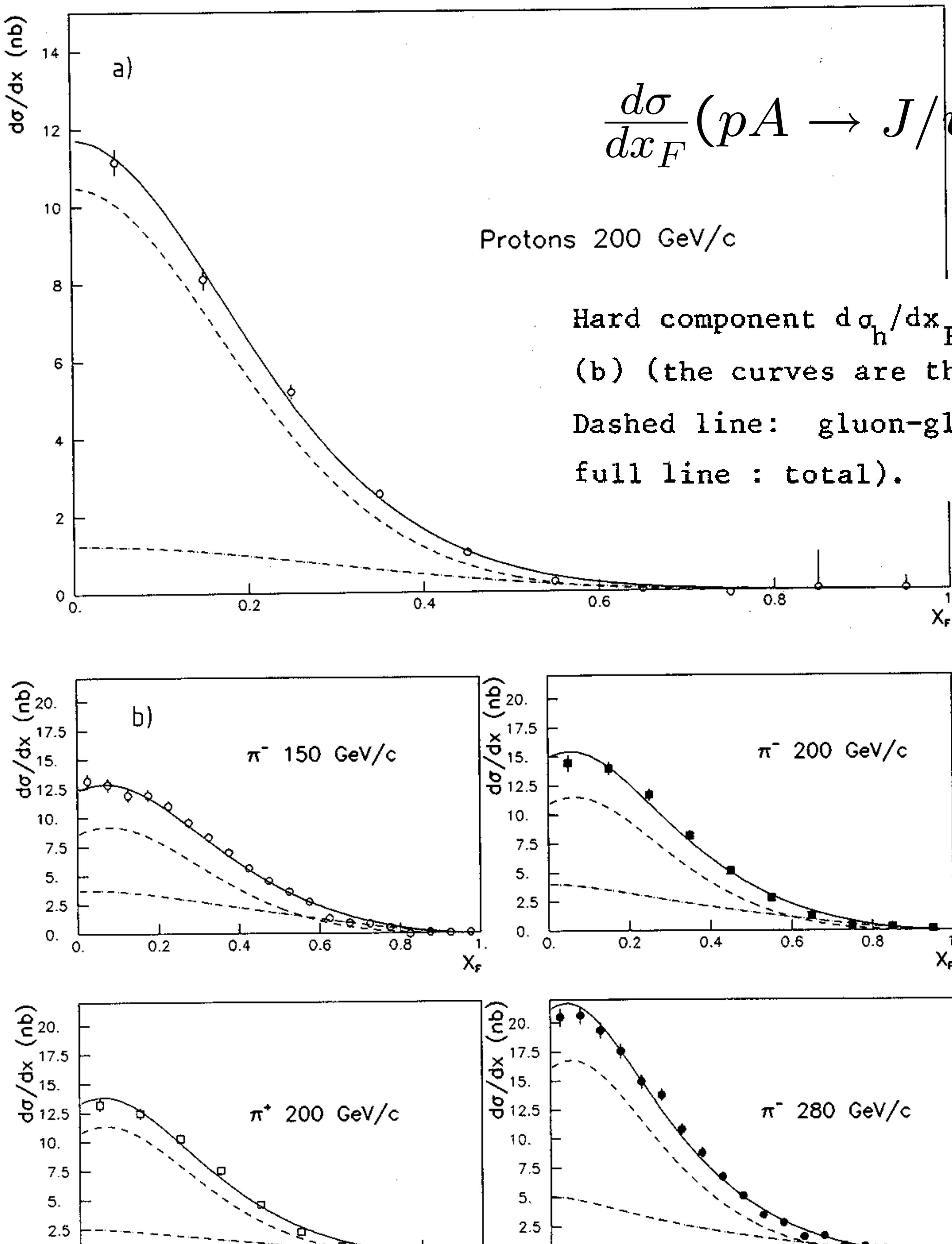
$$\frac{d\sigma}{dx_F}(pA \to J/\psi X) \propto A^{\alpha}$$



Clear dependence on x_F and beam energy

Dramatic change in nuclear dependence

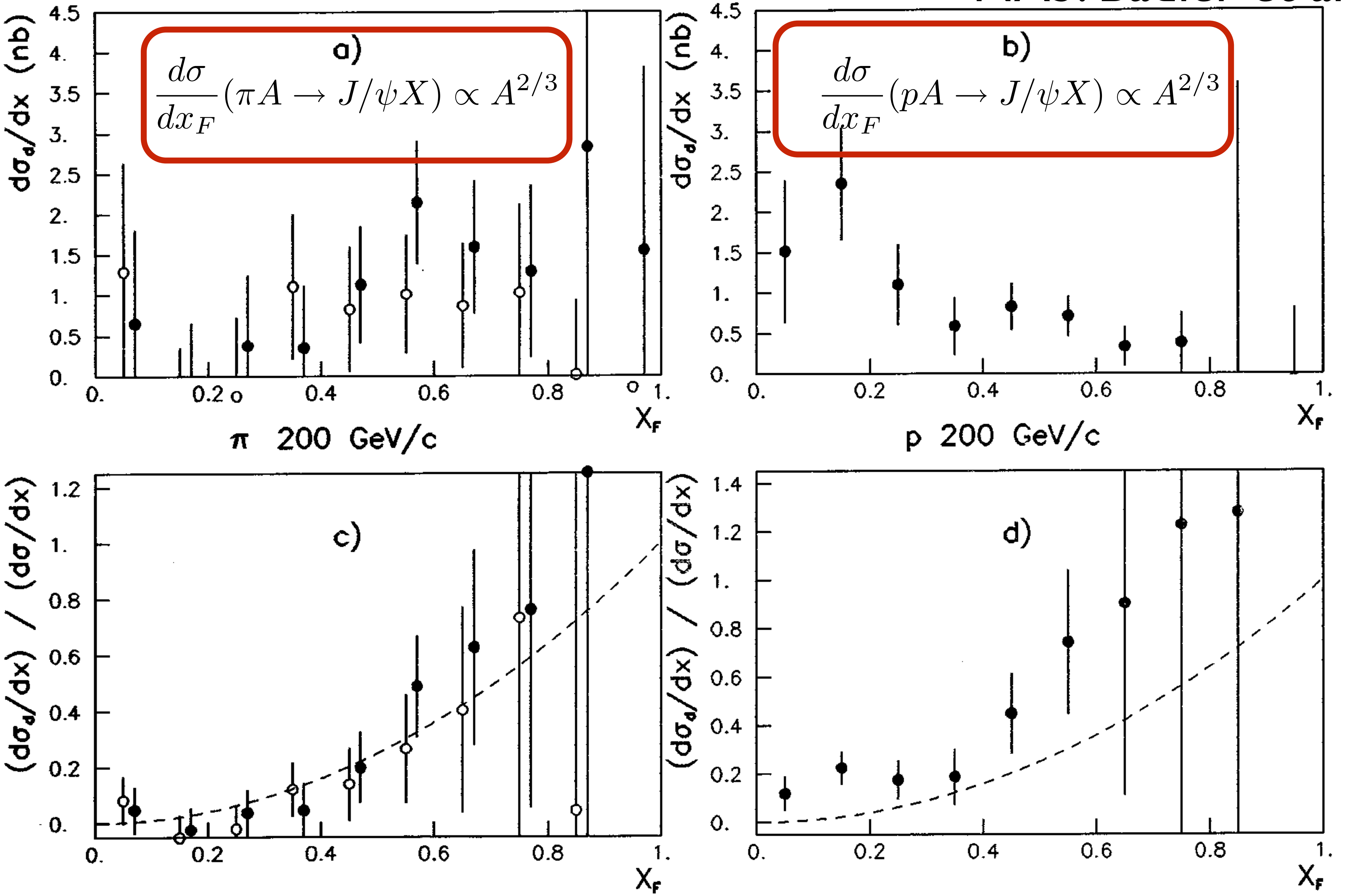
$$\frac{d\sigma}{dx_F}(pA \to J/\psi X) = A^1 \frac{d\sigma_1}{dx_F} + A^{2/3} \frac{d\sigma_{2/3}}{dx_F}$$



Hard component $d\sigma_h/dx_F$ for incident protons (a) and pions (b) (the curves are the result of the fit described in the text. Dashed line: gluon-gluon fusion; dash-dotted line : $q\bar{q}$ fusion; full line : total).

A^1 component consistent with sum of gg and $\bar{q}q$ fusion

NA3: Badier et al.

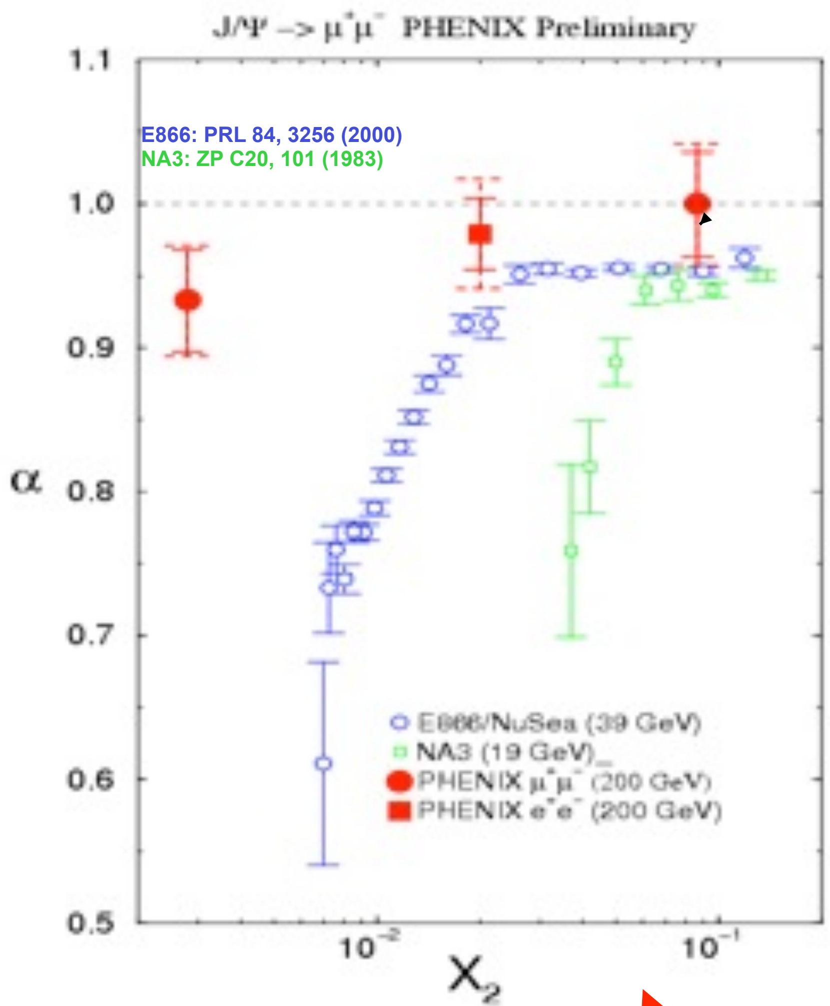


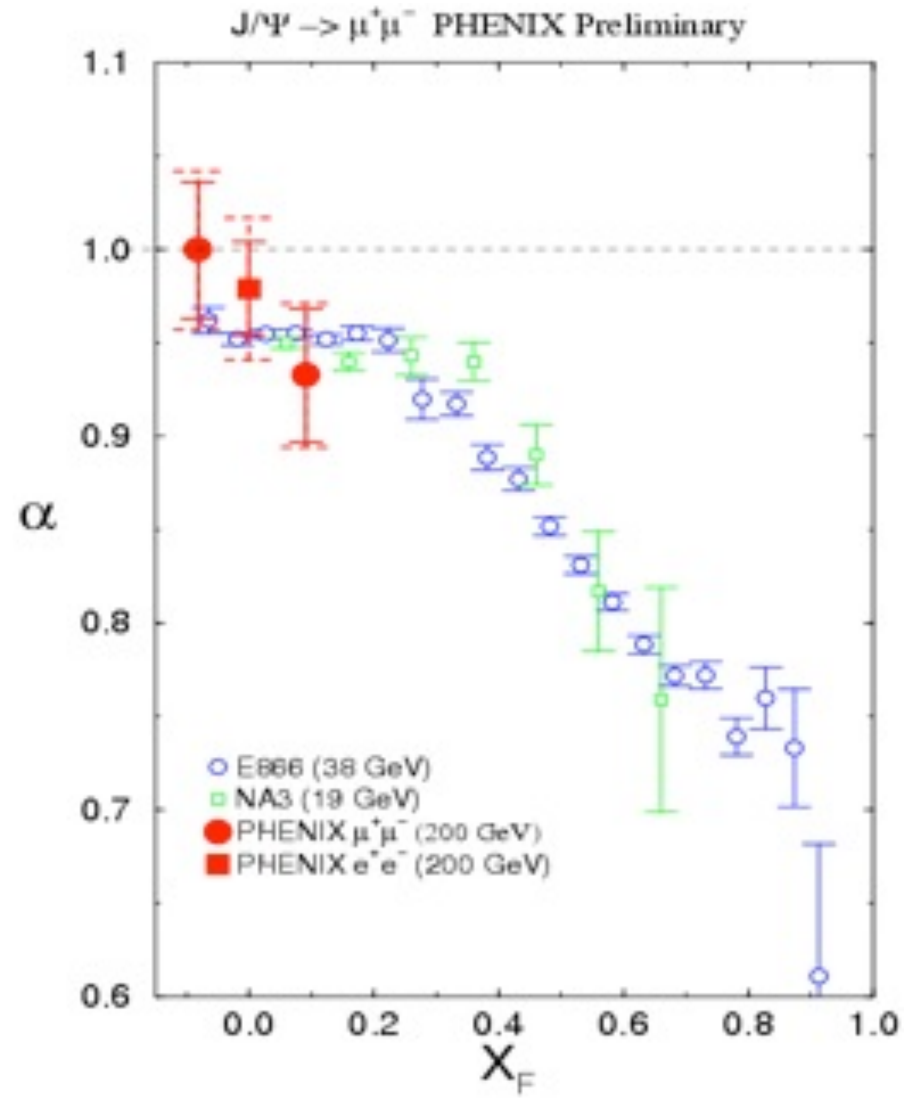
Flat x_F distribution explained by IC

J/ψ nuclear dependence versus rapidity, x_{Au}, x_F

M.Leitch

PHENIX compared to lower energy measurements





Huge "absorption" effect

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

Violates PQCD factorization!

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

Hoyer, Sukhatme, Vanttinen

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

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

Excludes `color drag' model

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

R. Vogt, sjb

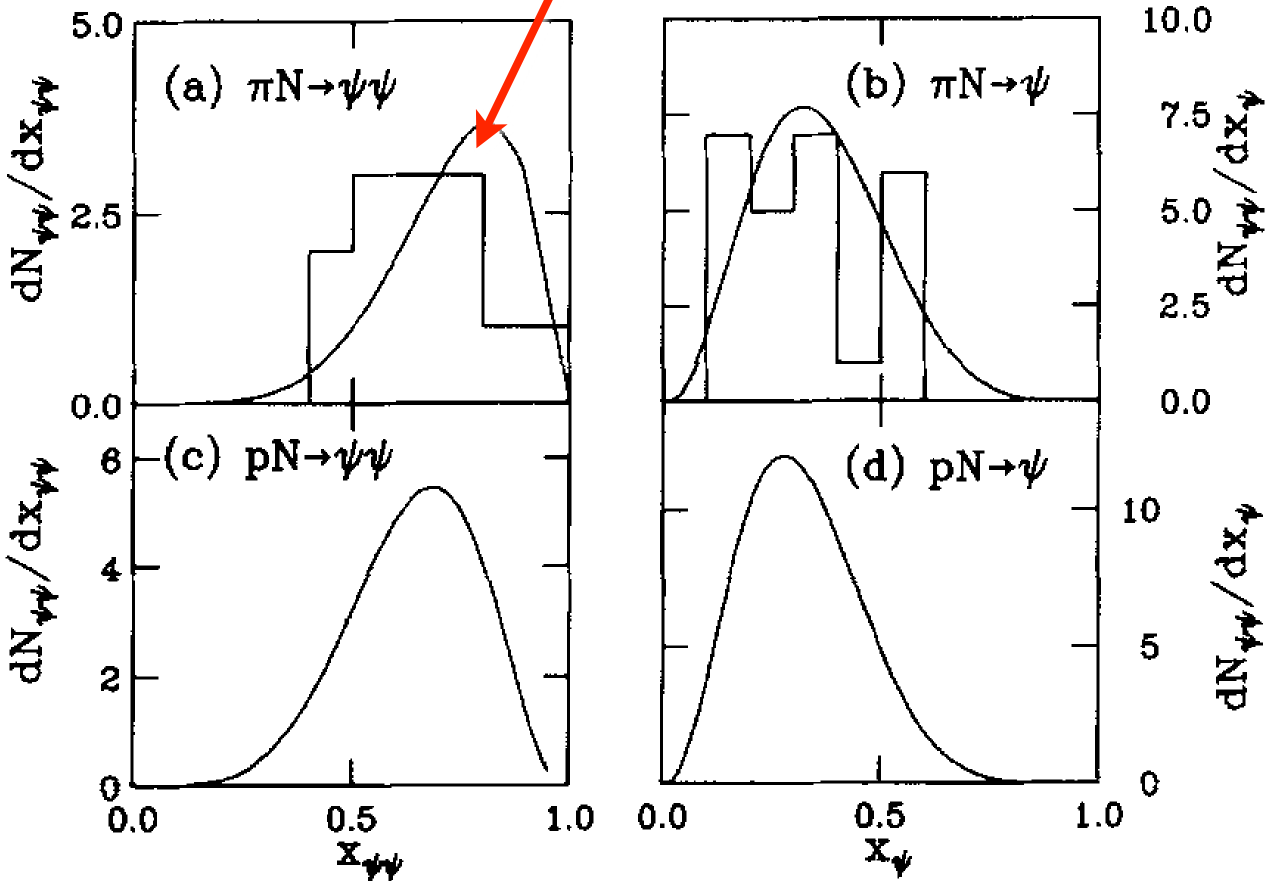


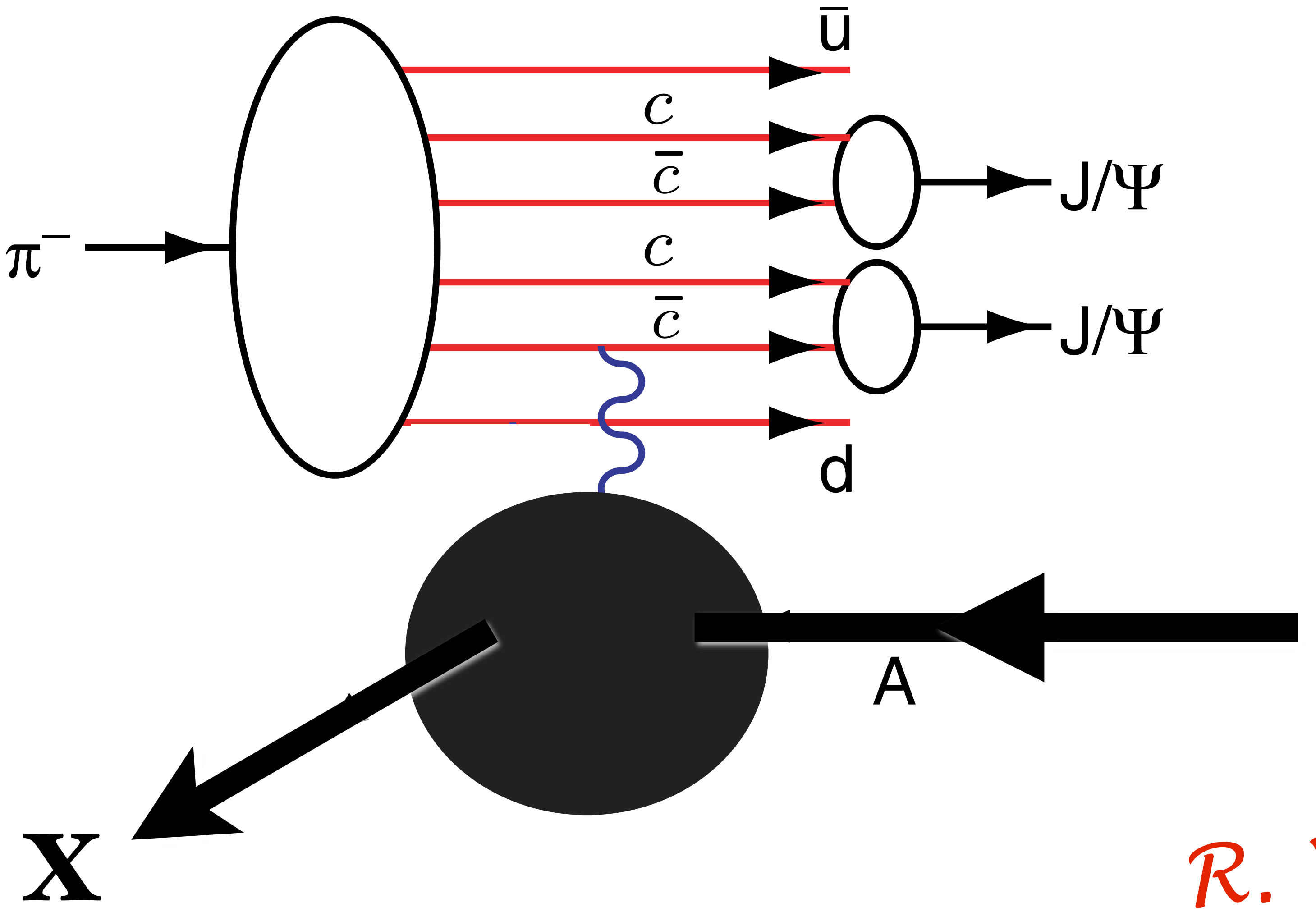
Fig. 3. The $\psi\psi$ pair distributions are shown in (a) and (c) for the pion and proton projectiles. Similarly, the distributions of J/ψ's from the pairs are shown in (b) and (d). Our calculations are compared with the $\pi^- N$ data at 150 and 280 GeV/c [1]. The $x_{\psi\psi}$ distributions are normalized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

