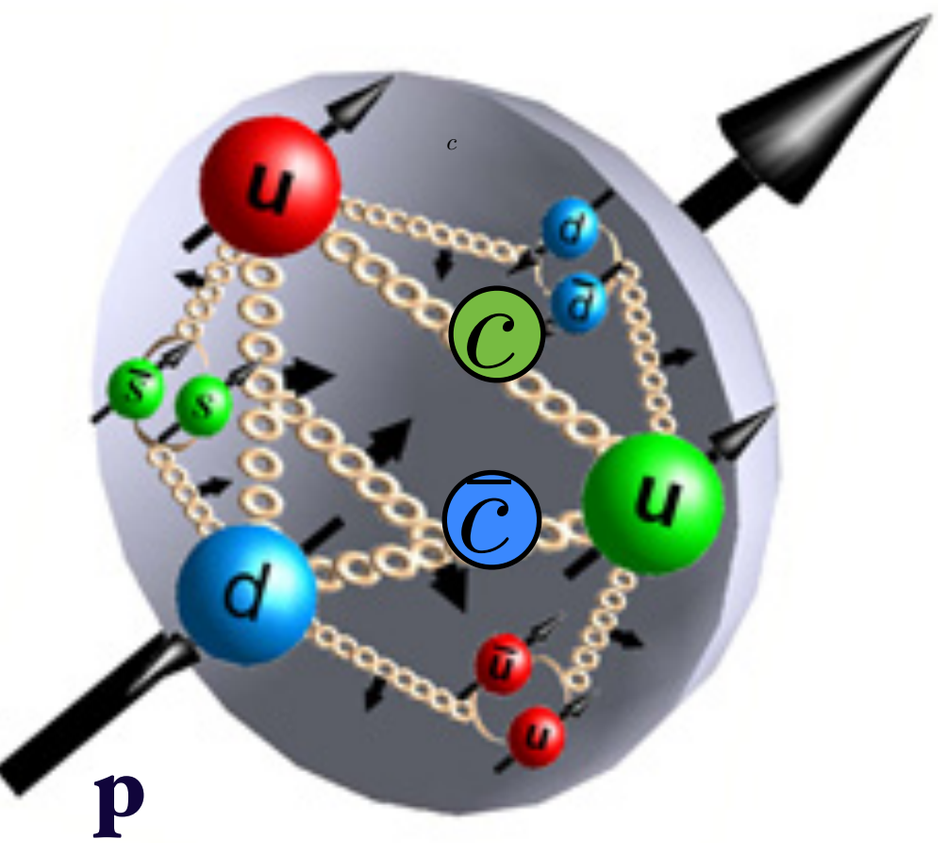
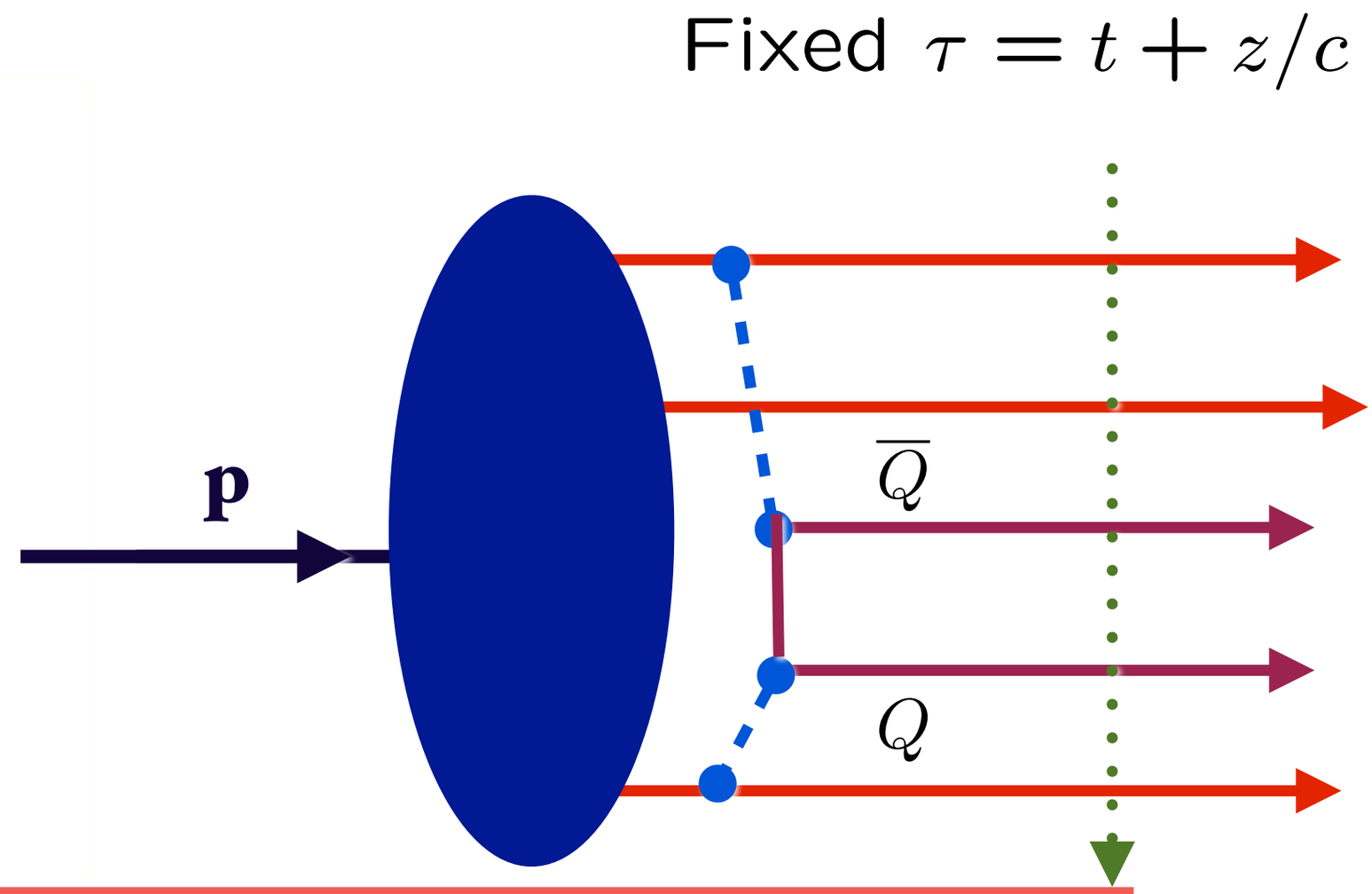
Novel Features of QCD Phenomenology at High X





CFNS workshop on Forward Physics And Instrumentation From Colliders To Cosmic Rays