NA3 Data

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

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

Cannot be explained
by Color Drag Model



R. Vogt, sjb

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

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

Rules out color drag (Pythia)

- 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)

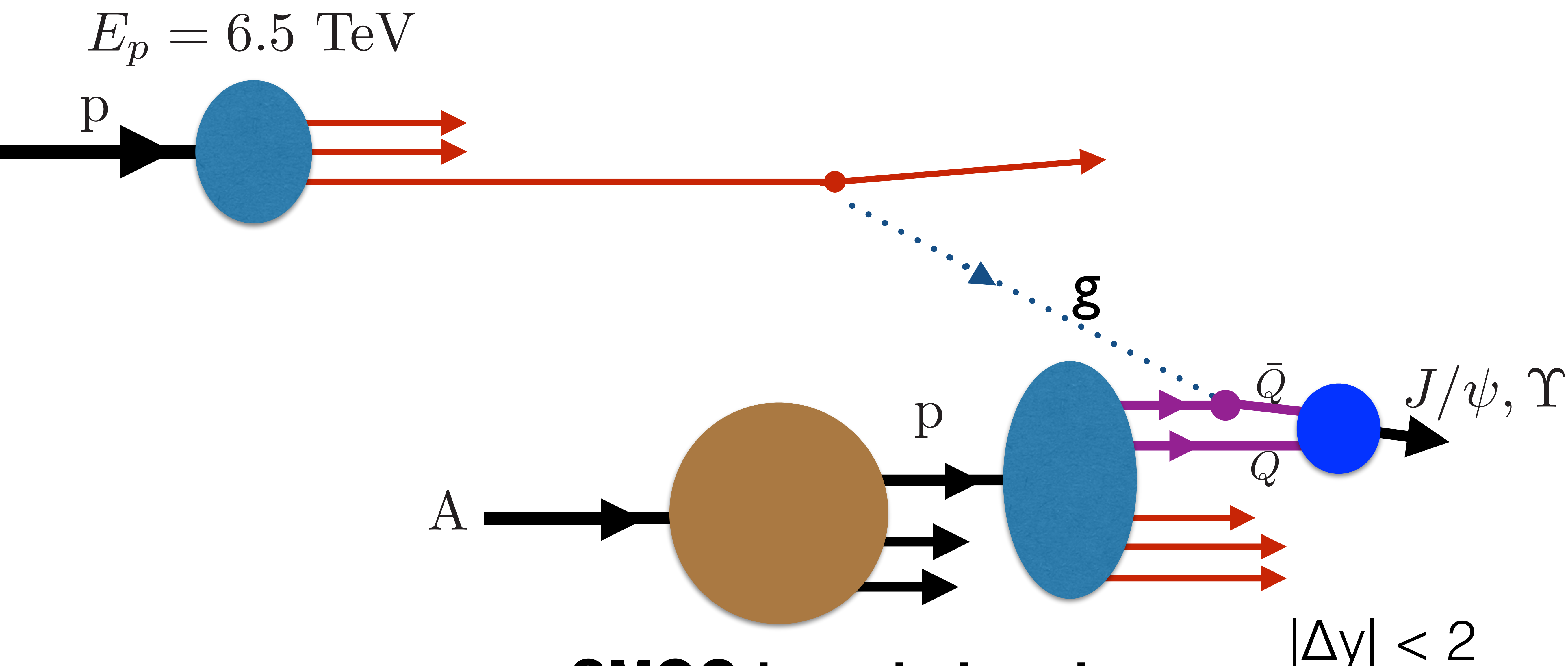
Explain Tevatron anomalies: $p\bar{p} \to \gamma c X, Z c X$

Interesting spin, charge asymmetry, threshold, spectator effects

Important corrections to B decays; Quarkonium decays

Gardner, Karliner, sjb

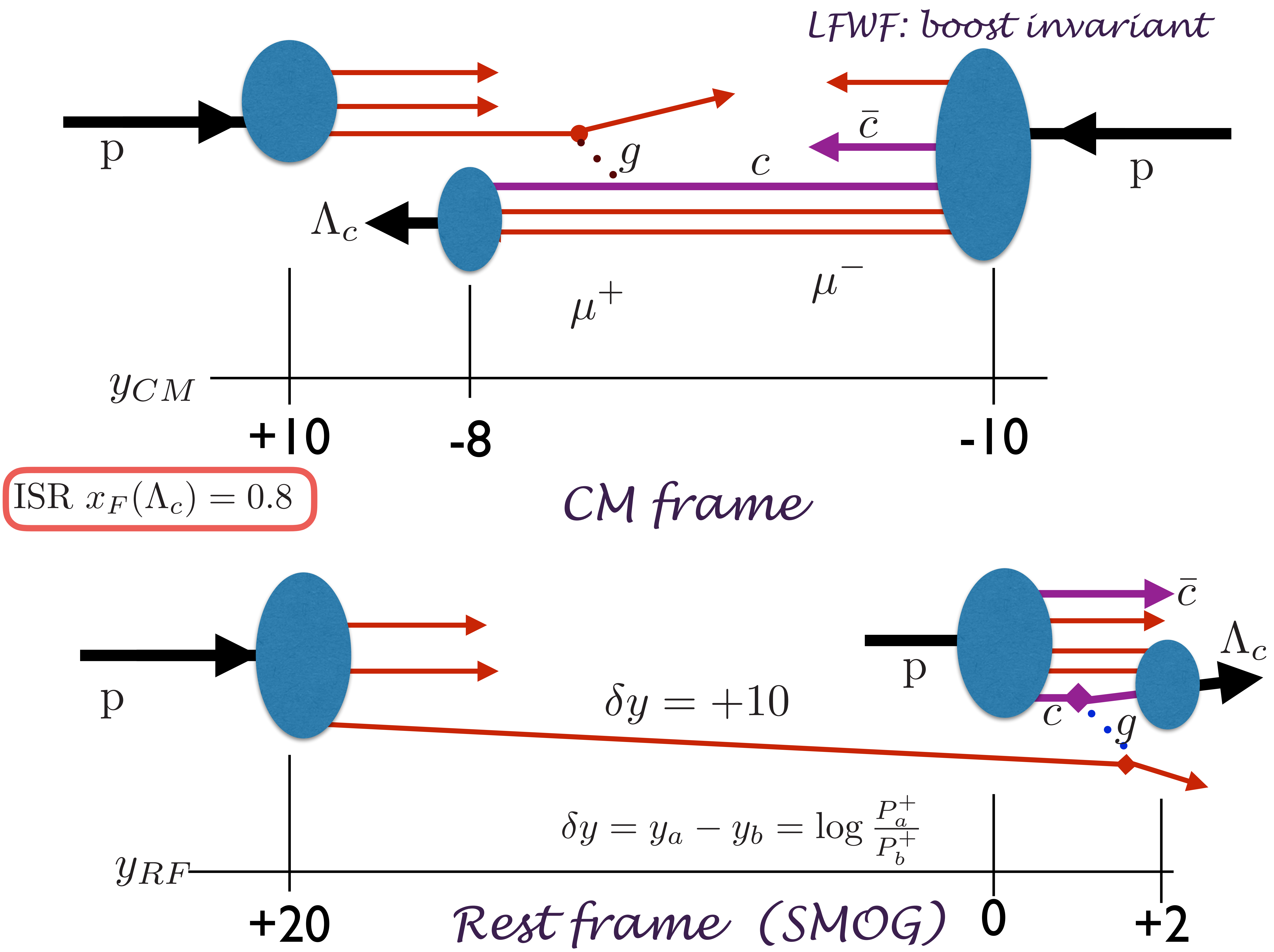
$$pA \to J/\psi X$$



SMOG target at rest

Intrinsic heavy quark probability in the nucleon maximal at minimum off-shellness

Quarkonium produced nearly at rest — has small rapidity in target rest frame



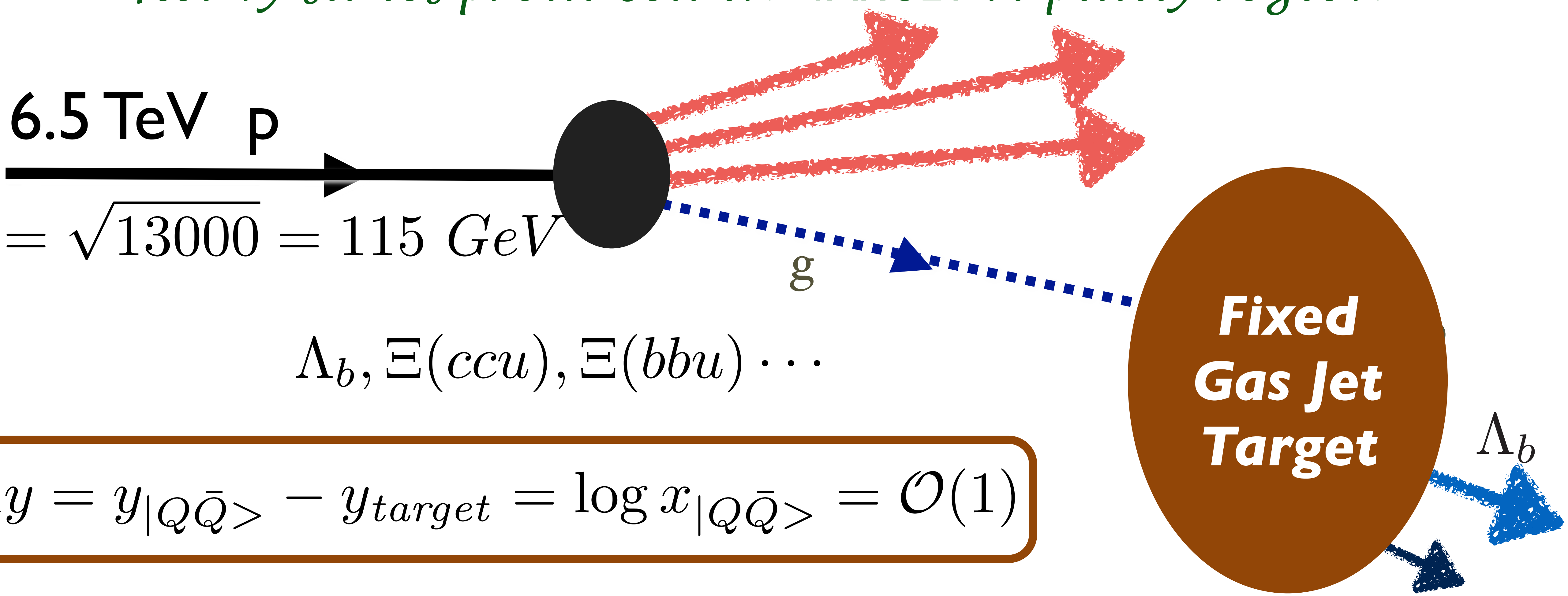
LFWF: boost invariant
p
$\bar{c}$
g
c
p
Λ_c
μ^+
μ^-
y_{CM}
+10
-8
-10
ISR $x_F(\Lambda_c) = 0.8$
CM frame
$\bar{c}$
Λ_c
p
p
$\delta y = +10$
c
g
$\delta y = y_a - y_b = \log \frac{P_a^+}{P_b^+}$
y_{RF}
+20
Rest frame (SMOG)
0
+2

Excitation of Intrinsic Heavy Quarks in a Fixed Target

Amplitude maximal at minimal invariant mass, in target rapidity domain!

$$x_i \sim \frac{m_{\perp i}}{\sum_j^n m_{\perp j}} \qquad \frac{d\sigma}{dy_{J/\psi}}(pA \to J/\psi X)$$

Heavy states produced in TARGET *rapidity region*



$$\sqrt{s} = \sqrt{13000} = 115\ GeV$$

$$\Lambda_b, \Xi(ccu), \Xi(bbu) \cdots$$

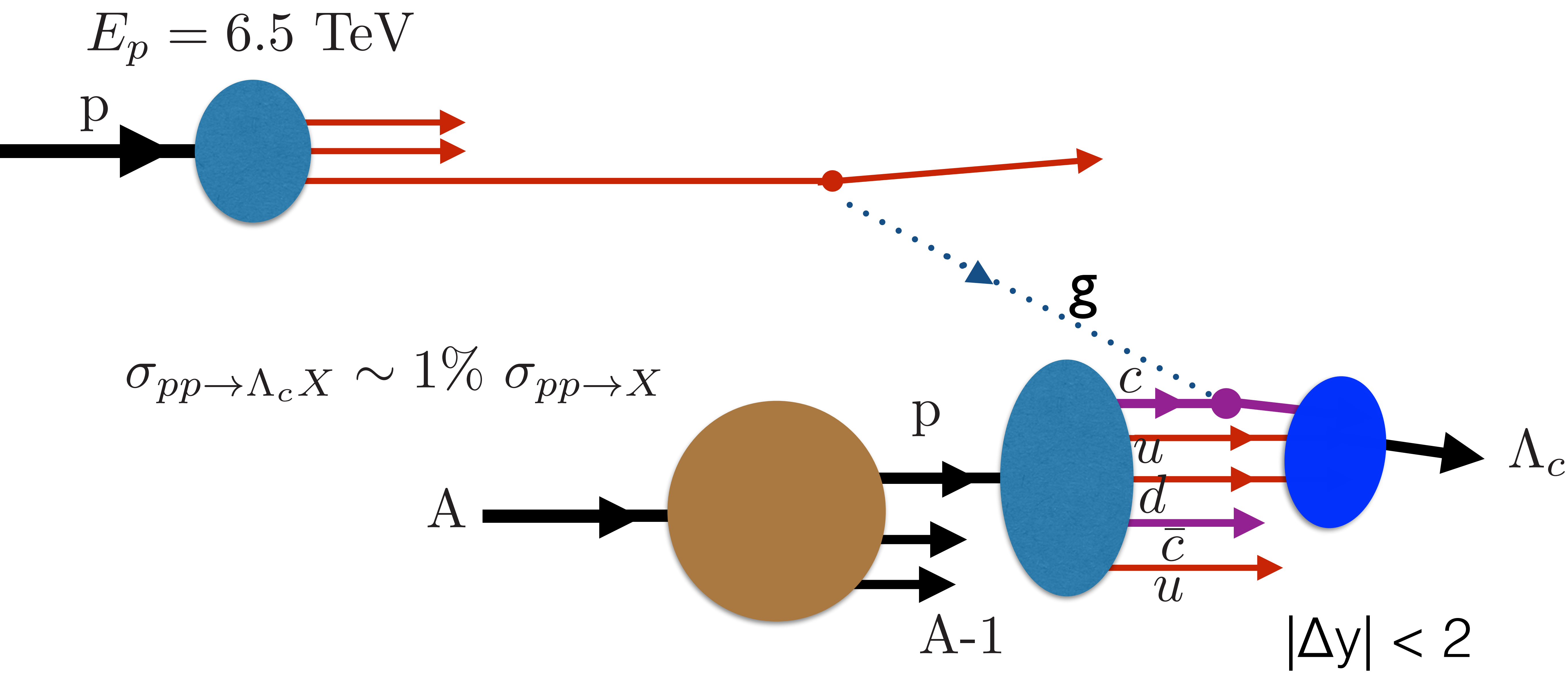
$$\boxed{\Delta y = y_{|Q\bar{Q}>} - y_{target} = \log x_{|Q\bar{Q}>} = \mathcal{O}(1)}$$

Produce $J/\psi, \Upsilon, \Lambda_c, \Lambda_b, |ccu>, |cud\bar{c}>, |cuuddduc\bar{c}>, \cdots$

Test at Smog@LHCb

discussions with M. Williams

$$pA \to \Lambda_c X$$

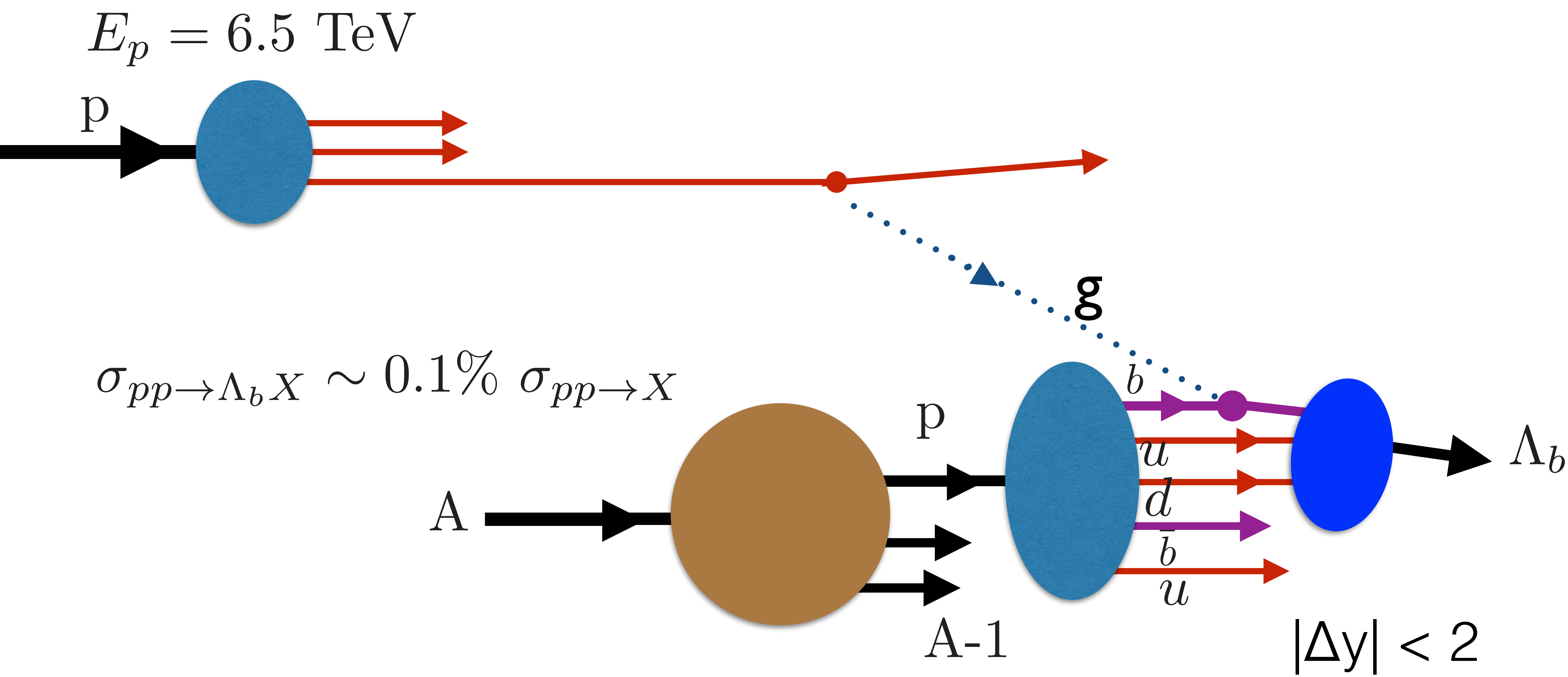


SMOG target at rest

Intrinsic heavy quark probability in the nucleon maximal at minimum off-shellness

Heavy hadrons produced nearly at rest — has small rapidity in target rest frame

$$pA \to \Lambda_b X$$

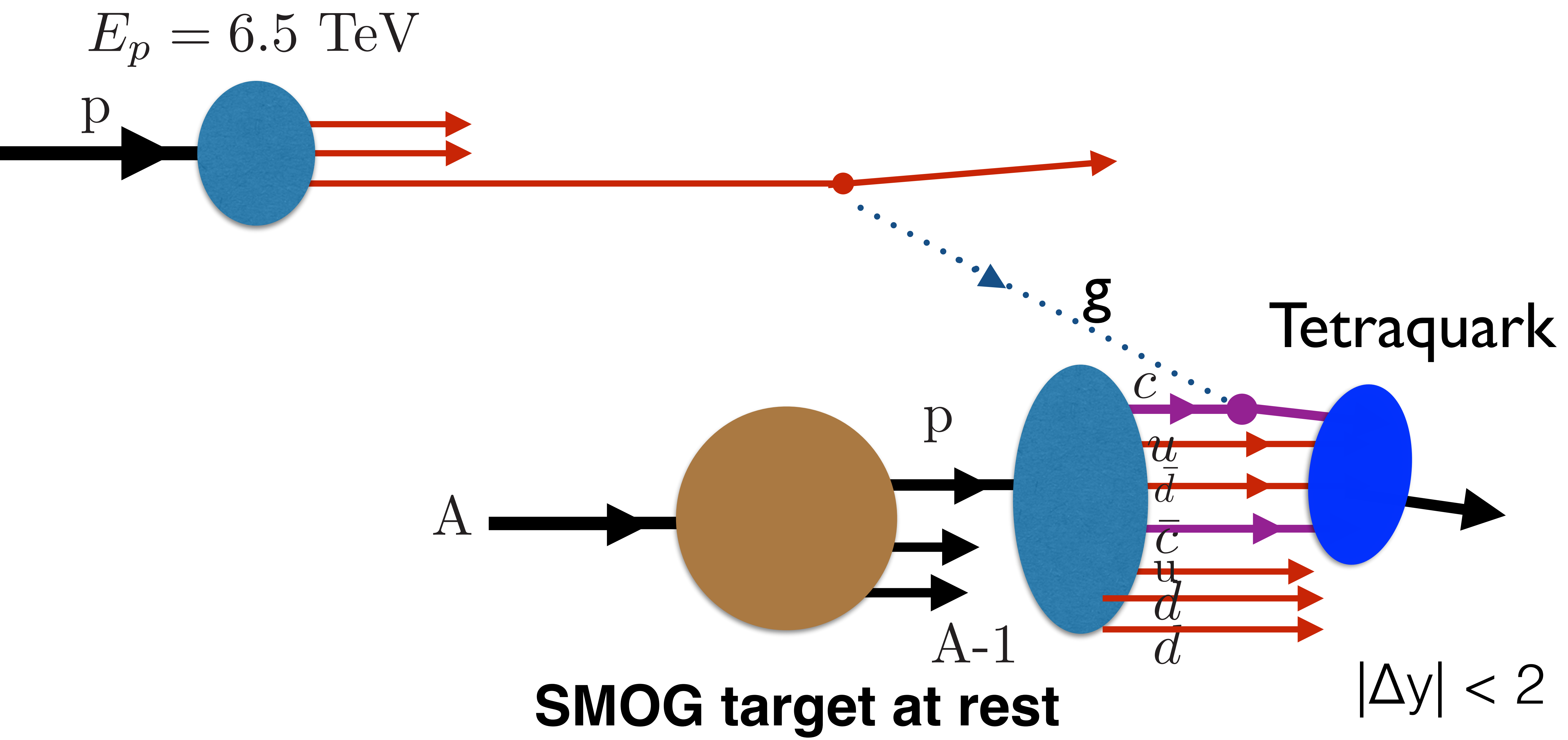


SMOG target at rest

Intrinsic heavy quark probability in the nucleon maximal at minimum off-shellness

Quarkonium produced nearly at rest — has small rapidity in target rest frame

$$pA \to Tetraquark(|cu\bar{c}\bar{d}>)X$$



Intrinsic heavy quark probability in the nucleon maximal at minimum off-shellness

Tetraquark produced nearly at rest — has small rapidity in target rest frame

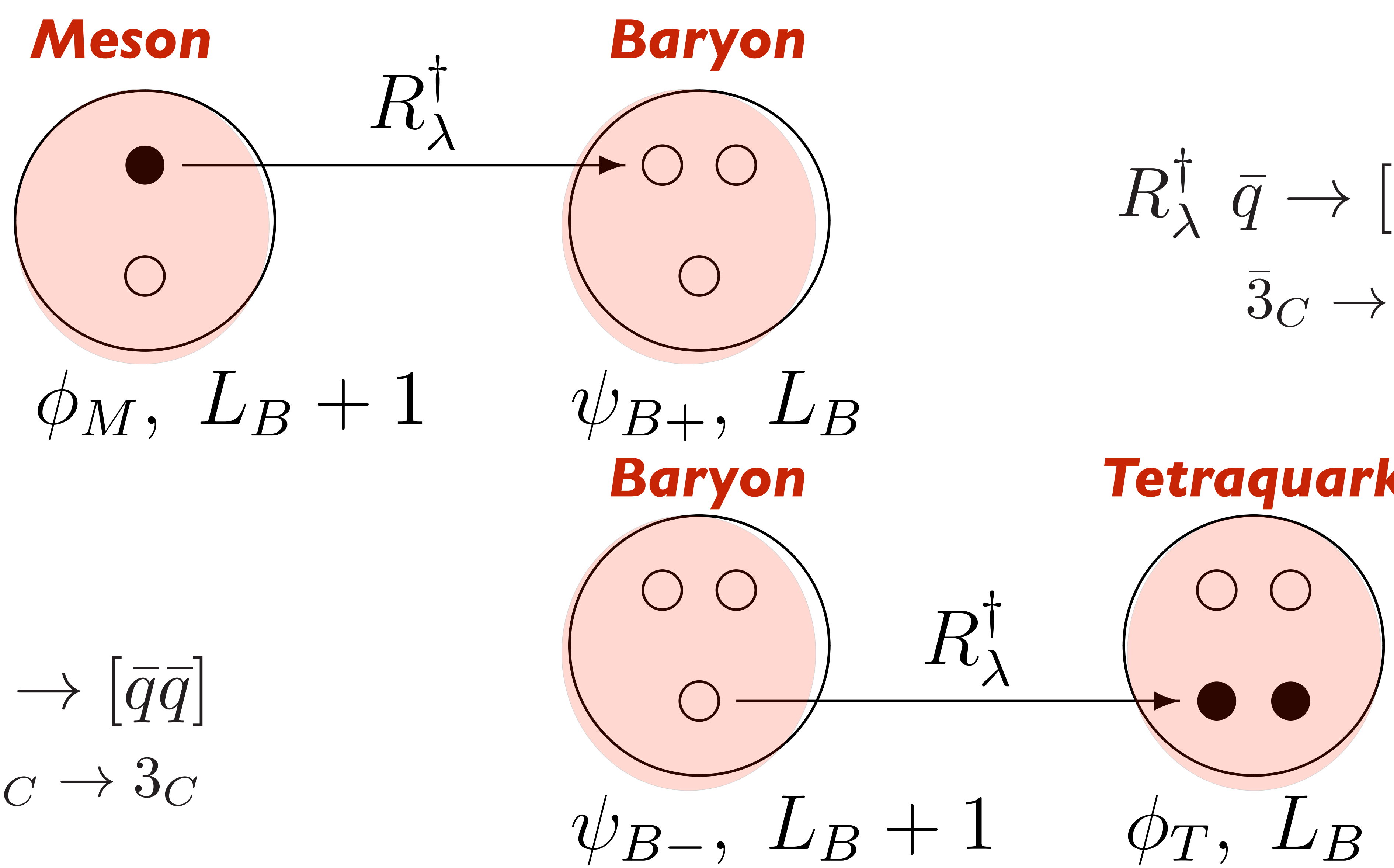
Fubini, Rabinovici

Guy de Tèramond, Hans Günter Dosch, sjb

Superconformal Algebra

2X2 Hadronic Multiplets: 4-Plet

Bosons, Fermions with Equal Mass!



$$R_\lambda^\dagger \ \bar{q} \rightarrow [qq]$$
$$\bar{3}_C \rightarrow \bar{3}_C$$

$$R_\lambda^\dagger \ q \rightarrow [\bar{q}\bar{q}]$$
$$3_C \rightarrow 3_C$$

Proton: |u[ud]> Quark + Scalar Diquark
Equal Weight: L=0, L=1

New World of Tetraquarks

de Tèramond, Dosch, Lorce, sjb

$$3_C \times 3_C = \bar{3}_C + 6_C$$

Bound!

- Diquark Color-Confined Constituents: Color $\bar{3}_C$
- Diquark-Antidiquark bound states

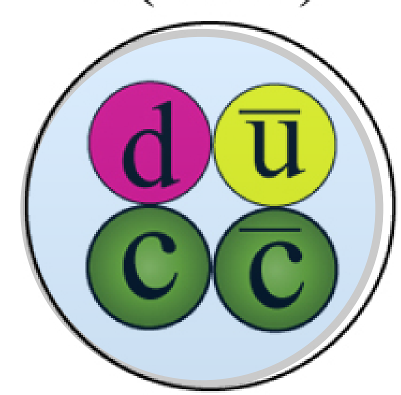
Complete Regge spectrum in n, L

- Confinement Force Similar to quark-antiquark mesons $\bar{3}_C \times 3_C = 1_C$
- Isospin $I = 0, \pm 1, \pm 2$ Charge $Q = 0, \pm 1, \pm 2$

$uu\bar{d}\bar{d}$ $\quad$ $uu\bar{s}\bar{d}$ $\quad$ $uu\bar{s}\bar{s}$

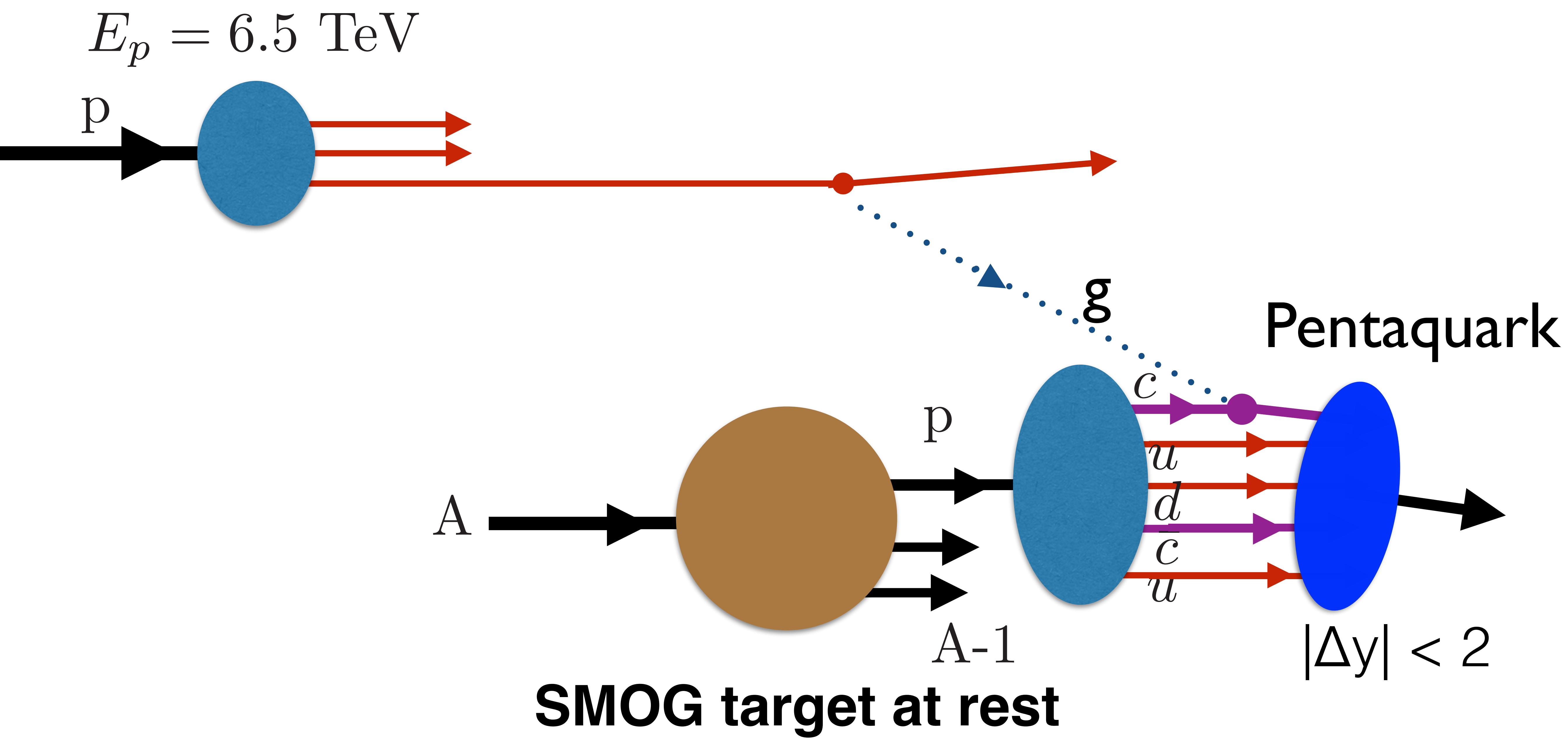
Q= +2

Z(4430)



Q= - 1

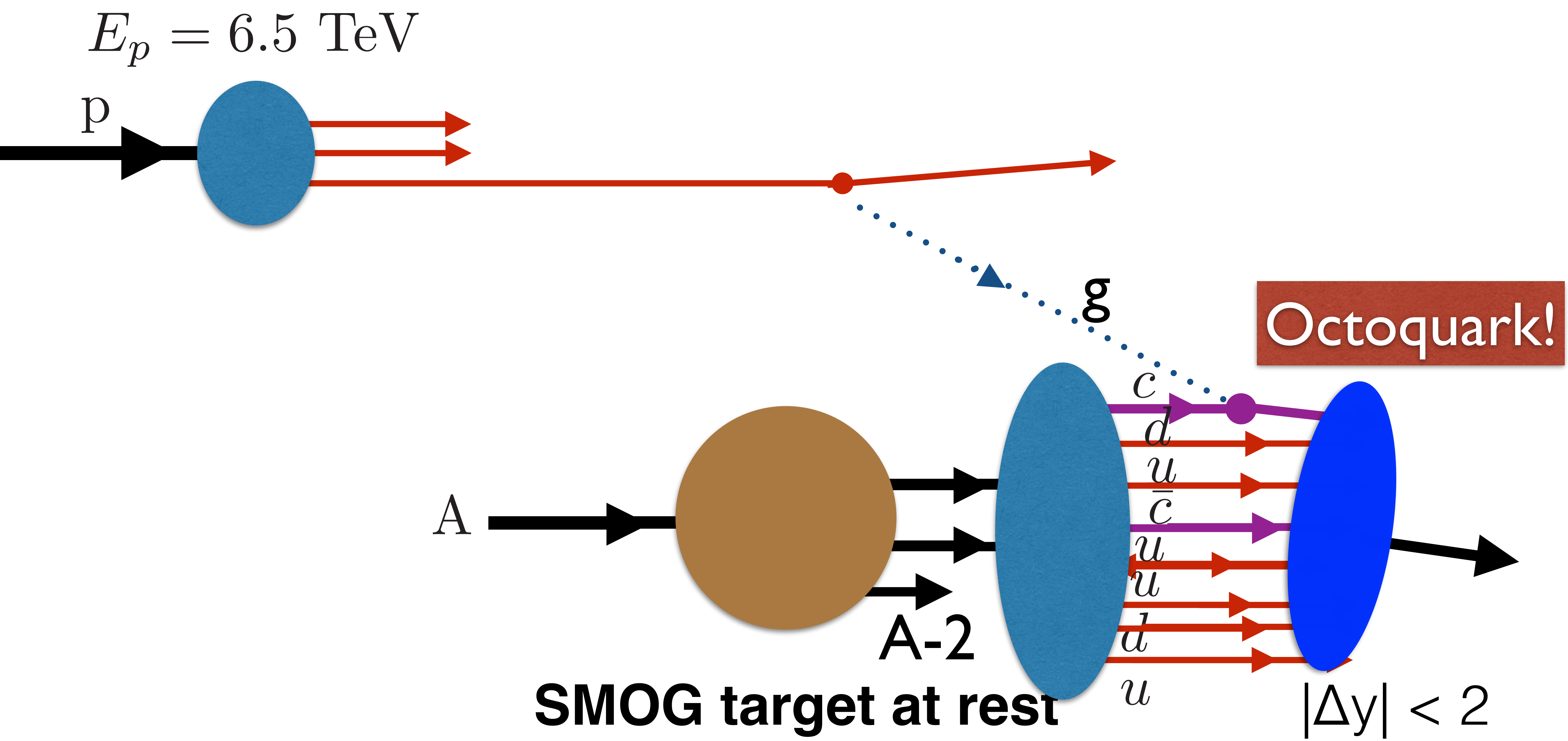
$$pA \rightarrow Pentaquark(|uudc\bar{c}>)X$$



Intrinsic heavy quark probability in the nucleon maximal at minimum off-shellness

Produced nearly at rest — has small rapidity in target rest frame

$$pA \to Octoquark(|uuduudc\bar{c}>)X$$

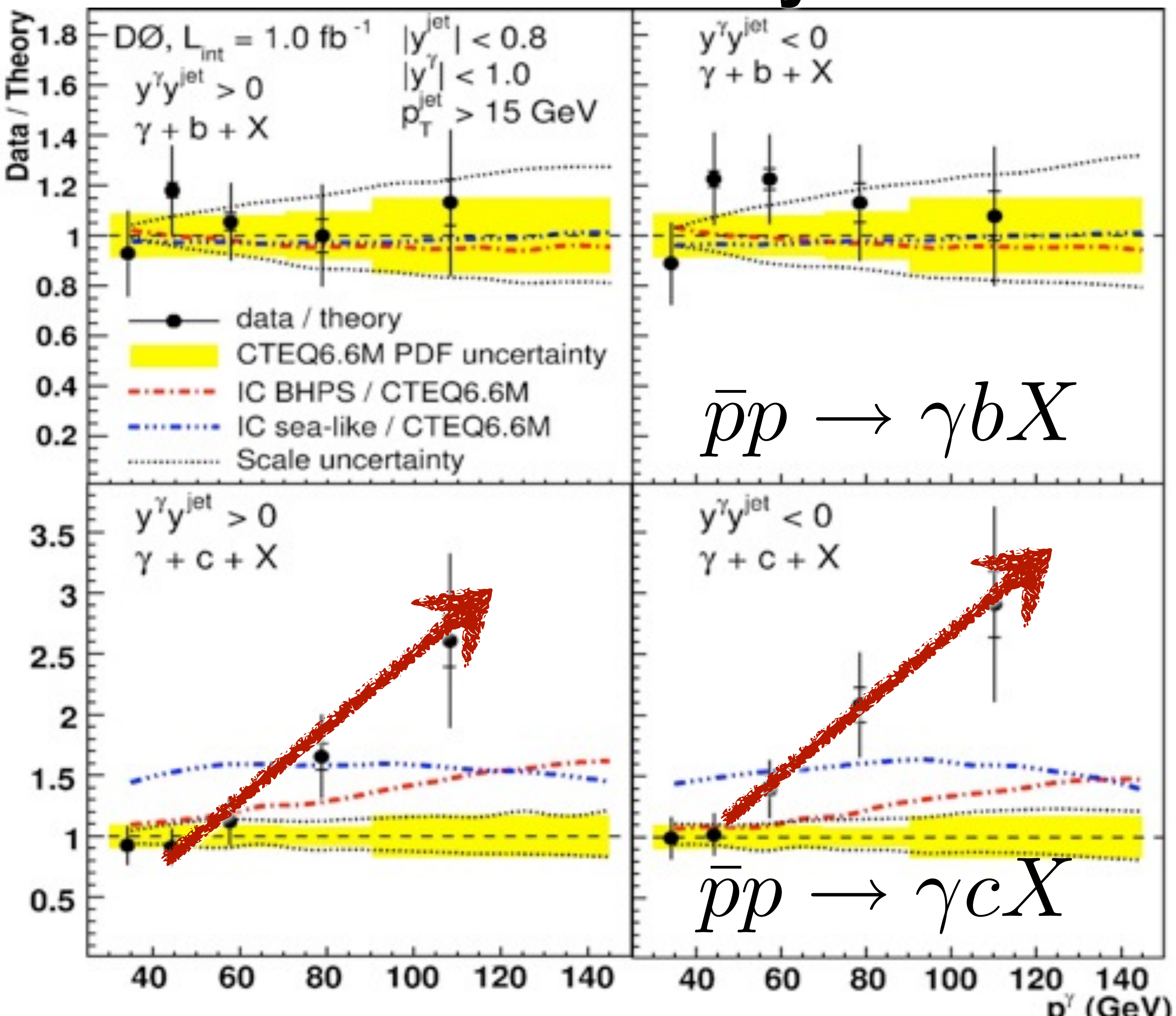


Intrinsic heavy quark probability in the nucleon maximal at minimum off-shellness