Center for Frontiers in Nuclear Science

Stony Brook
October 17, 2018

Stan Brodsky

SLAC NATIONAL ACCELERATOR LABORATORY

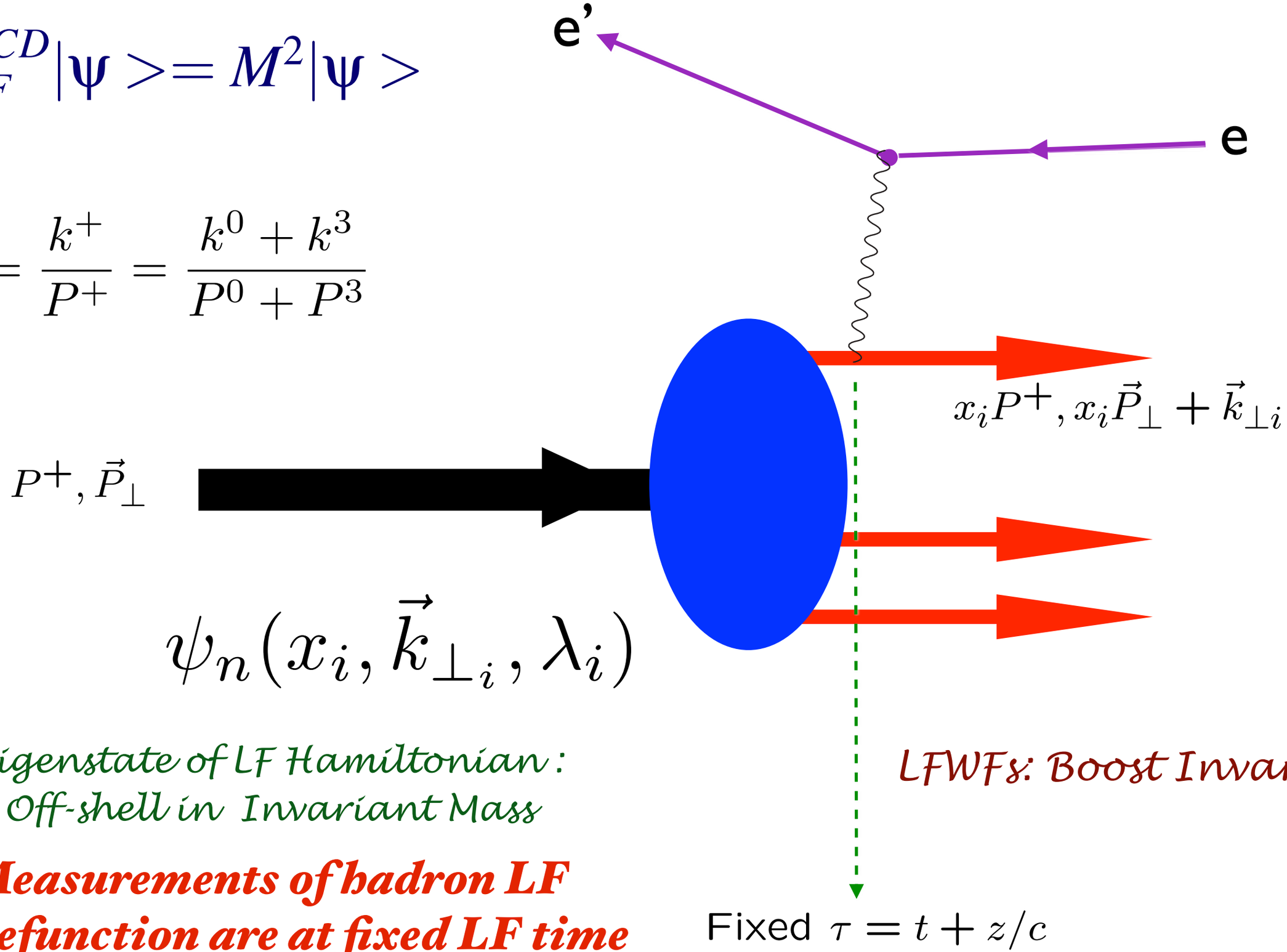
LELAND STANFORD JUNIOR UNIVERSITY

Vast array of novel physics studies possible at high x

- 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)

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

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



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

Eigenstate of LF Hamiltonian :
Off-shell in Invariant Mass

LFWFs: Boost Invariant

Measurements of hadron LF wavefunction are at fixed LF time

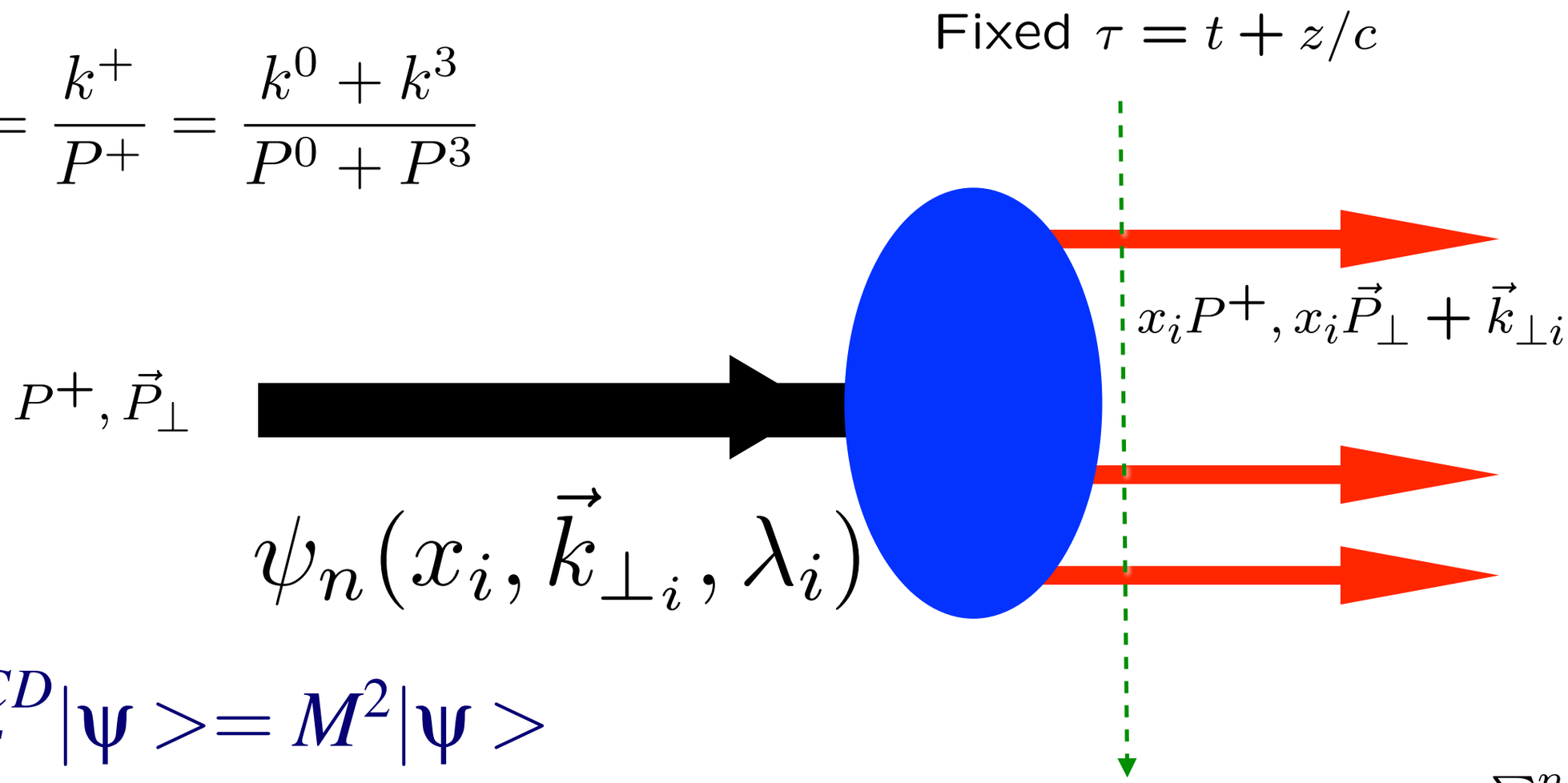
Like a flash photograph

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

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

Eigenstate of LF Hamiltonian

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



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

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

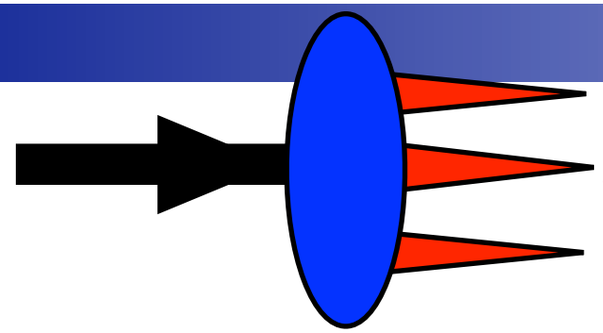
$$\sum_i^n x_i = 1$$

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

Invariant under boosts! Independent of P^μ

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

• Light Front Wavefunctions:



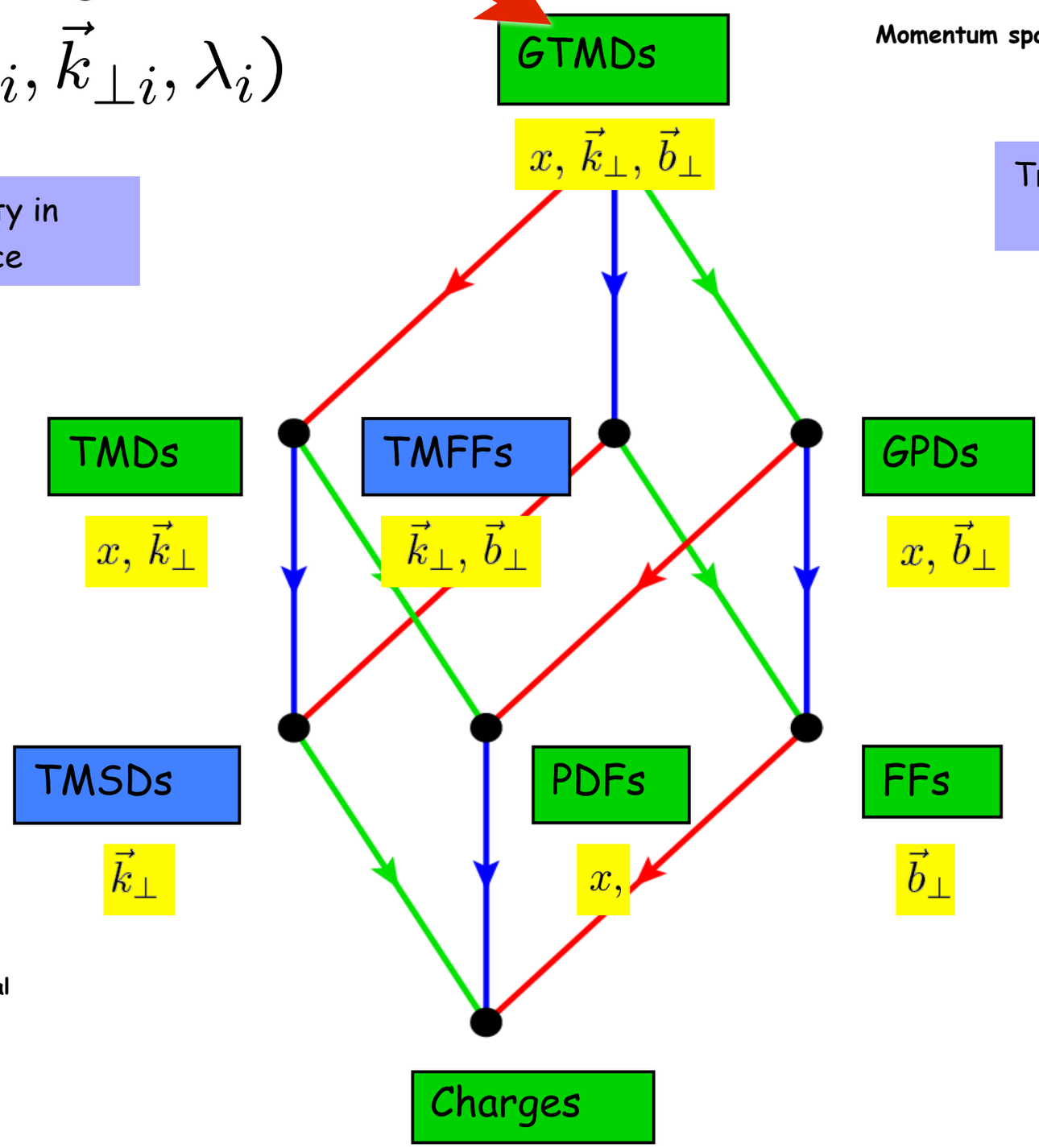
$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

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

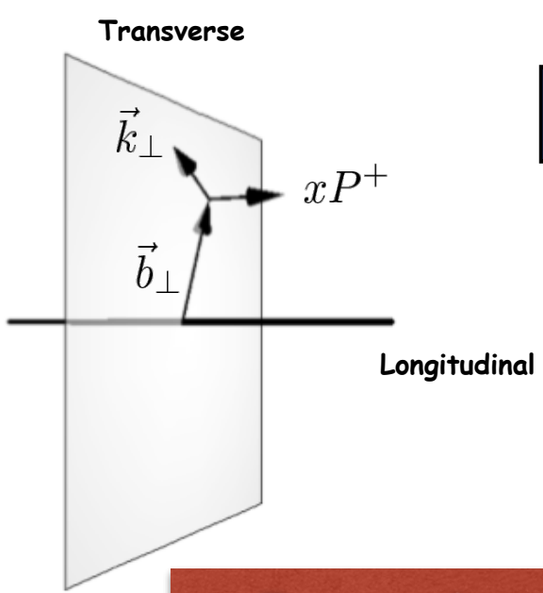
$\vec{\Delta}_\perp \leftrightarrow \vec{b}_\perp$