Produced nearly at rest — has small rapidity in target rest frame

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

Data/Theory



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

Ratio insensitive to gluon PDF, scales

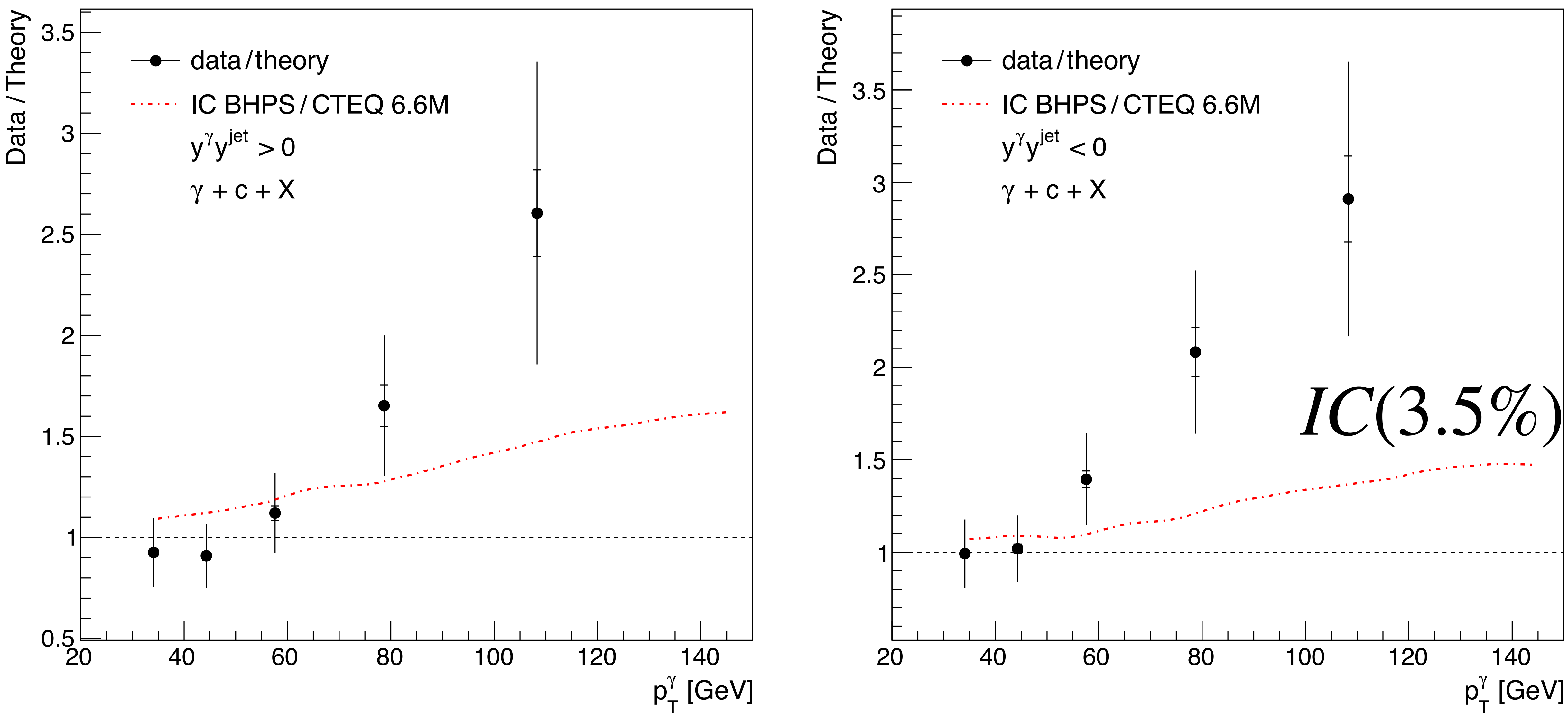
Signal for significant IC at x > 0.1

Consistent with EMC measurement of charm structure function at high x

Production of Prompt Photon and c or b-jet in Hard pp Collisions

$p\bar{p} \to \gamma c X$

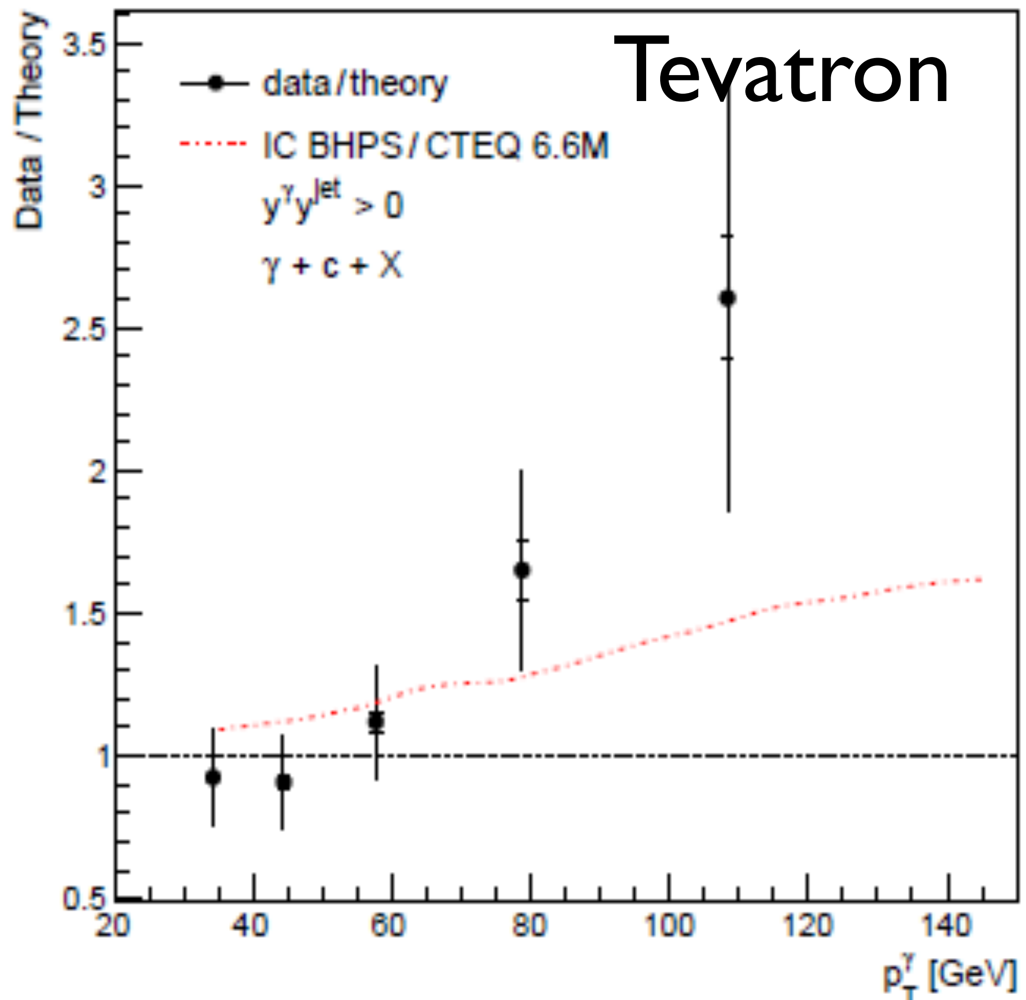
Juraj Smieško

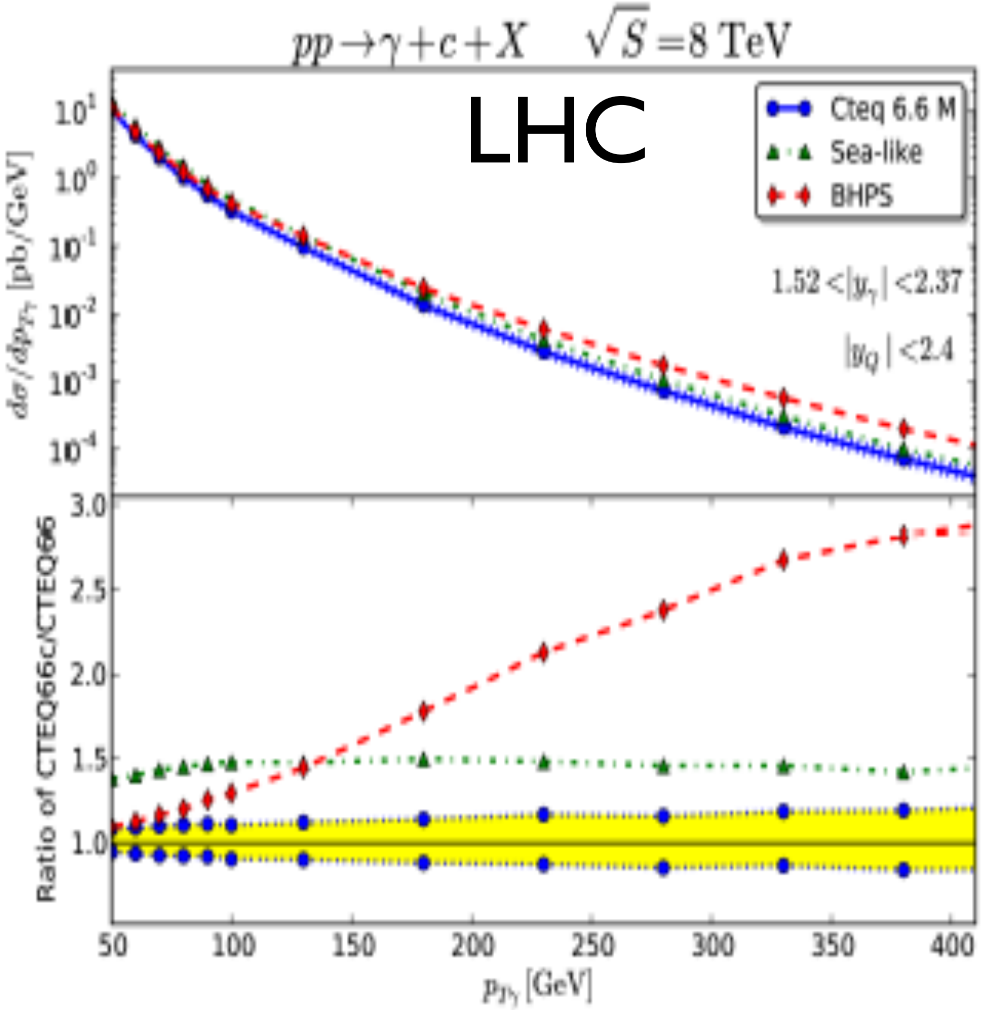


The data-to-theory ratio [8] for the processes $p\bar{p} \longrightarrow \gamma + c + X$, when $y^{\gamma}y^{\text{jet}} > 0$ (left) and the same ratio, when $y^{\gamma}y^{\text{jet}} < 0$ (right) at $\sqrt{s} = 1.96$ TeV. The dash-dotted line is the calculation of this ratio using the BHPS IC model with the IC probability about 3.5 %.

Ratio Data/Theory for p bar{p} -> γ + c +X (D0 experiment) at $s^{1/2}$ = 1.96 TeV (left)

p_T –spectrum in $pp \to \gamma + c(jet) + X$



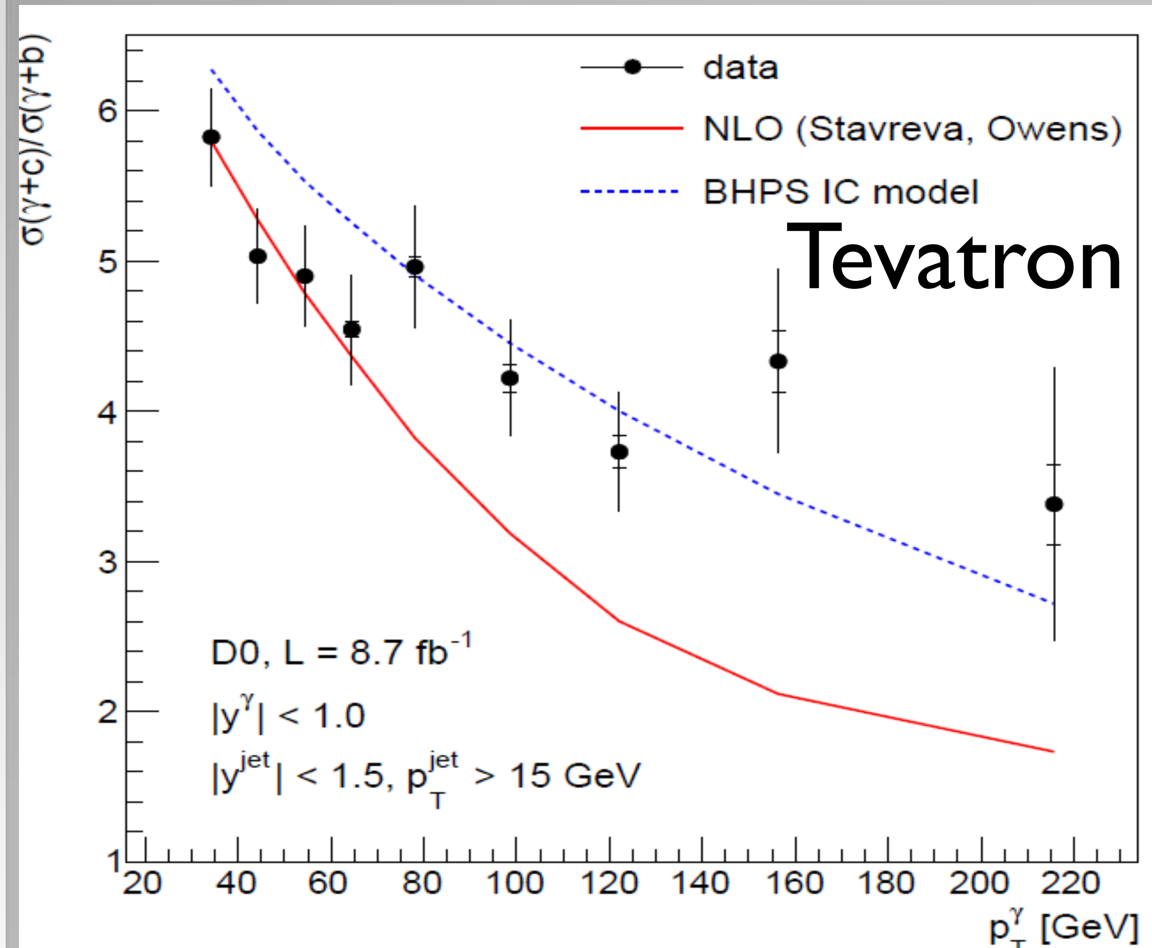


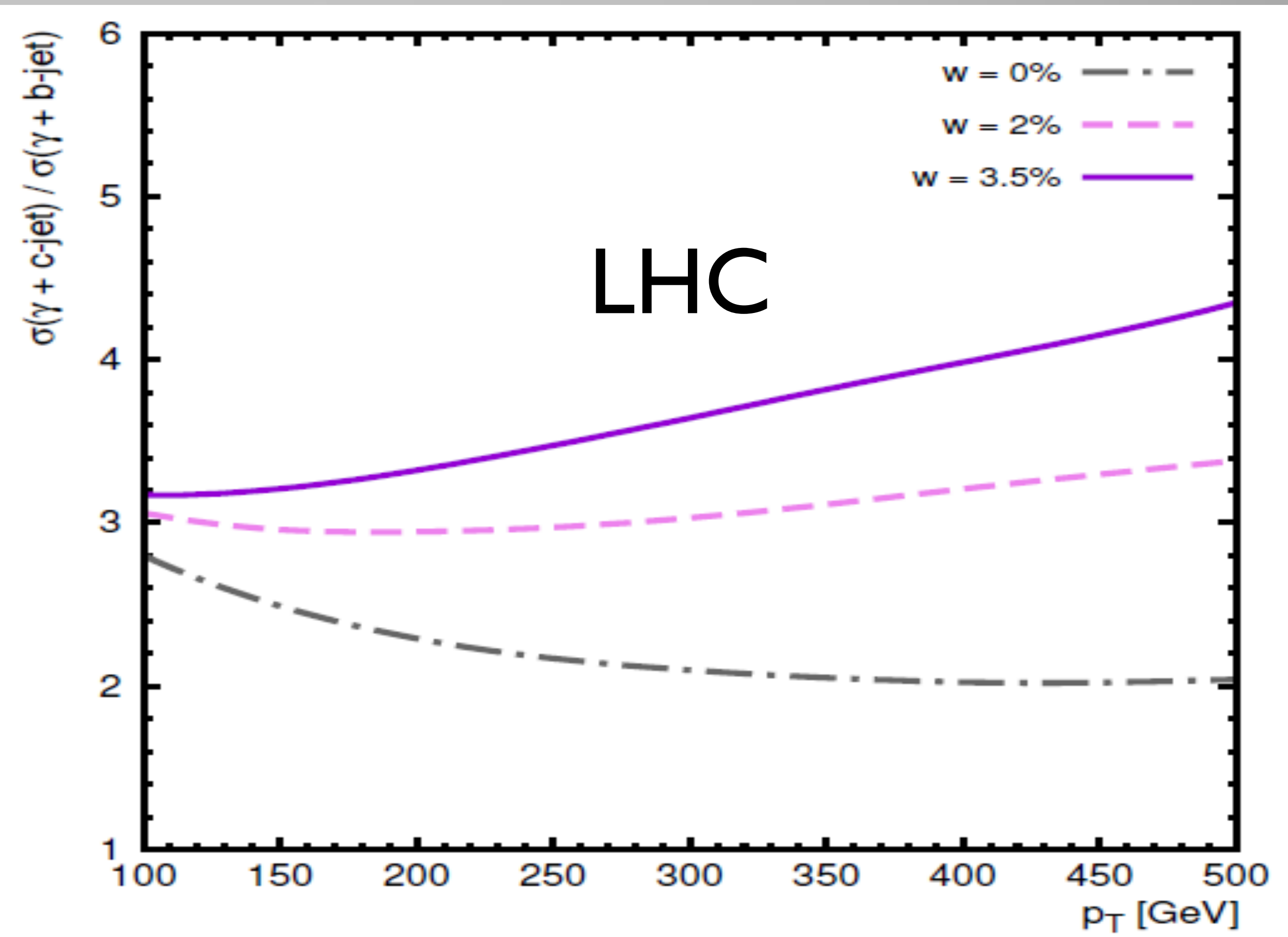
V,M,Abazov, et al. (D0) Phys.Rev.Lett. 102 (2009) 192002.

V.A.Bednyakov, M.A.Demichev,G.I.Lykasov, T.Stavreva, M.Stockton, Phys.Lett. B728 (2014) 602 (right).

R=σ(γ + c)/σ(γ + b) for p bar{p} -> γ + Q at $s^{1/2}$ = 1.98 TeV (left)

R=σ(γ + c)/σ(γ + b) for p p -> γ + Q at $s^{1/2}$ = 8 TeV (right)



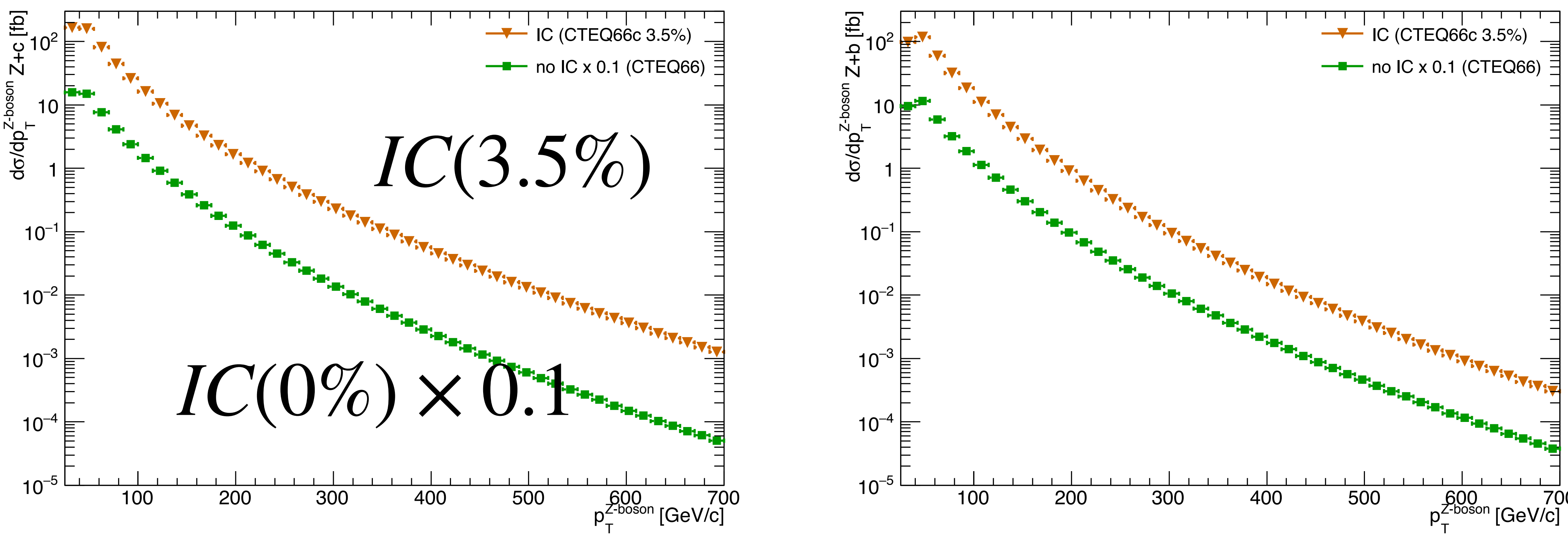


V,M,Abazov, et al. (D0) Phys.Lett. B719 (2013) 354 .

A.V.Lipatov, G.I.Lykasov, Yu.Yu.Stepanenko, V.A.Bednyakov, Phys.Rev. D94 , 053011 (2016) ;
S.J.Brodsky, V.A.Bednyakov, G.I.Lykasov, J.Smiesko, S.Tokar, arXiv:1612.01351 , Prog. Part.Nucl.Phys. in press

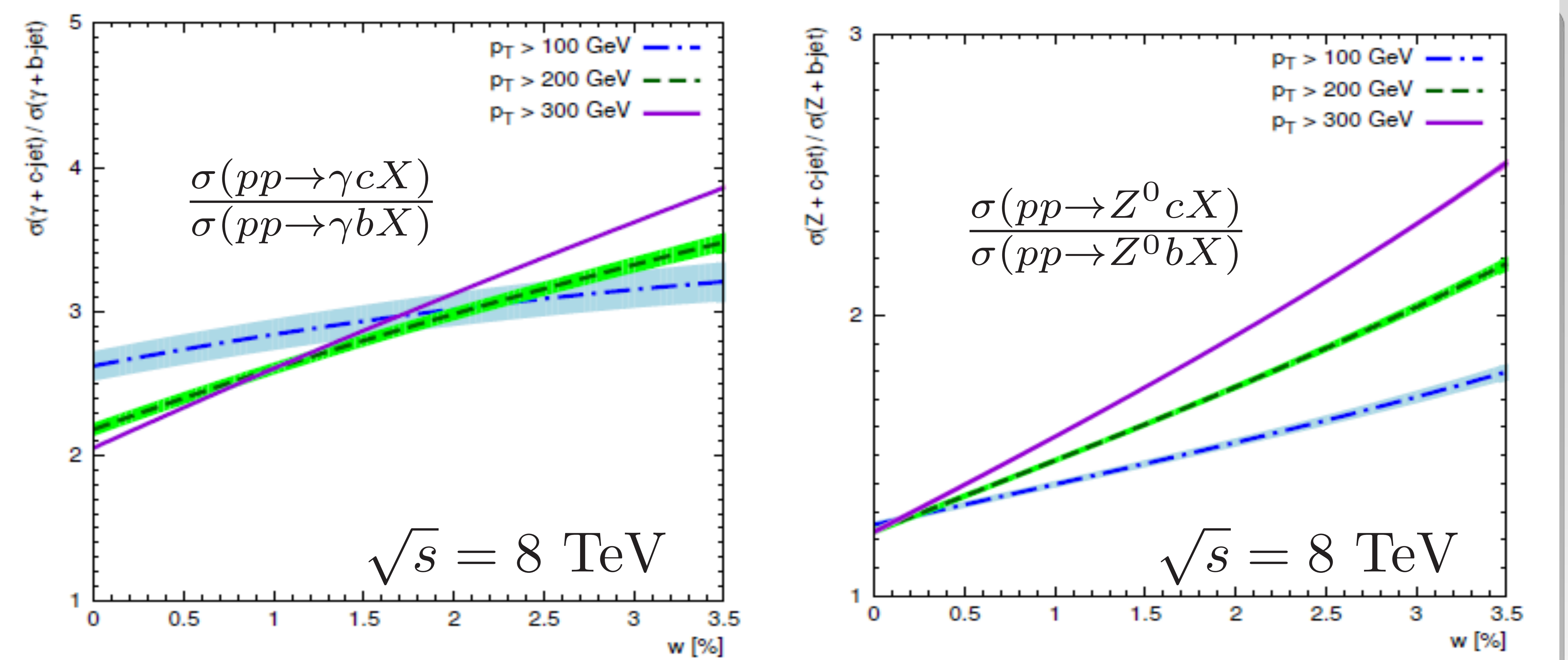
$$\frac{\sigma(pp\to\gamma cX)}{\sigma(pp\to\gamma bX)}$$

$$\frac{d\sigma}{dp_T}(pp \to Z + c + X)(fb) \qquad \frac{d\sigma}{dp_T}(pp \to Z + b + X)(fb)$$



The cross-sections of the associated $Z+c$ (left) and $Z+b$ (right) production in pp collision calculated as a function of the Z boson transverse momentum p_{T} at $\sqrt{s} = 13$ TeV within the MCFM routine.

$$\sqrt{s} = 13\ TeV$$



Ratio between the x-sections of γ +c and γ + b production in p-p collision at $s^{1/2}$ = 8 TeV integrated over p_T (left) and the similar ratio between Z+c and Z+b production cross sections (right). Bands mean the QCD scale uncertainty .

A.V.Lipatov, G.I.Lykasov, Yu.Yu.Stepanenko, V.A.Bednyakov, Phys.Rev. D94 , 053011 (2016) ;

S.J.Brodsky, V.A.Bednyakov, G.I.Lykasov, J.Smiesko, S.Tokar, arXiv:1612.01351 , Prog. Part.Nucl.Phys. in press

Why is Intrinsic Heavy Quark Phenomena Important?

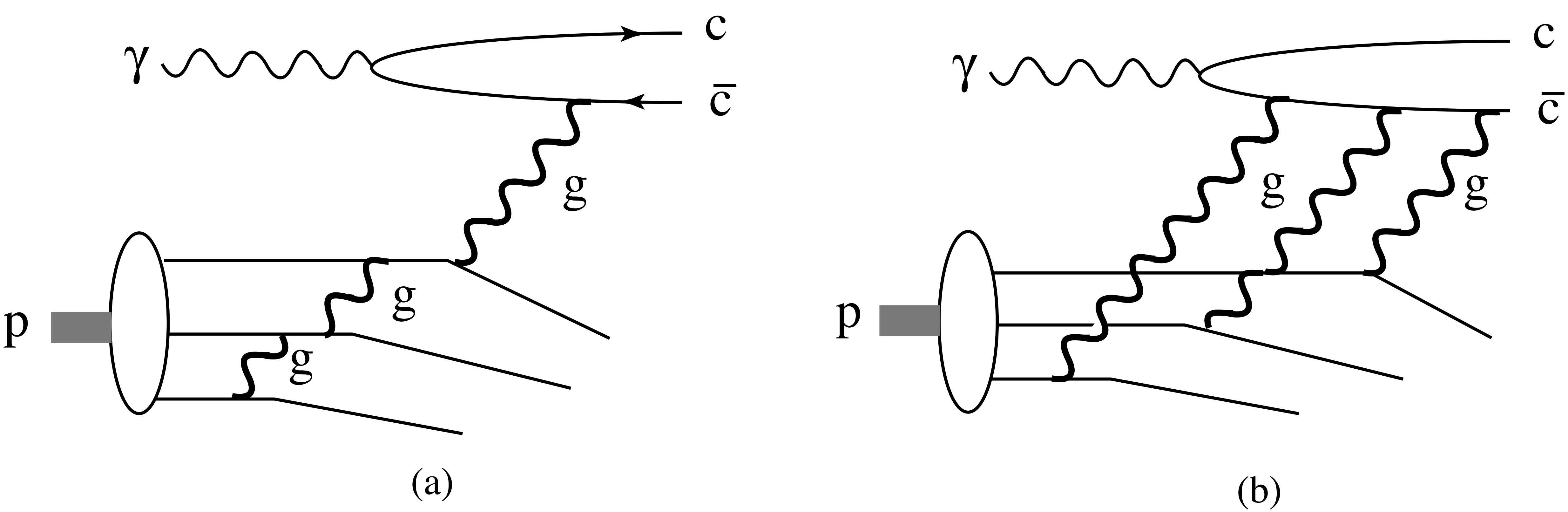
- **Test Fundamental QCD predictions OPE, Non-Abelian QCD**

  Non-Abelian: $P_{Q\bar{Q}} \propto \frac{1}{M^2_{Q\bar{Q}}}$ Abelian: $P_{Q\bar{Q}} \propto \frac{1}{M^4_{Q\bar{Q}}}$

- **Test non-perturbative effects**
- **Important for correctly identifying the gluon distribution**
- **High-x_F open and hidden charm and bottom; discover exotic states**
- **Explain anomalous high pT charm jet + γ data at Tevatron**
- **Important source of high energy ν at IceCube**

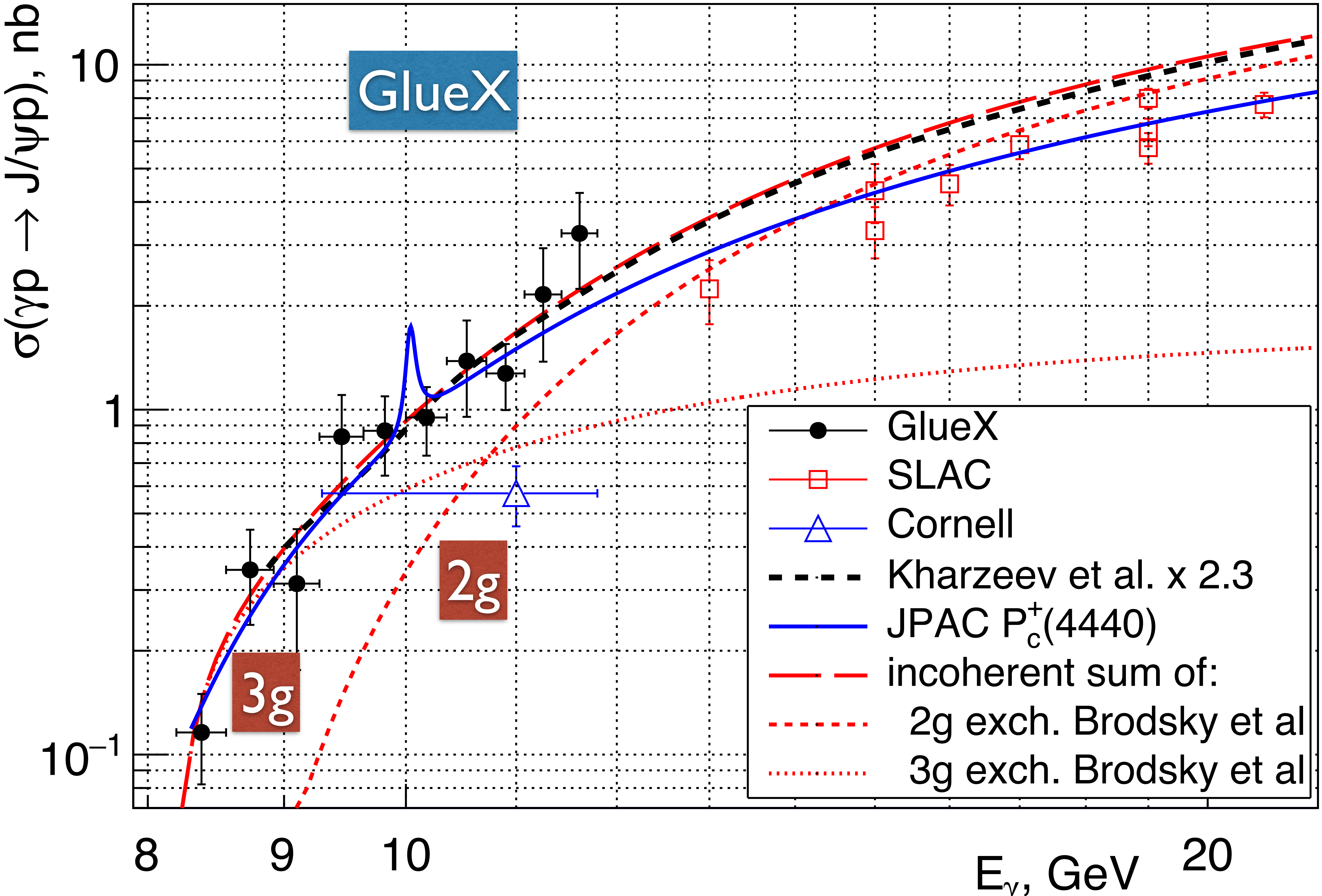
Photoproduction of charm near threshold

S. J. Brodsky,[1] E. Chudakov,[2] P. Hoyer,[3] J.M. Laget,[4]



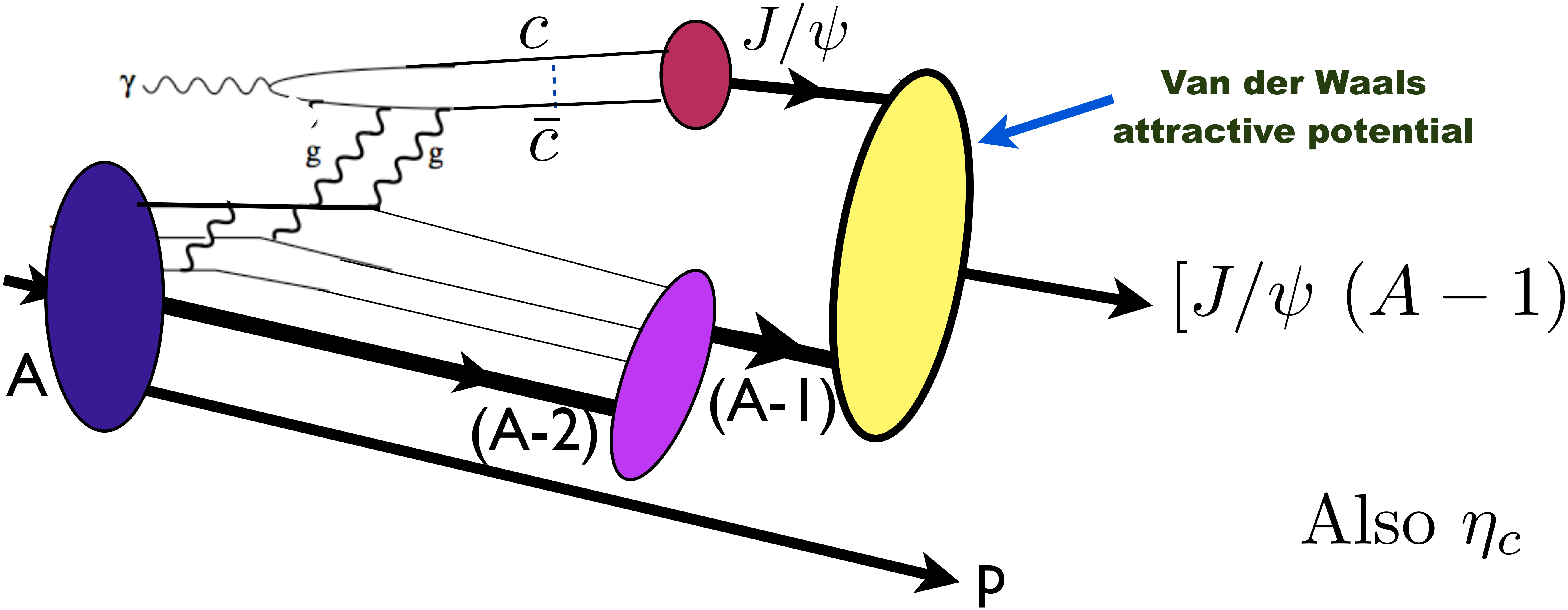
Another aspect of IC

First measurement of near-threshold J/ψ exclusive photoproduction off the proton



GlueX results for the J/ψ total cross section vs beam energy, compared to the Cornell [15] and SLAC [16] data, the theoretical predictions [11, 13], and the JPAC model [6] corresponding to $\mathcal{B}(P_c^+(4440) \to J/\psi p) = 1.6\%$ for the $J^P = 3/2^-$ case as discussed in the text. All curves are fitted/scaled to the GlueX data only. For our data the quadratic sums of statistical and systematic errors are shown; the overall normalization uncertainty is 27%.

Charmonium Production at Threshold



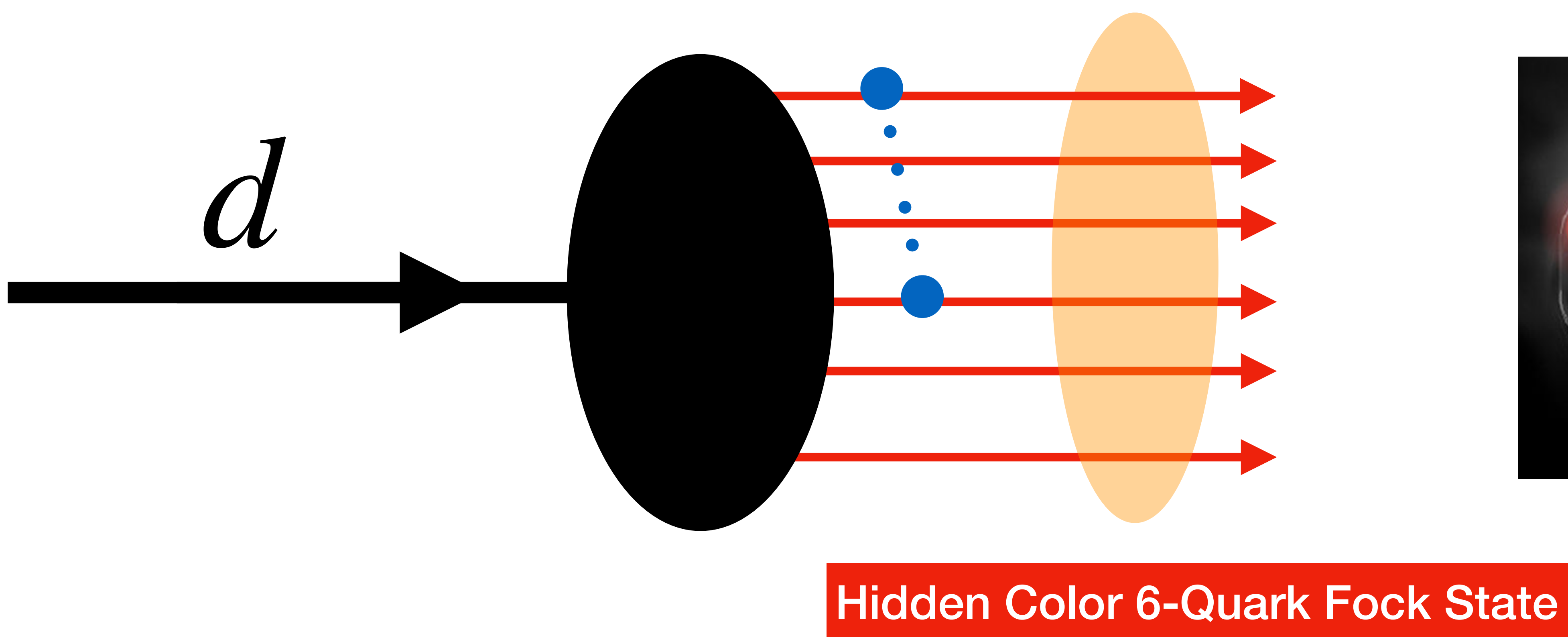
Also η_c

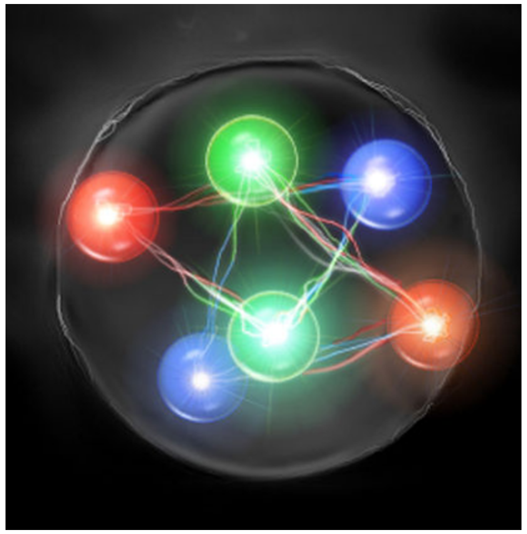
$$\gamma\ A \to [J/\psi\ (A-1)]\ p$$

Form nuclear bound-charmonium bound state!

Hidden Color in QCD

- Deuteron: Five color-singlet combinations of 6 color-triplets
- One Fock state is n-p nucleon cluster, one state is Δ-Δ



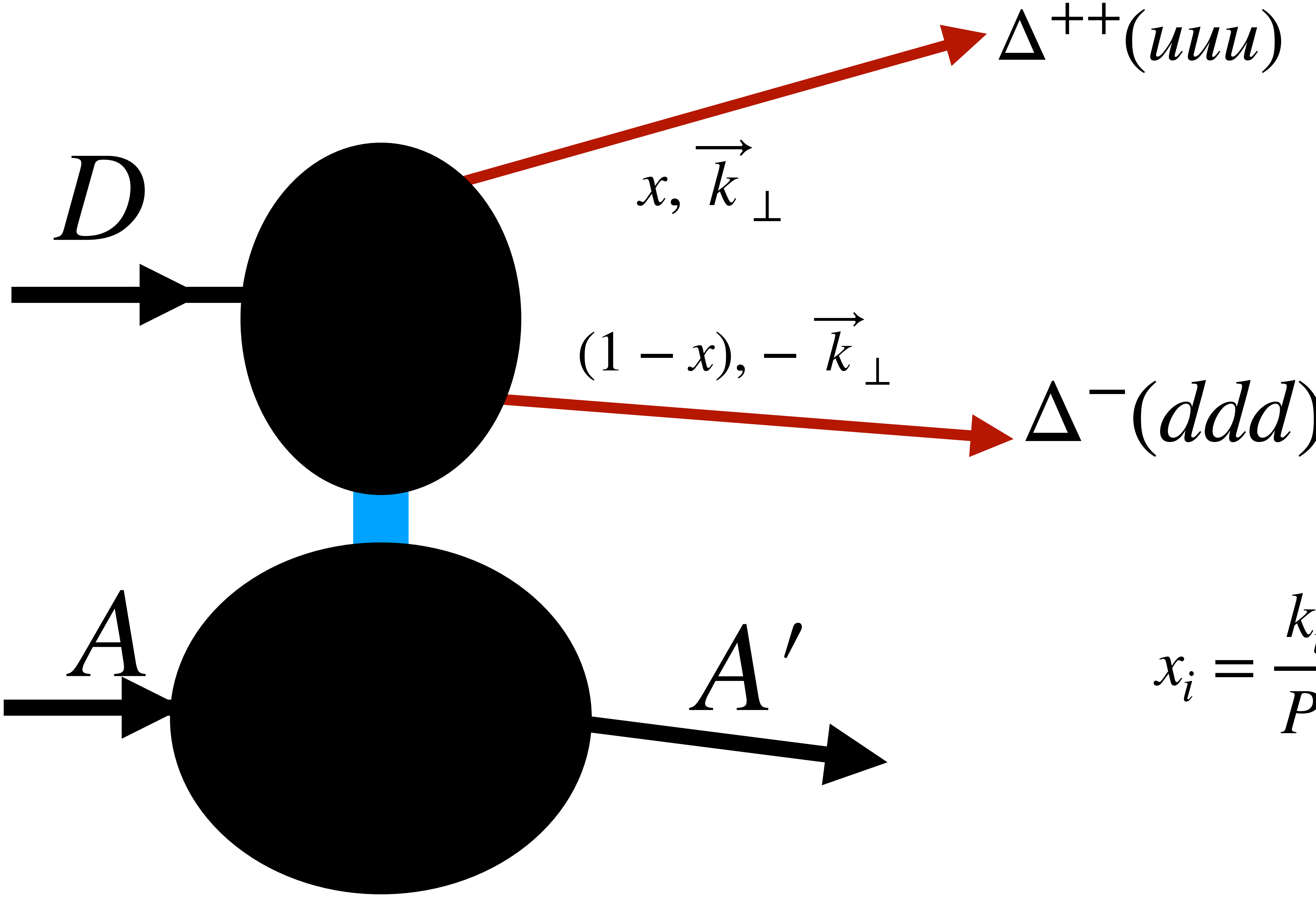


Rigorous Feature of QCD!