Transverse density in momentum space

Transverse density in position space



Lorce, Pasquini



$\int \mathrm{d}^2 b_\perp$

$\int \mathrm{d}x$

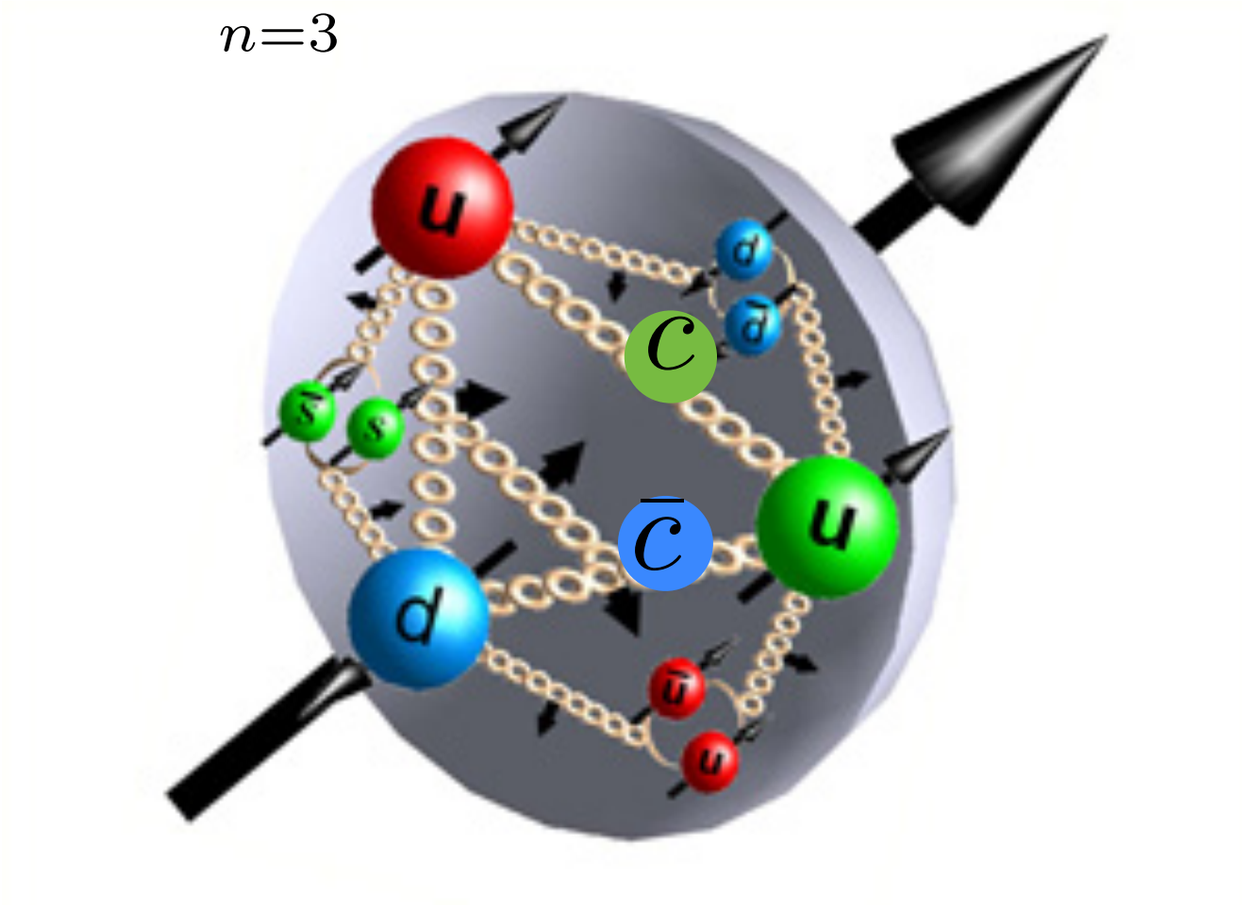
$\int \mathrm{d}^2 k_\perp$

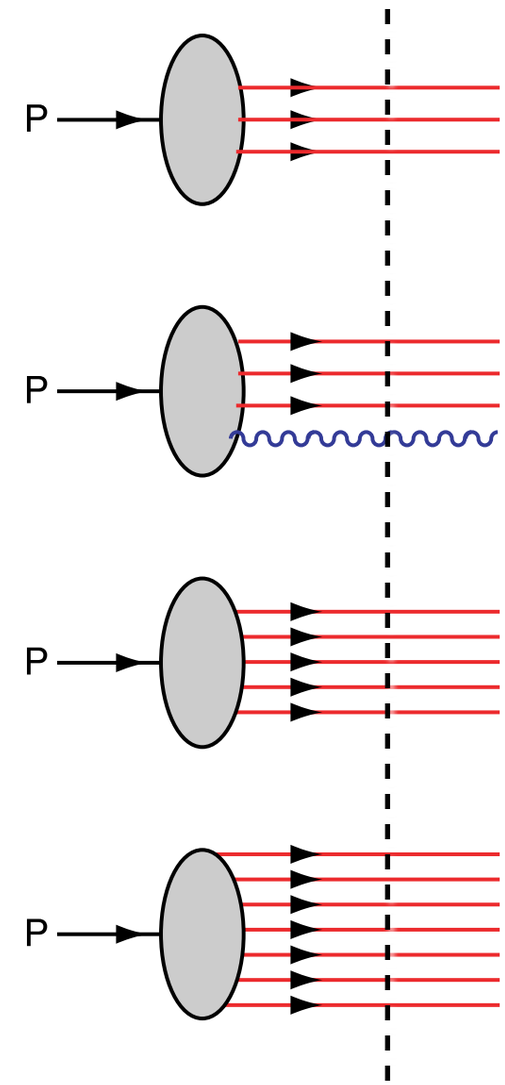
+ Factorization-Breaking Lensing Corrections: Sivers, T-odd

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

Eigenstate of LF Hamiltonian : all Fock states contribute

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





Higher Fock States of the Proton

Fixed LF time

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

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

The Light Front Fock State Wavefunctions

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

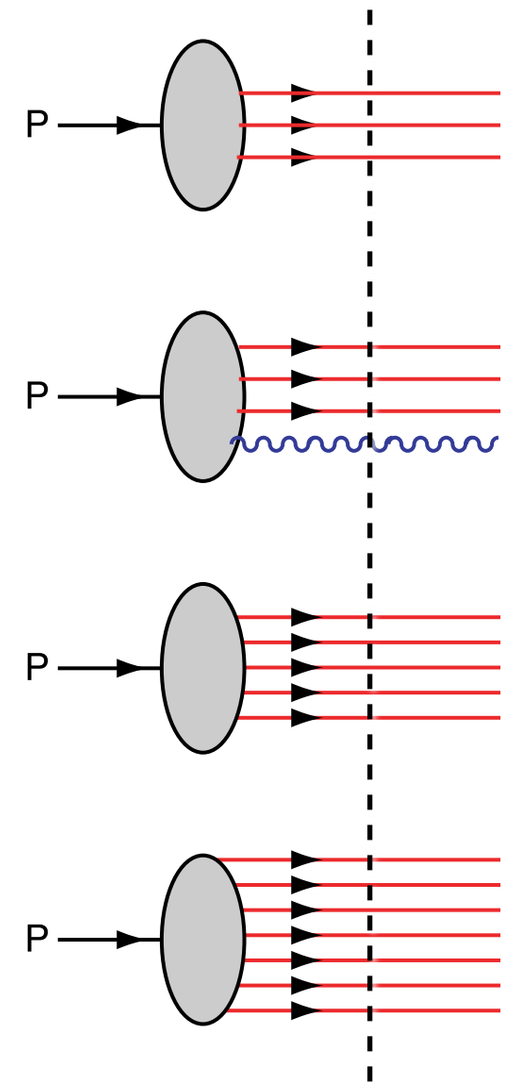
are boost invariant; they are independent of the hadron's energy and momentum P^μ.

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

$$\tau = t + z/c$$

Intrinsic heavy quarks

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

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

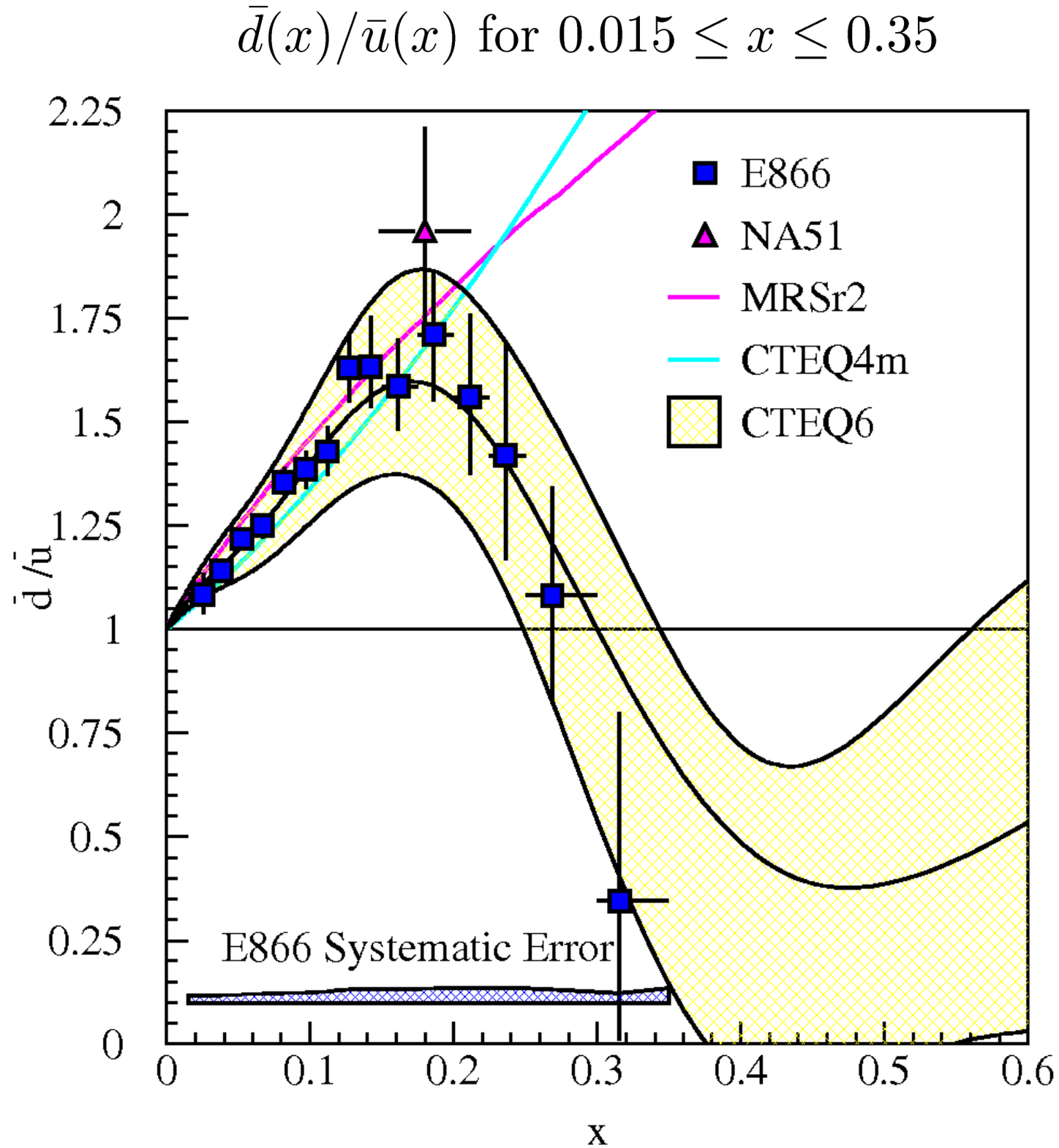
Deuteron: Hidden Color

- 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



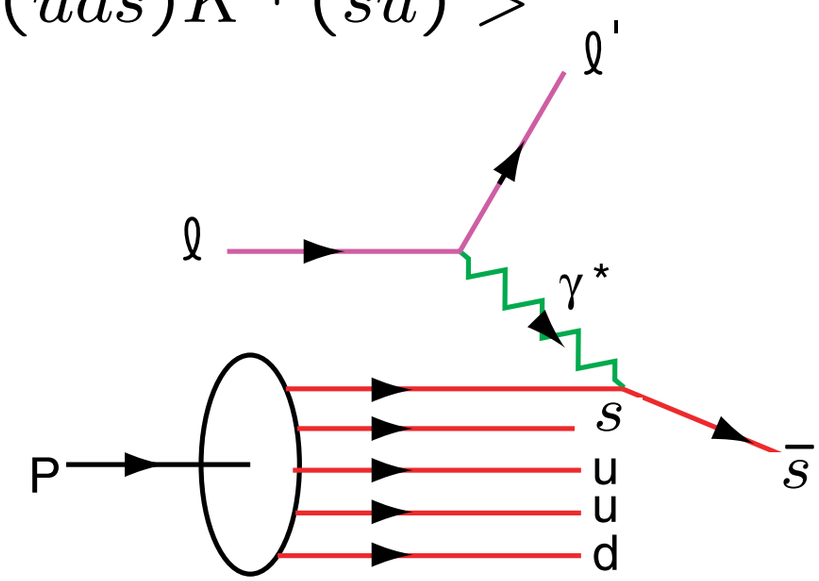
Measure strangeness distribution in Semi-Inclusive DIS at JLab

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

- **Non-symmetric strange and antistrange sea?**
- **Non-perturbative physics**

$$|uuds\bar{s}> \simeq |\Lambda(uds)K^+(\bar{s}u)>$$

B. Q. Ma, sjb



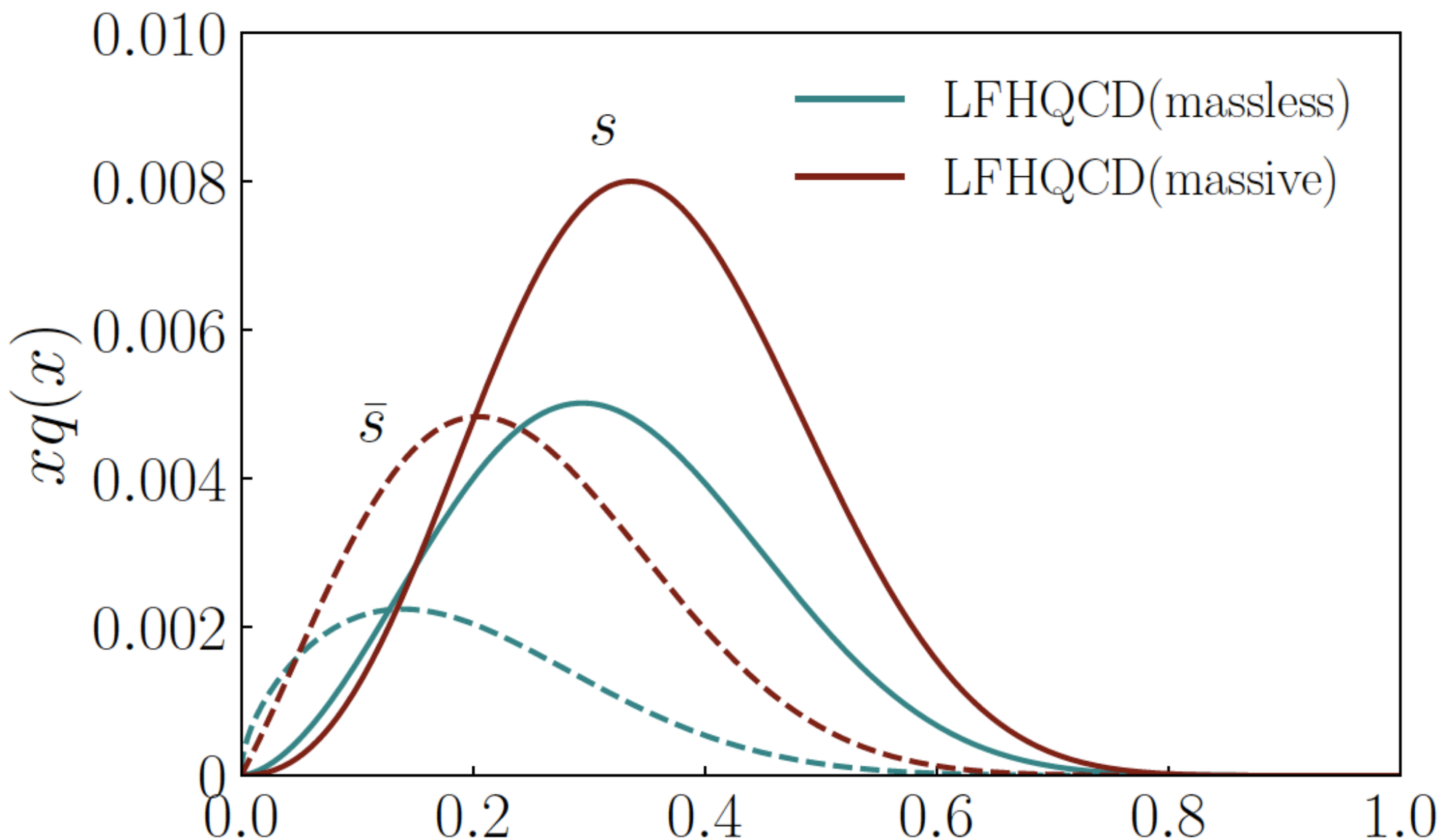
Tag struck quark flavor in semi-inclusive DIS $ep \to e' K^+ X$