Lepage, Ji, sjb

Measure Hidden-Color Fock state of the Deuteron LFWF

$$\psi_D^{\Delta\Delta}(x, \overrightarrow{k}_\perp) = < \Delta^{++}(x, \overrightarrow{k}_\perp)\Delta^{-}(1-x, -\overrightarrow{k}_\perp \,|\, \Psi_D >$$



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

$D + A \to \Delta^{++}\ \Delta^{-} + A'$

$$\textit{Measure}\ \mathscr{M}_{pn}^2 = (p_{\Delta^{++}} + p_{\Delta^{-}})^2 = \frac{k_\perp^2 + M_\Delta^2}{x(1-x)}$$

- 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

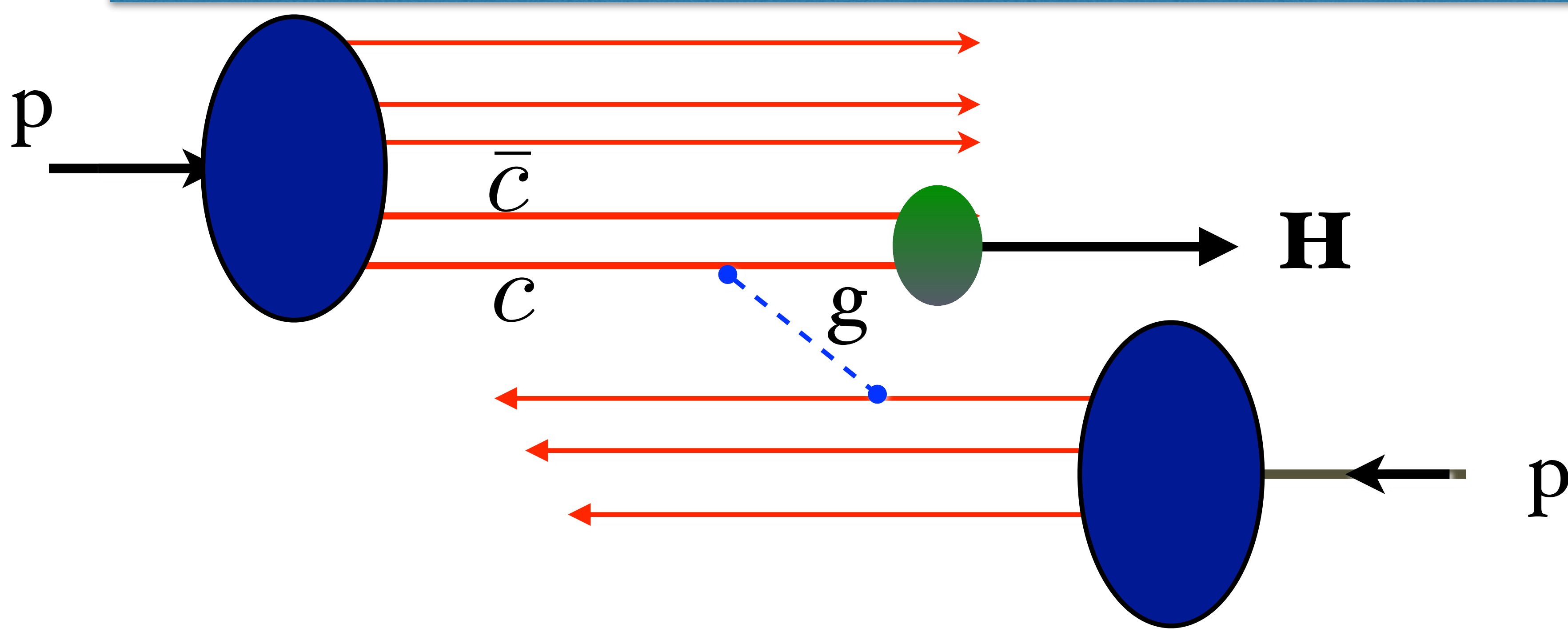
- IC Explains $J/\psi \to \rho\pi$ puzzle (Karliner, SJB)

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

Higgs production at $x_F = 0.8$

Goldhaber, Kopeliovich, Schmidt, Soffer, sjb

Intrinsic Heavy Quark Contribution to Inclusive Higgs Production



$pp \to H X$

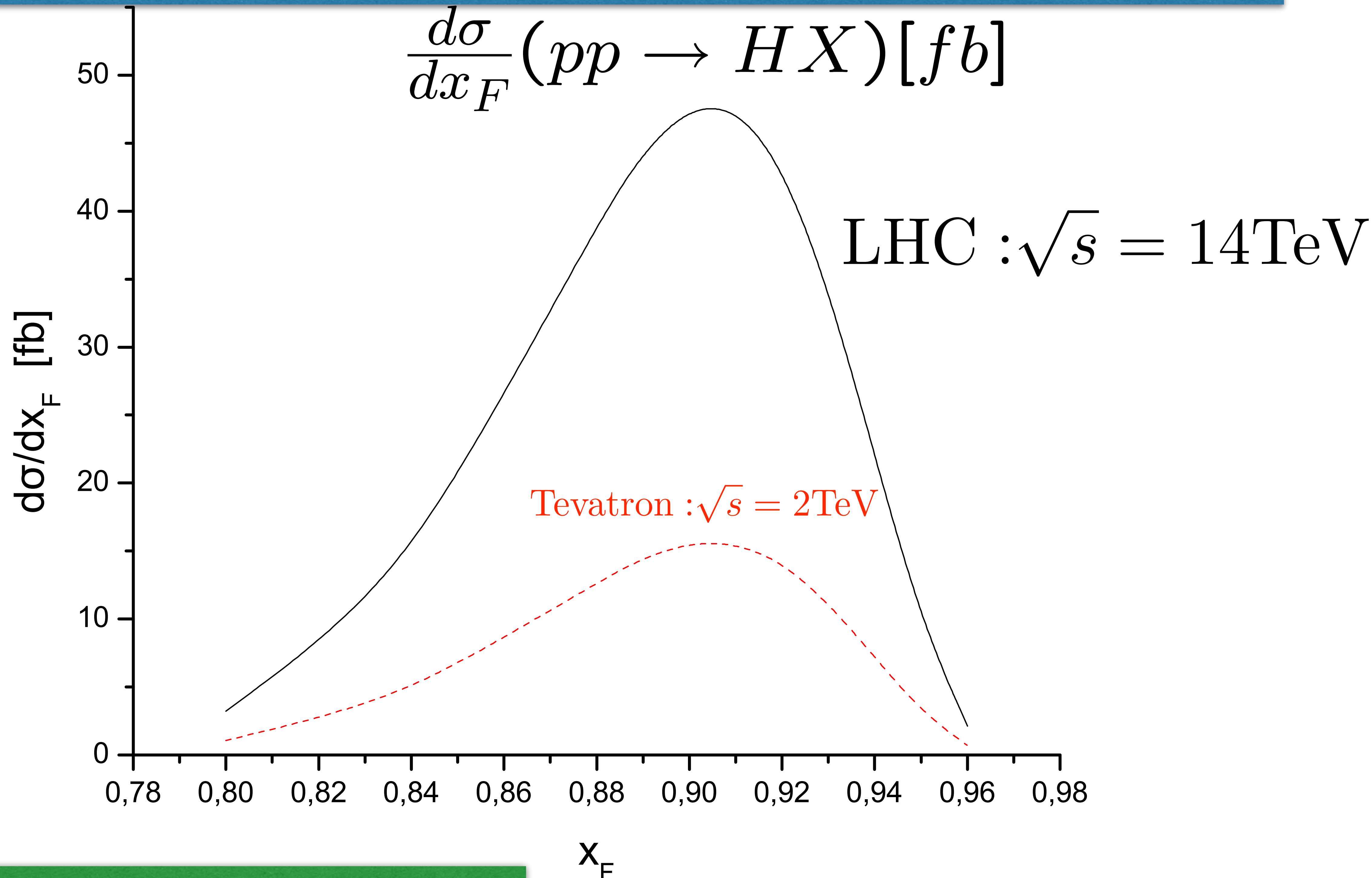
Also: intrinsic strangeness, bottom, top

Higgs can have > 80% of Proton Momentum!

New production mechanism for Higgs at the LHC

AFTER: Higgs production at threshold!

Intrinsic Heavy Quark Contribution to High x_F Inclusive Higgs Production



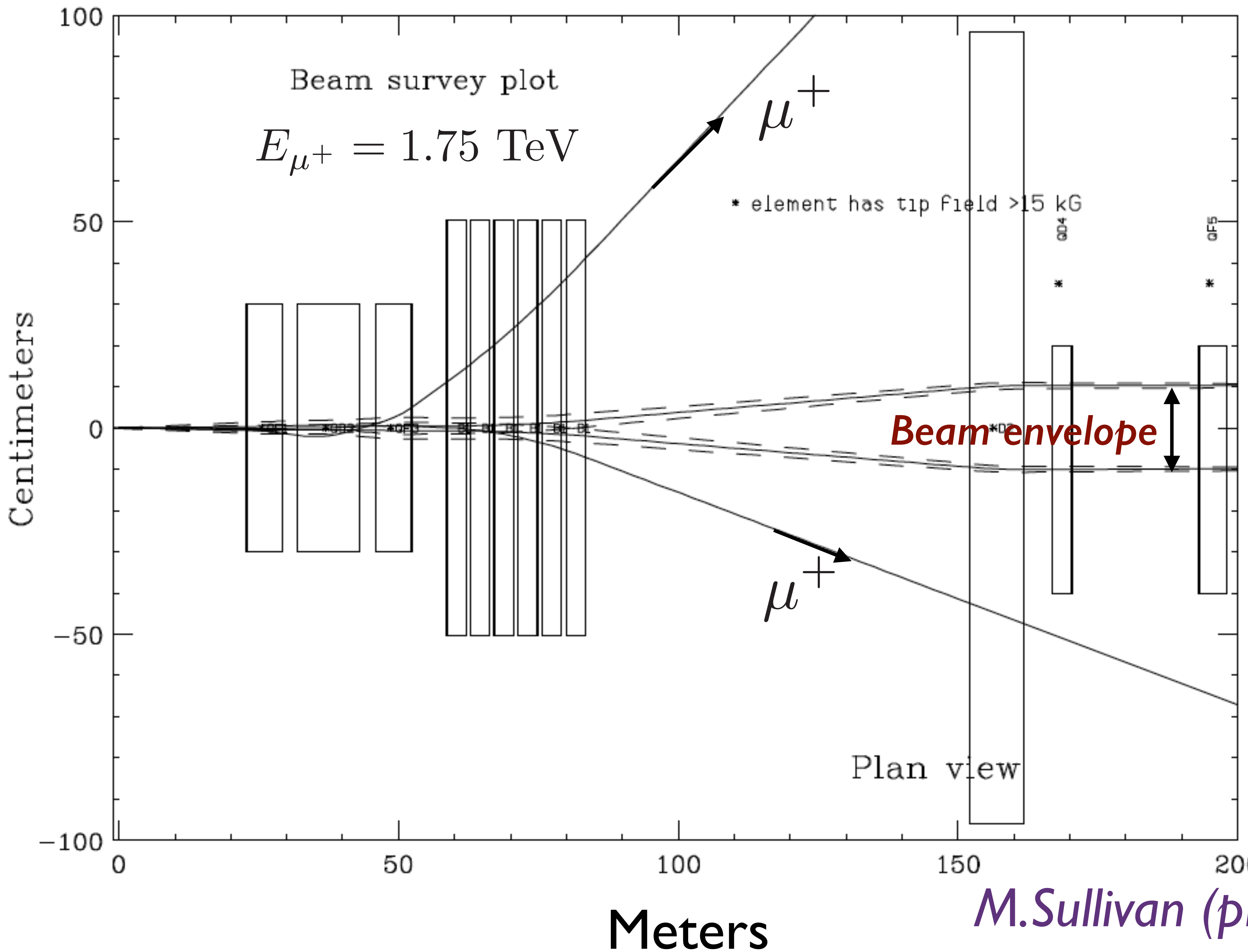
Need High x_F Acceptance

Most practical: Higgs to 4 muons

Goldhaber, Kopeliovich, Schmidt, Soffer, sjb

Use LHC Magnetic Field as Downstream Muon Spectrometer

$$pp \to HX \to \mu^+\mu^-\mu^+\mu^- X$$



M.Sullivan (preliminary)

Measure exotic events at SMOG@LHCb such as

$$\boxed{pA \to \Upsilon + J/\psi X \to \mu^+\mu^-\mu^+\mu^- X}$$

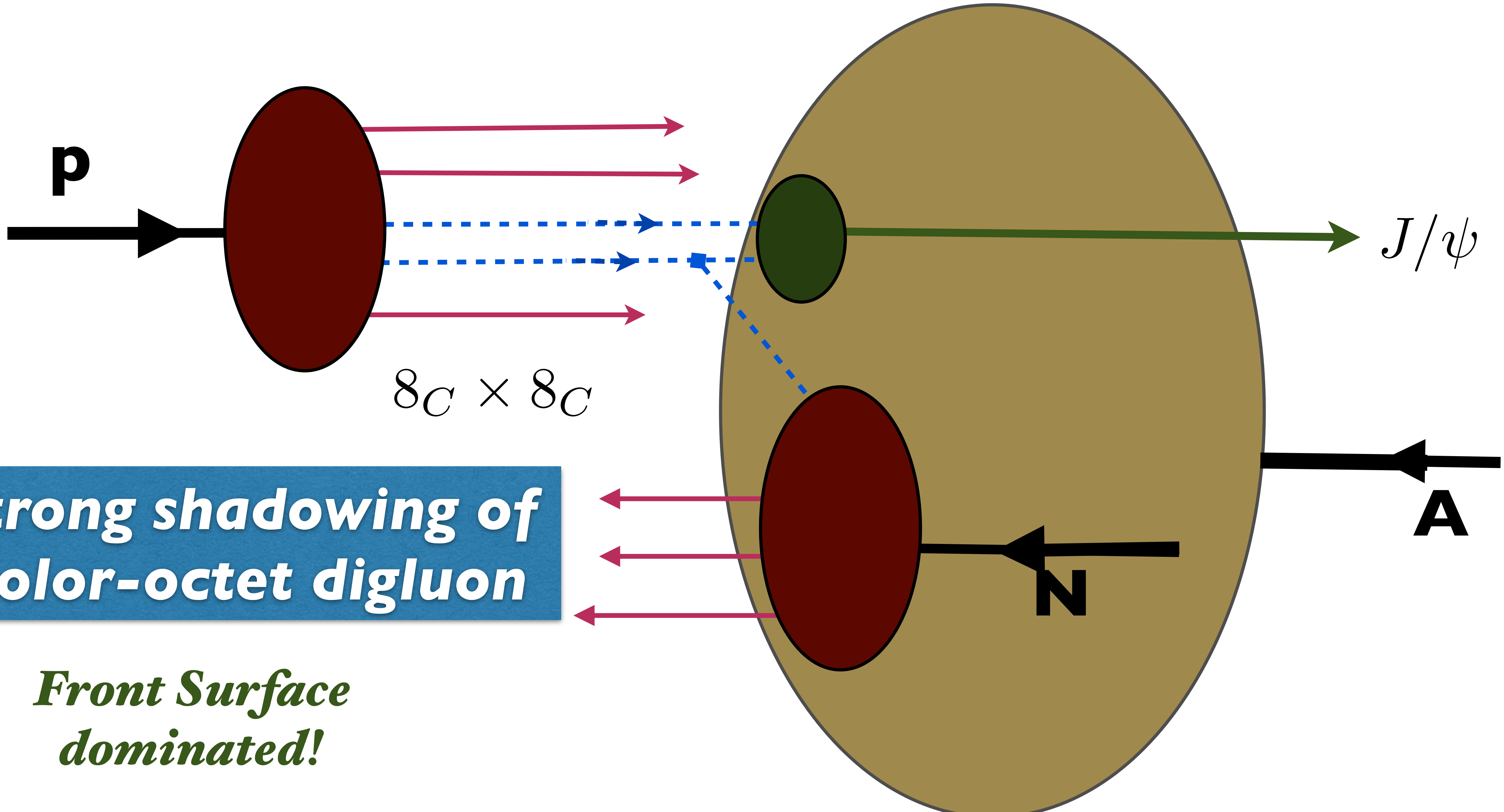
Digluon-initiated subprocess!

Forward rapidity y ~4

Another mechanism

$$pA \to J/\psi X$$

$$(gg)_{8_C} + g_{8_C} \to J/\psi$$



Strong shadowing of color-octet digluon

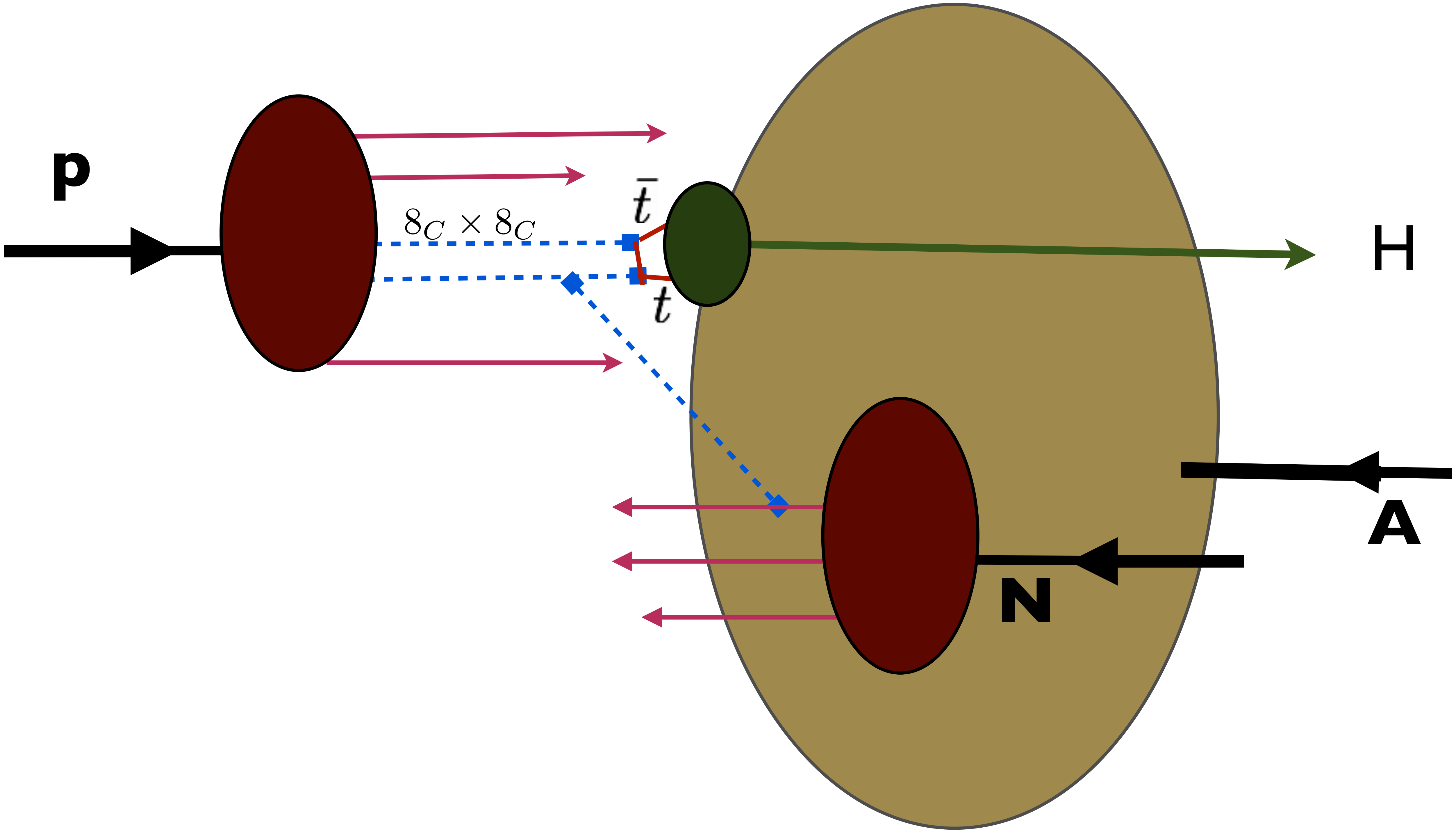
Front Surface dominated!