JLAB-THY-18-2803
SLAC-PUB-17327

Nonperturbative strange-quark sea from lattice QCD, light-front holography, and meson-baryon fluctuation models

Raza Sabbir Sufian,[1] Tianbo Liu,[1,2,*] Guy F. de Téramond,[3] Hans Günter Dosch,[4]
Stanley J. Brodsky,[5] Alexandre Deur,[1] Mohammad T. Islam,[6] and Bo-Qiang Ma[7,8,9]

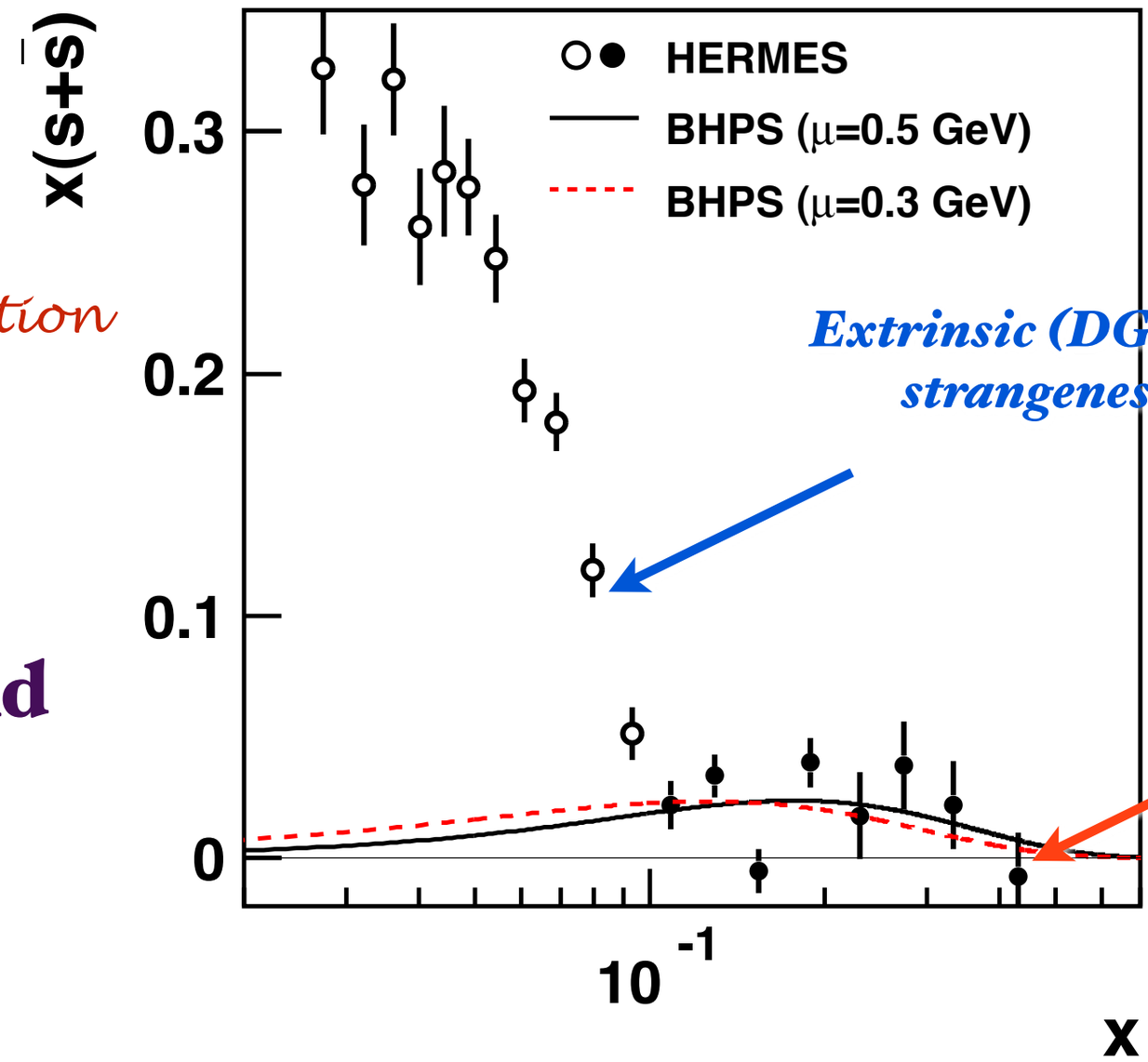
(HLFHS Collaboration)



HERMES: Two components to $s(x,Q^2)$!

BHPS: Hoyer, Sakai, Peterson, sjb

Sensitive to Fragmentation Function



Extrinsic (DGLAP) strangeness!

Intrinsic strangeness!

Consistent with intrinsic charm data

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

arXiv:1105.2381

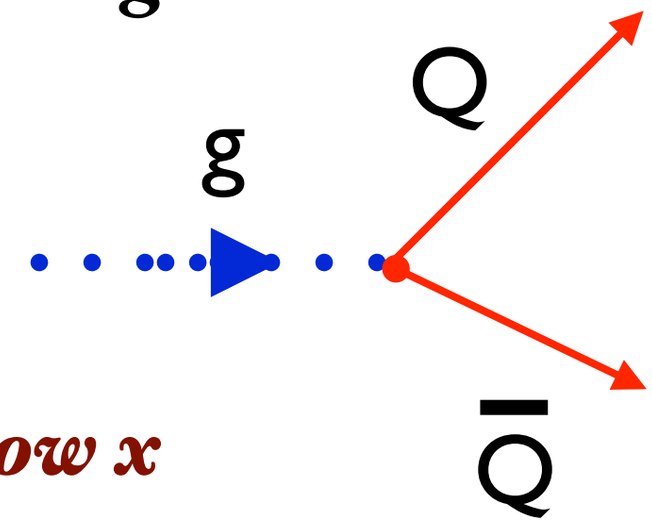
QCD: $\frac{1}{M_Q^2}$ scalin

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.

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

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

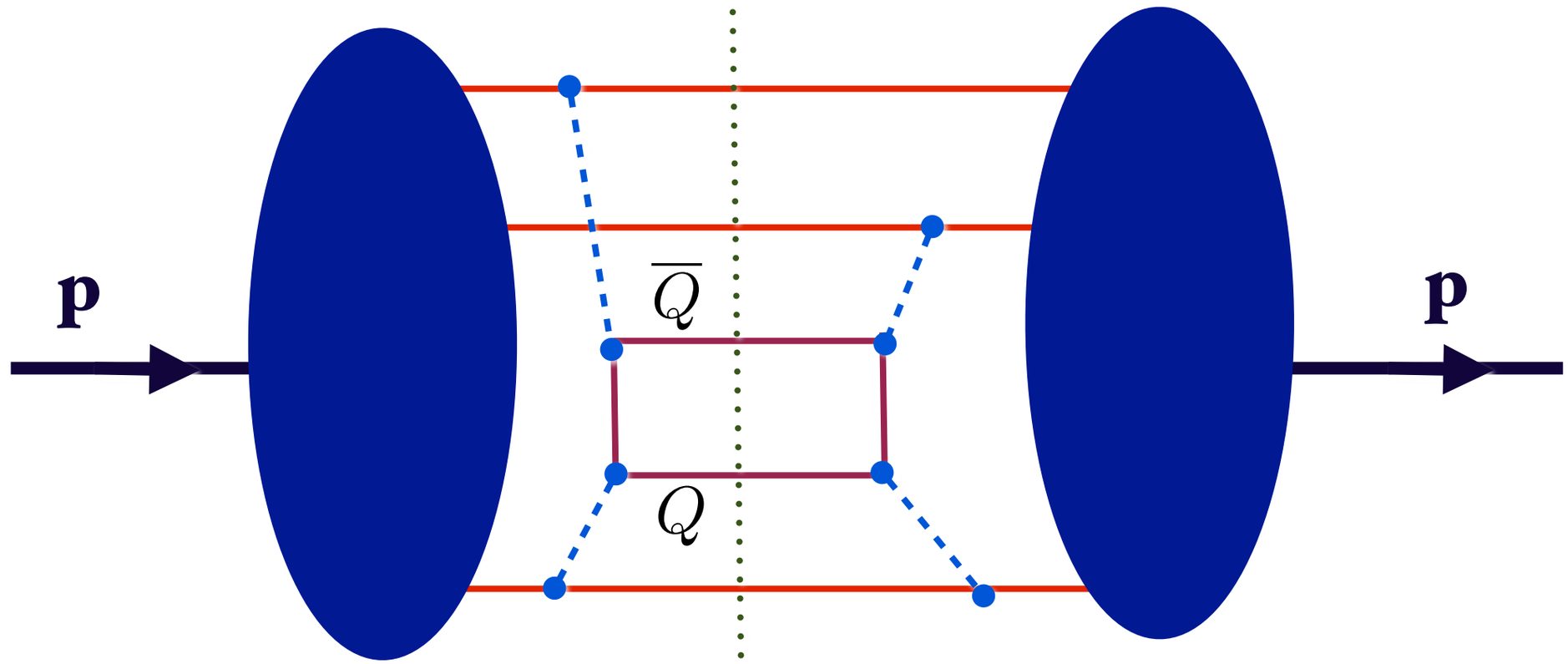
$$s(x,\mu_F^2) = c(x,\mu_F^2) = b(x,\mu_F^2) \equiv 0$$

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

Conventional wisdom is wrong even in QED!

Fixed LF time

Proton Self Energy
Intrinsic Heavy Quarks



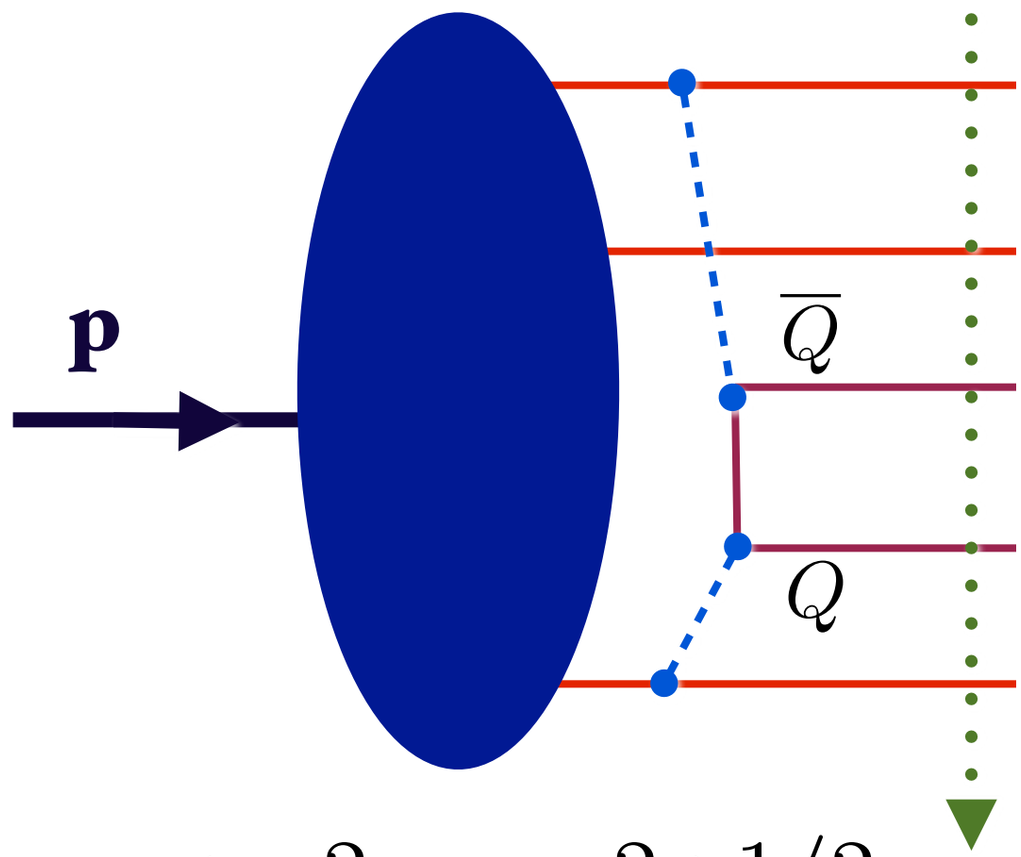
$$\text{Probability (QED)} \propto \frac{1}{M_\ell^4} \qquad \text{Probability (QCD)} \propto \frac{1}{M_Q^2}$$

Rigorous OPE Analysis

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

Fixed LF time

Proton 5-quark Fock State :
Intrinsic Heavy Quarks



QCD predicts
Intrinsic Heavy
Quarks at high x!

Minimal off-shellness

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

Maximum at Equal rapidity!

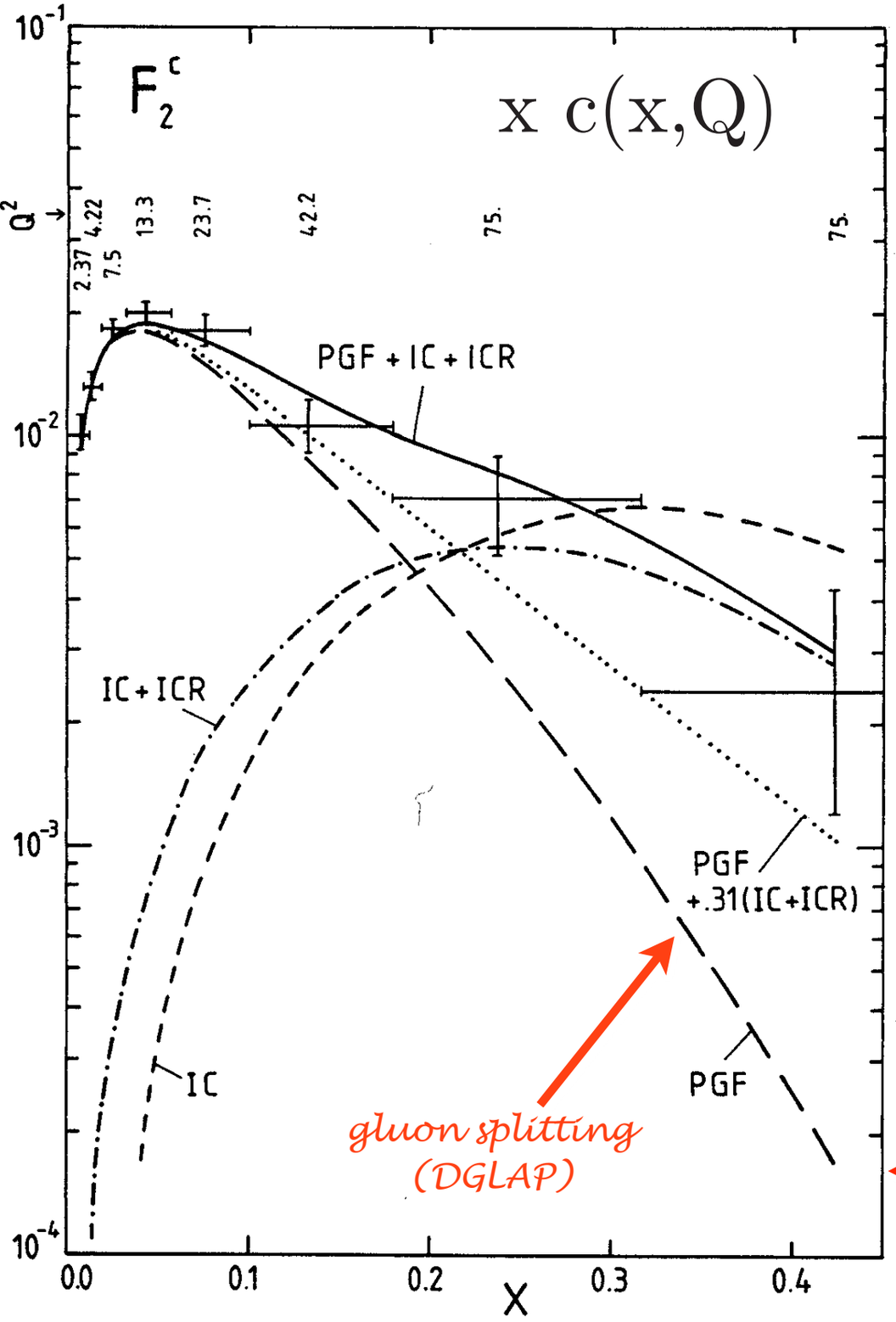
$$\text{Probability (QED)} \propto \frac{1}{M_\ell^4} \qquad \text{Probability (QCD)} \propto \frac{1}{M_Q^2}$$