ψ' suppressed as it propagates through the nucleus

Crossing: Diffractive & pomeron exchange

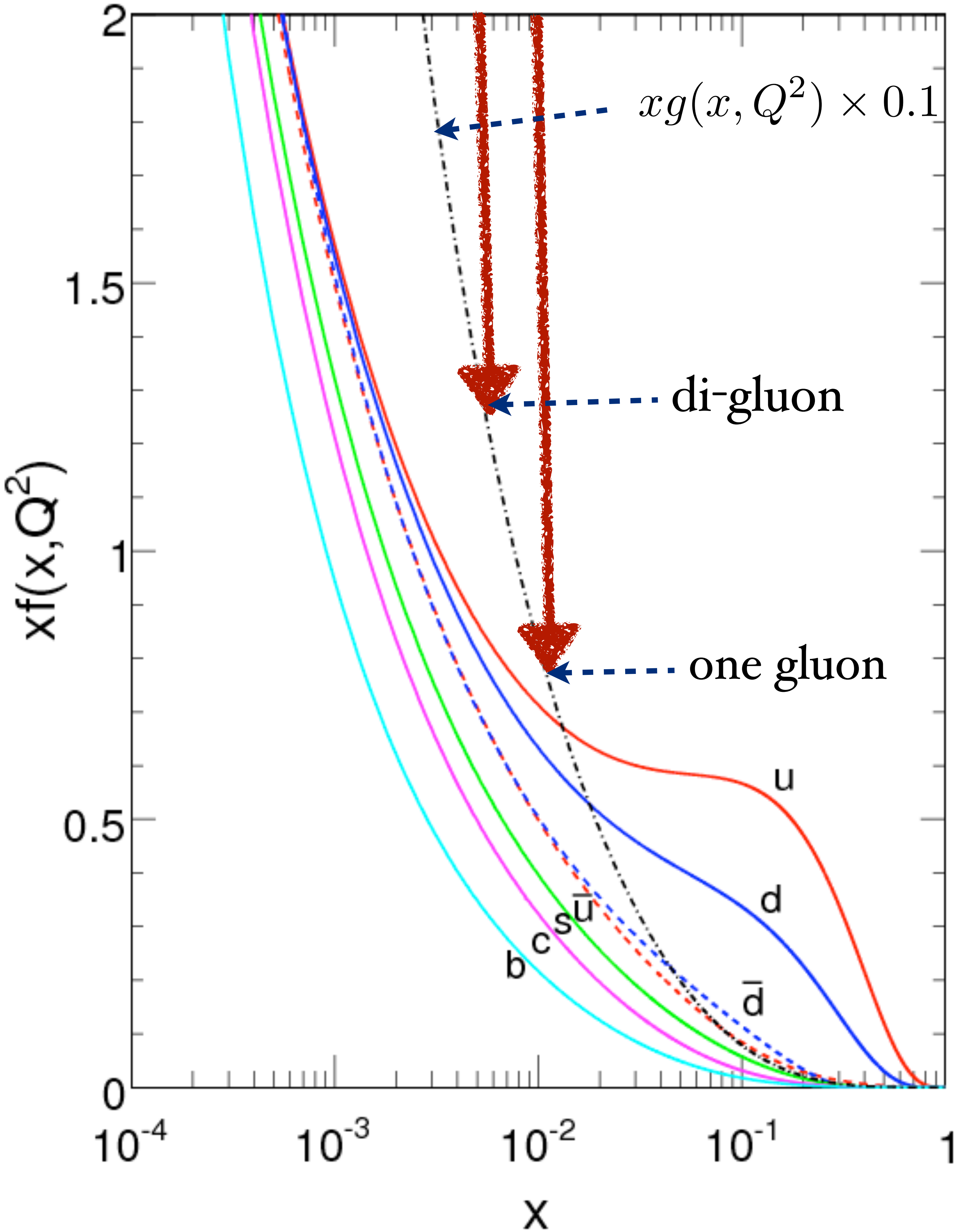
$$pA \to HX$$

$$(gg)_{8_C} + g_{8_C} \to H$$



Double-gluon subprocess for Higgs production at forward rapidity

Two gluons at $g(0.005) \sim \frac{13}{0.005} = 2600$ vs. one gluon at $g(0.01) \sim \frac{8}{0.01} = 800$



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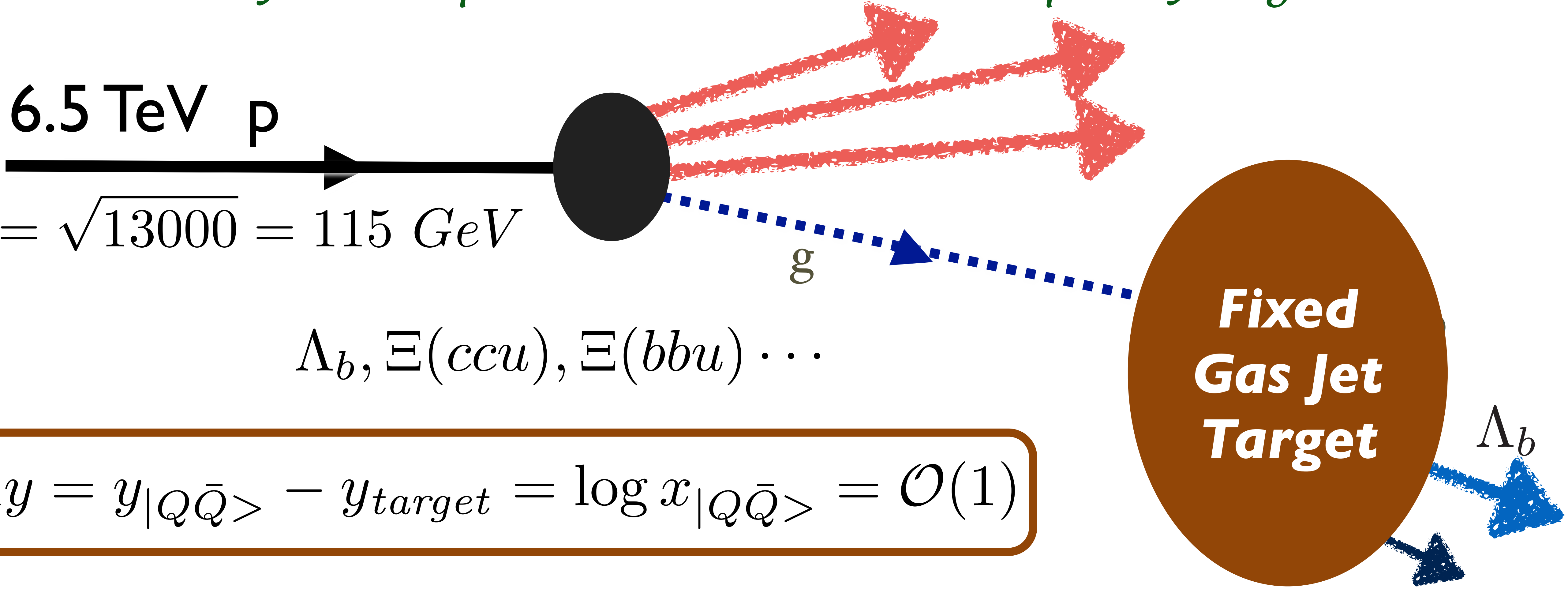
Heavy states produced in TARGET *rapidity region*



$$\sqrt{s} = \sqrt{13000} = 115\ GeV$$

$$\Lambda_b, \Xi(ccu), \Xi(bbu)\cdots$$

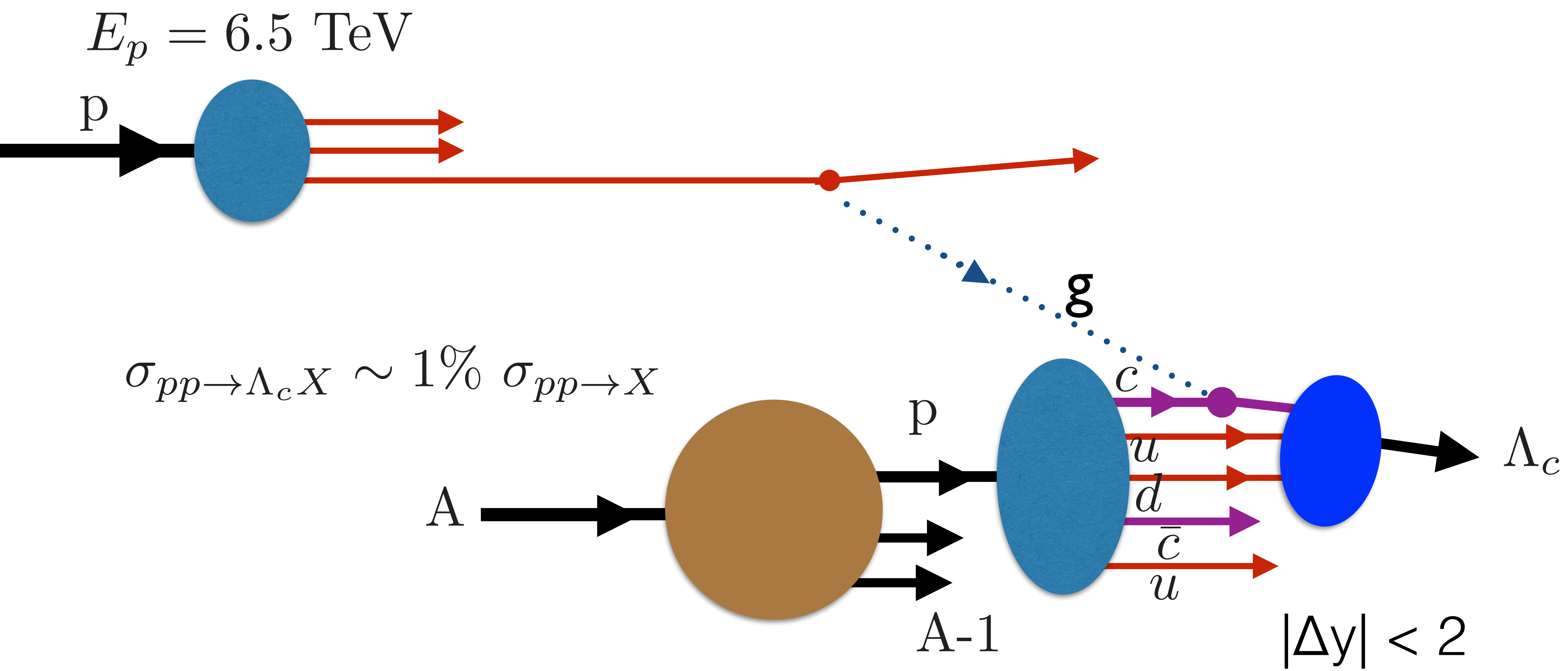
$$\boxed{\Delta y = y_{|Q\bar{Q}>} - y_{target} = \log x_{|Q\bar{Q}>} = \mathcal{O}(1)}$$

Produce $J/\psi, \Upsilon, \Lambda_c, \Lambda_b, |ccu>, |cud\bar{c}>, |cuudddu\bar{c}>, \cdots$

Test at Smog@LHCb

discussions with M. Williams

$$pA \to \Lambda_c X$$



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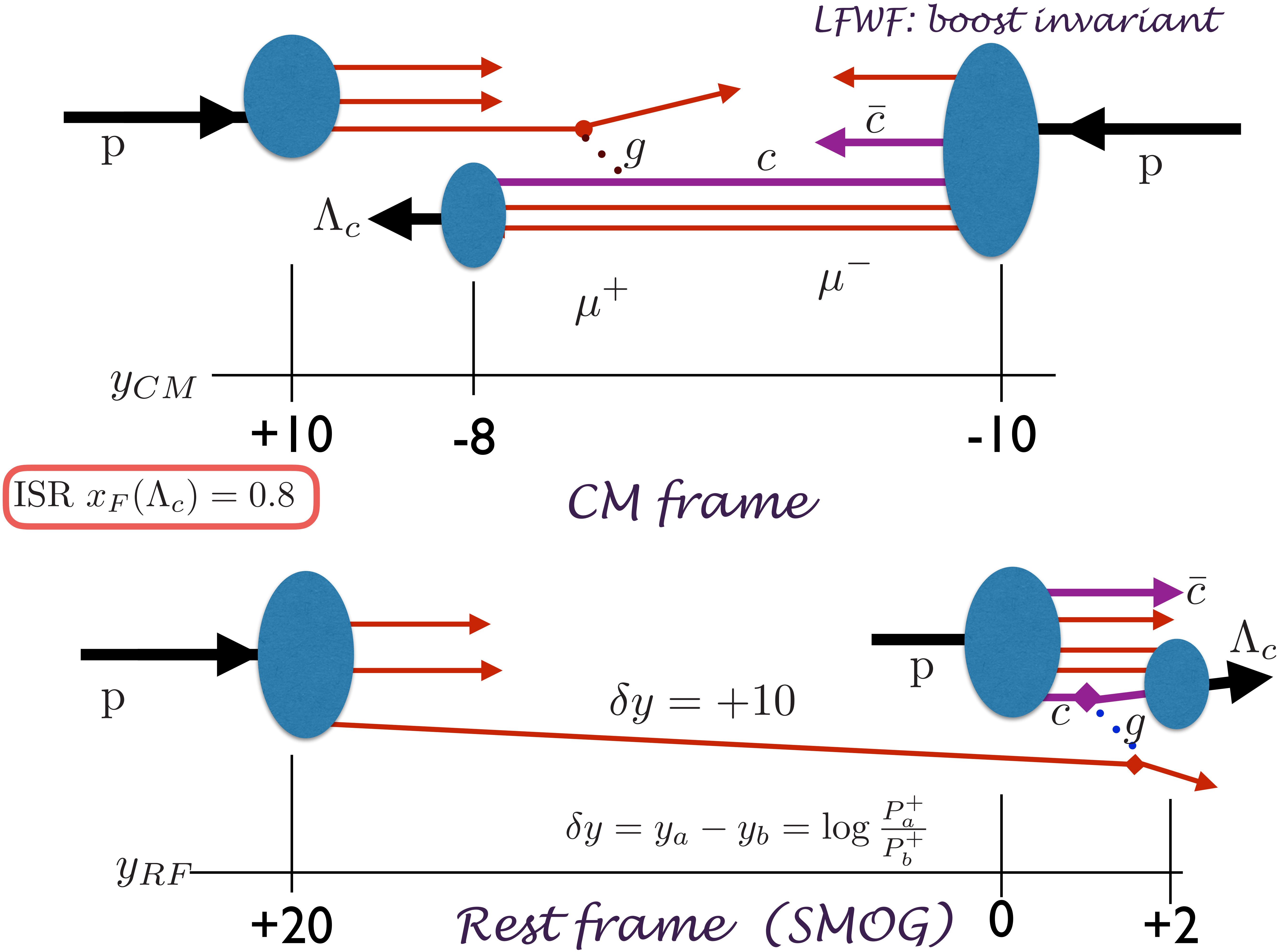
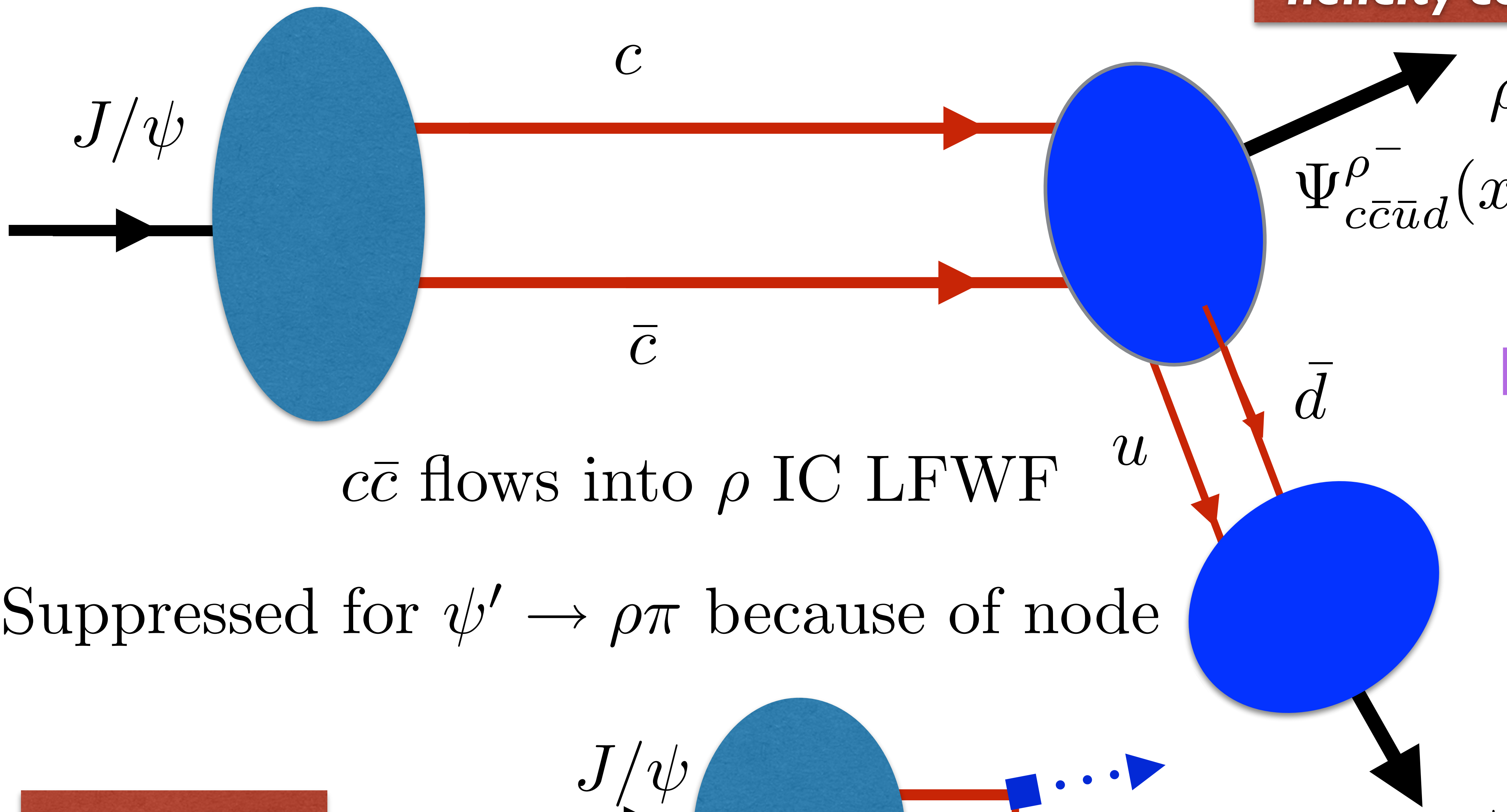

LFWF: boost invariant
p
$\bar{c}$
g
c
p
Λ_c
μ^+
μ^-
y_{CM}
+10
-8
-10
ISR $x_F(\Lambda_c) = 0.8$
CM frame
$\bar{c}$
Λ_c
p
p
$\delta y = +10$
c
g
$\delta y = y_a - y_b = \log \frac{P_a^+}{P_b^+}$
y_{RF}
+20
Rest frame (SMOG)
0
+2

J/Ψ to $\rho\ \pi$ Puzzle

$$\frac{\Gamma(\psi(2S) \to \rho\pi))/\Gamma_{\rm tot}}{\Gamma(J/\psi \to \rho\pi))/\Gamma_{\rm tot}} = \frac{3.2 \pm 1.2 \times 10^{-5}}{1.69 \pm 0.15 \times 10^{-2}} \simeq 0.2\%.$$

Not 13%
VP decay violates hadron helicity conservation

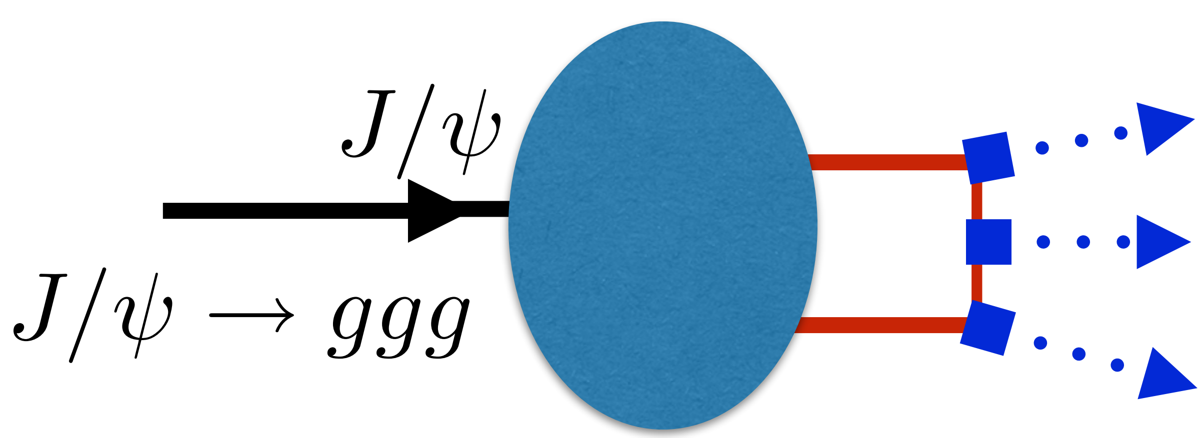


Karliner, sjb

$c\bar{c}$ flows into ρ IC LFWF

Suppressed for $\psi' \to \rho\pi$ because of node

Not OZI



Vast array of novel physics studies at LHCb and SMOG@LHCb

- Heavy Quark Phenomena: Intrinsic + Extrinsic
- High-x Gluon Distributions
- Exotic Heavy Quark Spectroscopy
- Higher Fock States of Proton and Nuclei
- Strangeness Asymmetry
- Novel Drell-Yan Studies
- Nuclear and Heavy Ion Effects: Ridge, baryon to meson
- Ultra-Peripheral Collisions
- Single-Spin Asymmetries
- Many Advantages of Fixed Target at LHC (AFTER and SMOG@LHCb

Novel Drell-Yan Physics Topics at LHCb

- Sivers effect: sign change in single-spin asymmetry
- Double Boer-Mulders Effect: Double initial-state interactions at leading twist
- Breakdown of Lam Tung and factorization theorems
- Flavor-Dependent Antishadowing (Explains NuTeV?) $pA \to \ell\bar{\ell}X$
- Analogous effects in gluon subprocesses $gg \to Q\bar{Q}$

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
- QCD gives 10^{42} to the cosmological constant
- Colliding Pancakes

Features of the Principle of Maximum Conformality

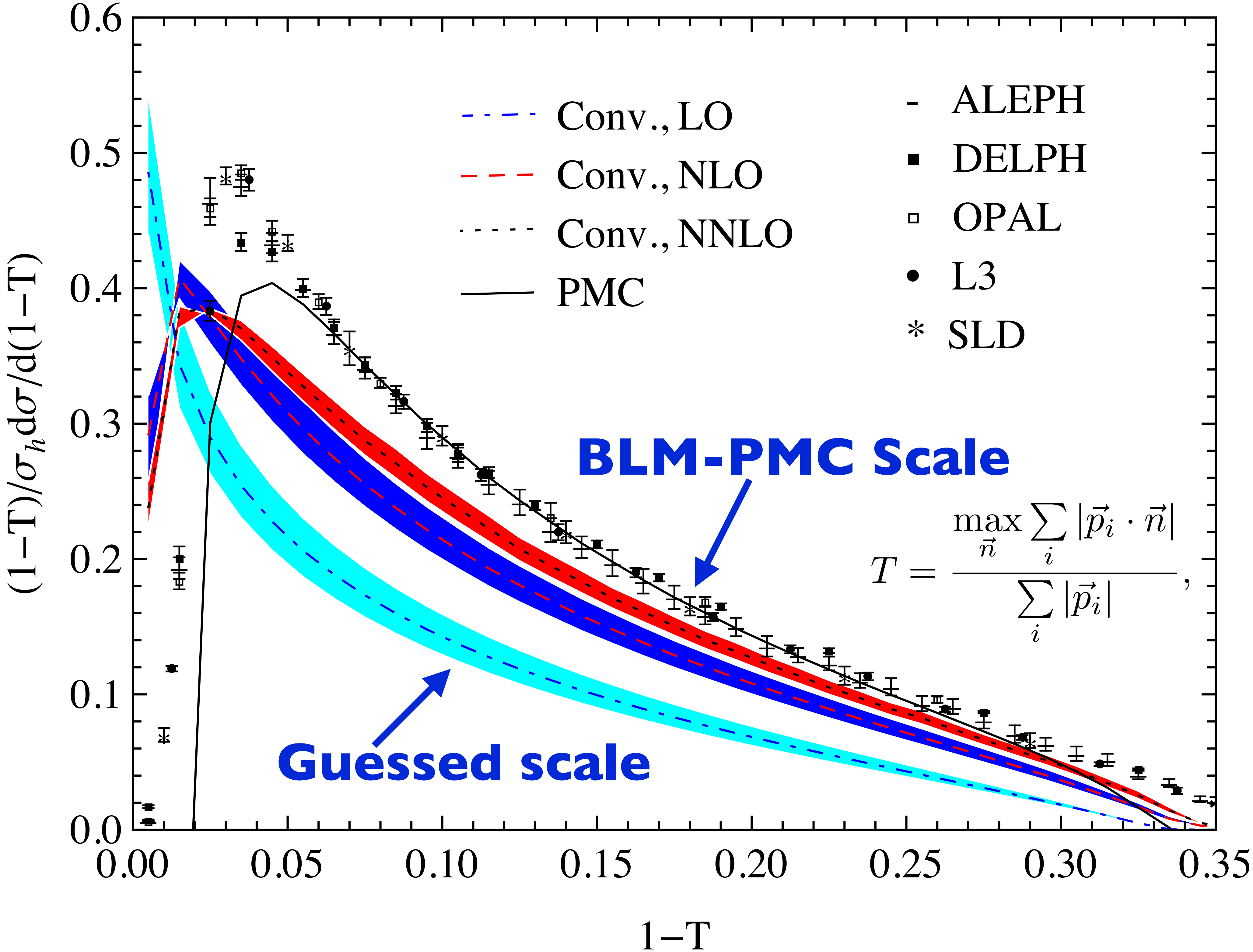
Lepage, Mackenzie, sjb
Ellis, Gardi, Karliner, Samuel, sjb

Wu, Mojaza, di Giustino, sjb

- ***Predictions are scheme-independent***
- ***Matches conformal series***
- ***Commensurate Scale Relations between observables: Generalized Crewther Relation***
- ***No n! Renormalon growth***
- ***New scale at each order; n_F determined at each order***
- ***Multiple Physical Scales Incorporated***
- ***Rigorous: Satisfies all Renormalization Group Principles***
- ***Reduces to standard Gell-Mann — Low Scale Setting for N_C=0***
- ***Realistic Estimate of Higher-Order Terms***
- ***Eliminates unnecessary theory error***
- ***Increases sensitivity to new physics***

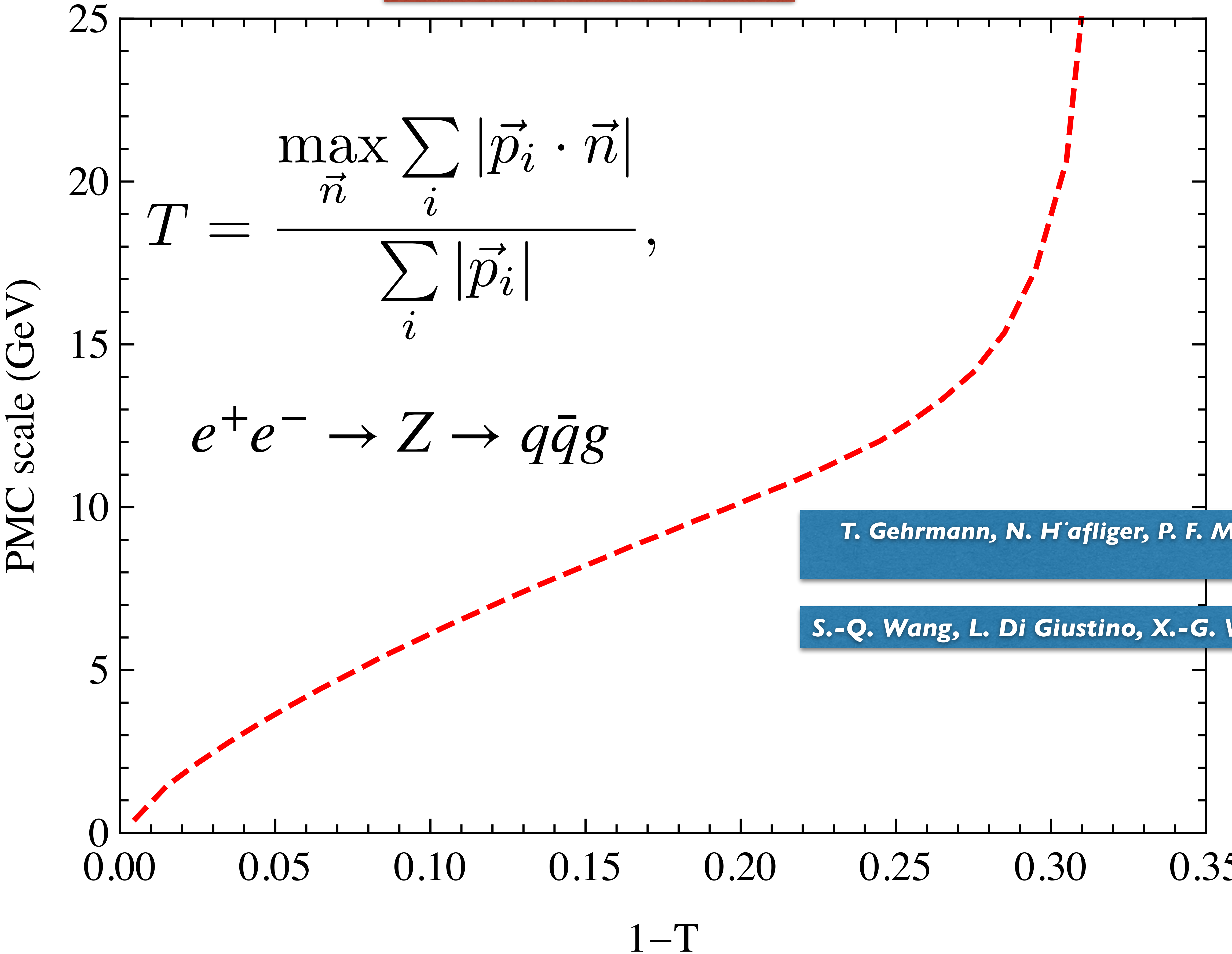
T. Gehrmann, N. H˙afliger, P. F. Monni

S.-Q. Wang, L. Di Giustino, X.-G. Wu, sjb



Principle of Maximum Conformality (PMC)

Renormalization scale depends on the thrust
Not constant



$$T = \frac{\max_{\vec{n}} \sum_i |\vec{p}_i \cdot \vec{n}|}{\sum_i |\vec{p}_i|},$$

$$e^+e^- \to Z \to q\bar{q}g$$

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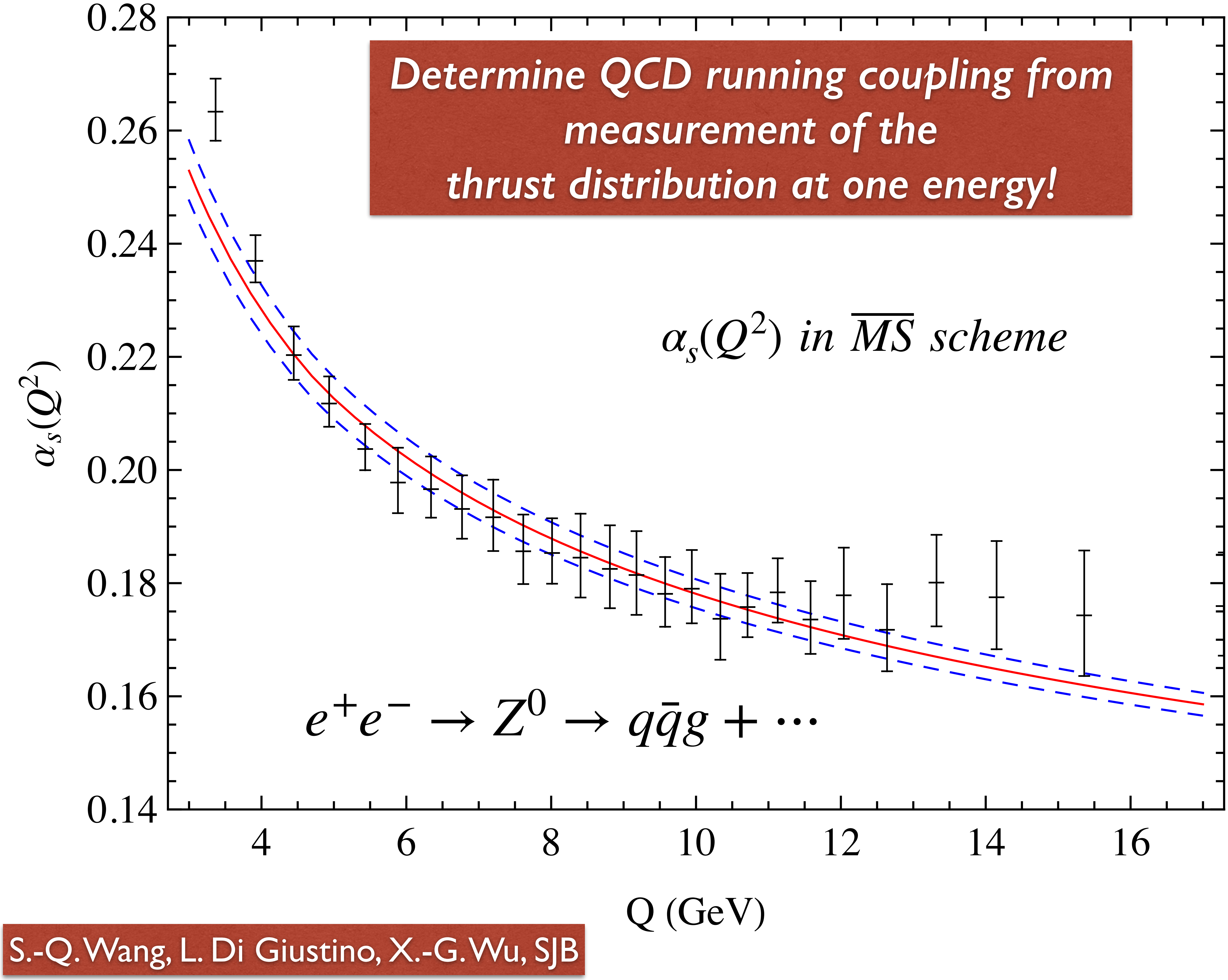
Determine QCD running coupling from measurement of the thrust distribution at one energy!
$\alpha_s(Q^2)$ in $\overline{MS}$ scheme
$e^+e^- \to Z^0 \to q\bar{q}g + \cdots$
$\alpha_s(Q^2)$
Q (GeV)
0.28
0.26
0.24
0.22
0.20
0.18
0.16
0.14
4
6
8
10
12
14
16
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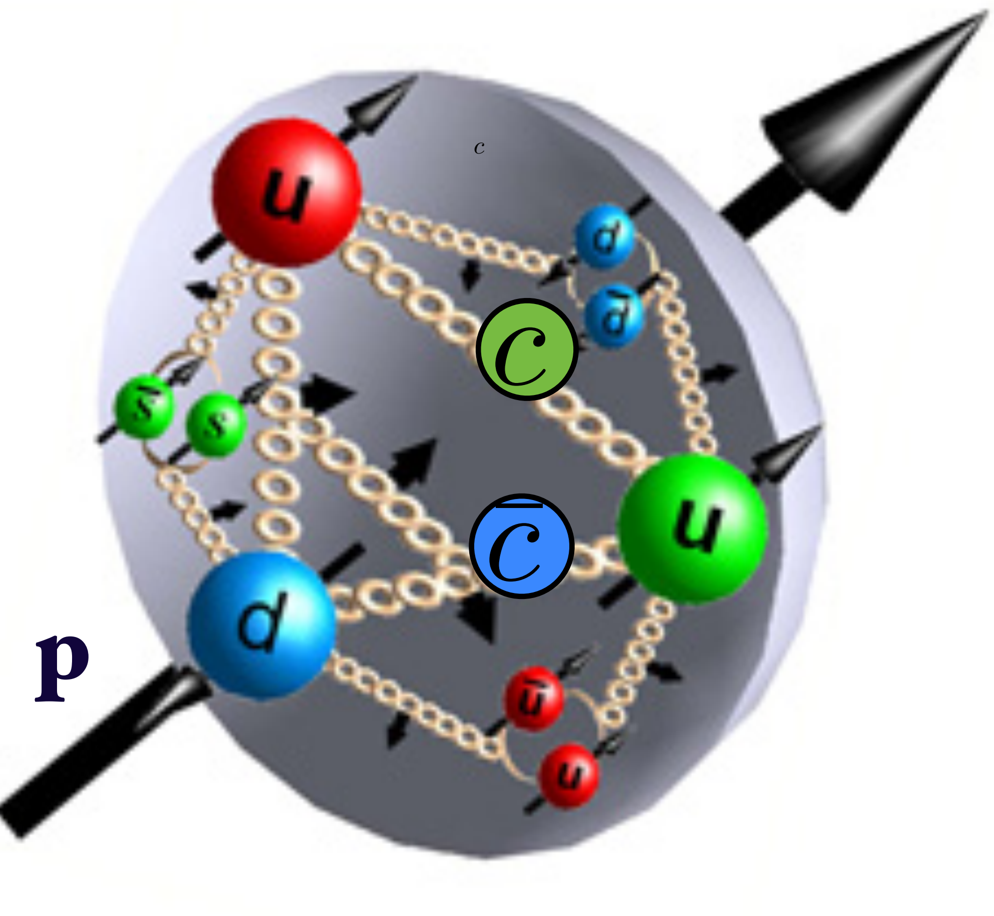
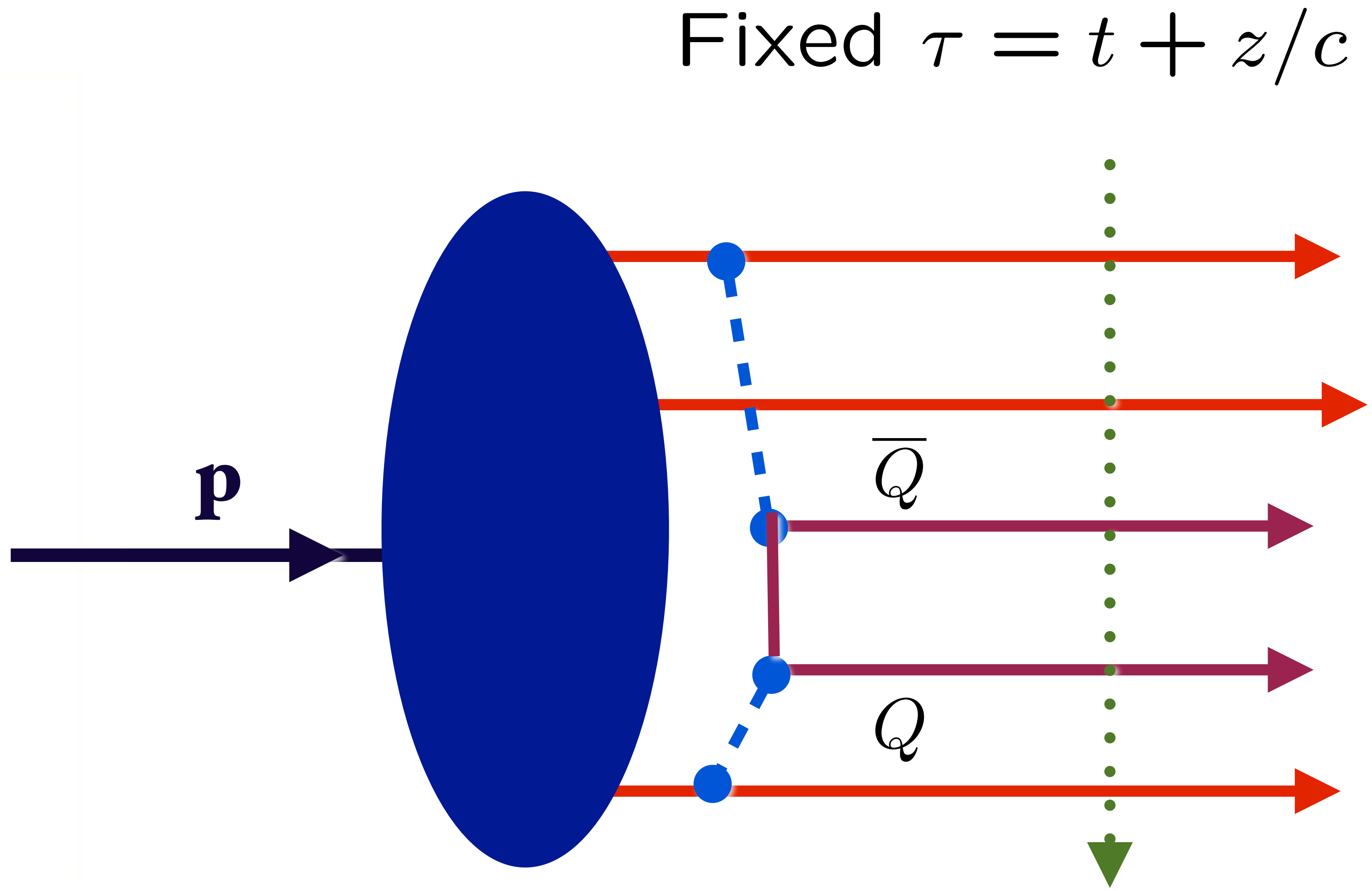
Invariance Principles of Quantum Field Theory

- *PoIncarè Invariance: Physical predictions must be independent of the observer's Lorentz frame: Front Form*
- *Causality: Information within causal horizon: Front Form*
- *Gauge Invariance: Physical predictions of gauge theories must be independent of the choice of gauge*
- *Scheme-Independence: Physical predictions of a renormalizable theory must be independent of the choice of the renormalization scheme —Principle of Maximum Conformality (PMC)*
- *Mass-Scale Invariance:*
  Conformal Invariance of the Action (DAFF)

QCD, Heavy Flavors, and Higgs Production in the Very Forward Region





Workshop on Forward Physics and QCD at the LHC, the Future Electron Collider, and Cosmic Ray Physics

Stan Brodsky

Hotel Guanajuato,
Ciudad de Guanajuato,
Mexico

November 18, 2019

SLAC NATIONAL ACCELERATOR LABORATORY