Rigorous OPE
Analysis

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

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).

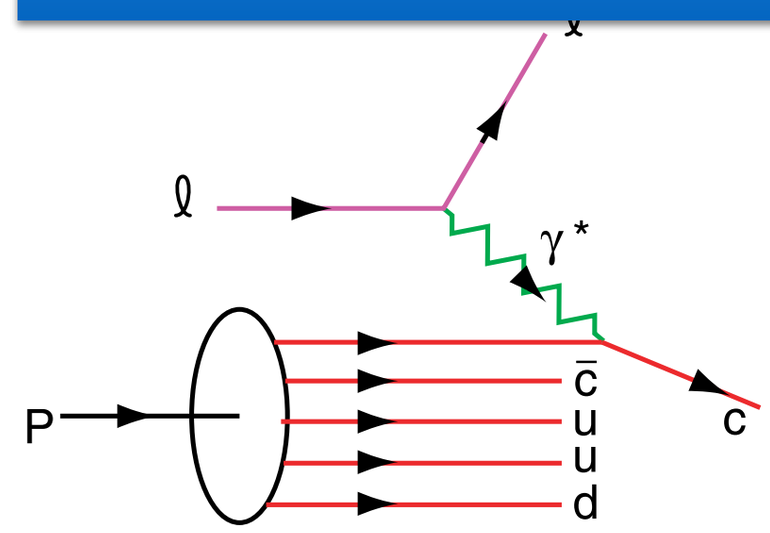


Evidence for Intrinsic Charm

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

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 !



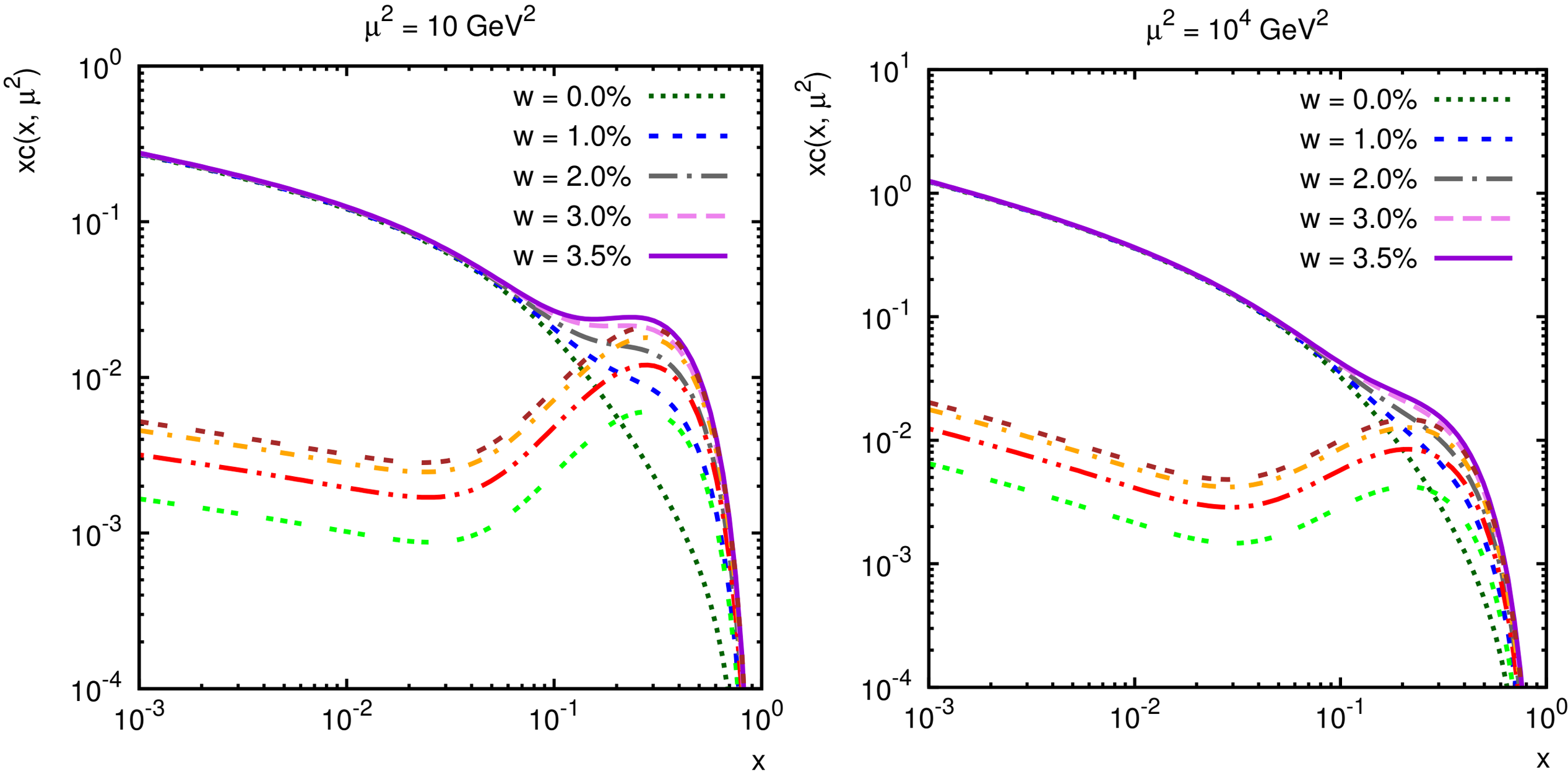
DGLAP / Photon-Gluon Fusion: factor of 30 too small

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

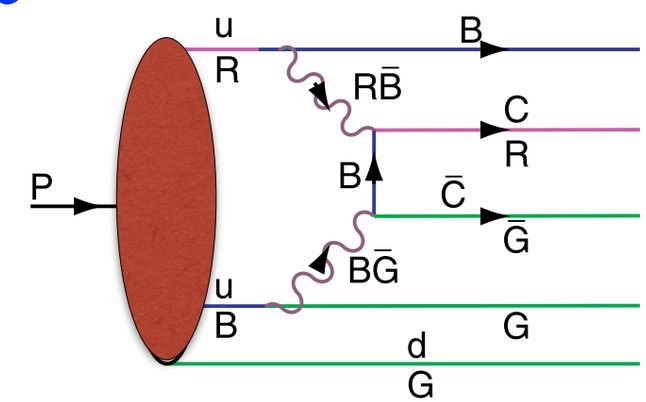
$$xc(x,\mu^2)$$



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

Hoyer, Peterson, Sakai, sjb

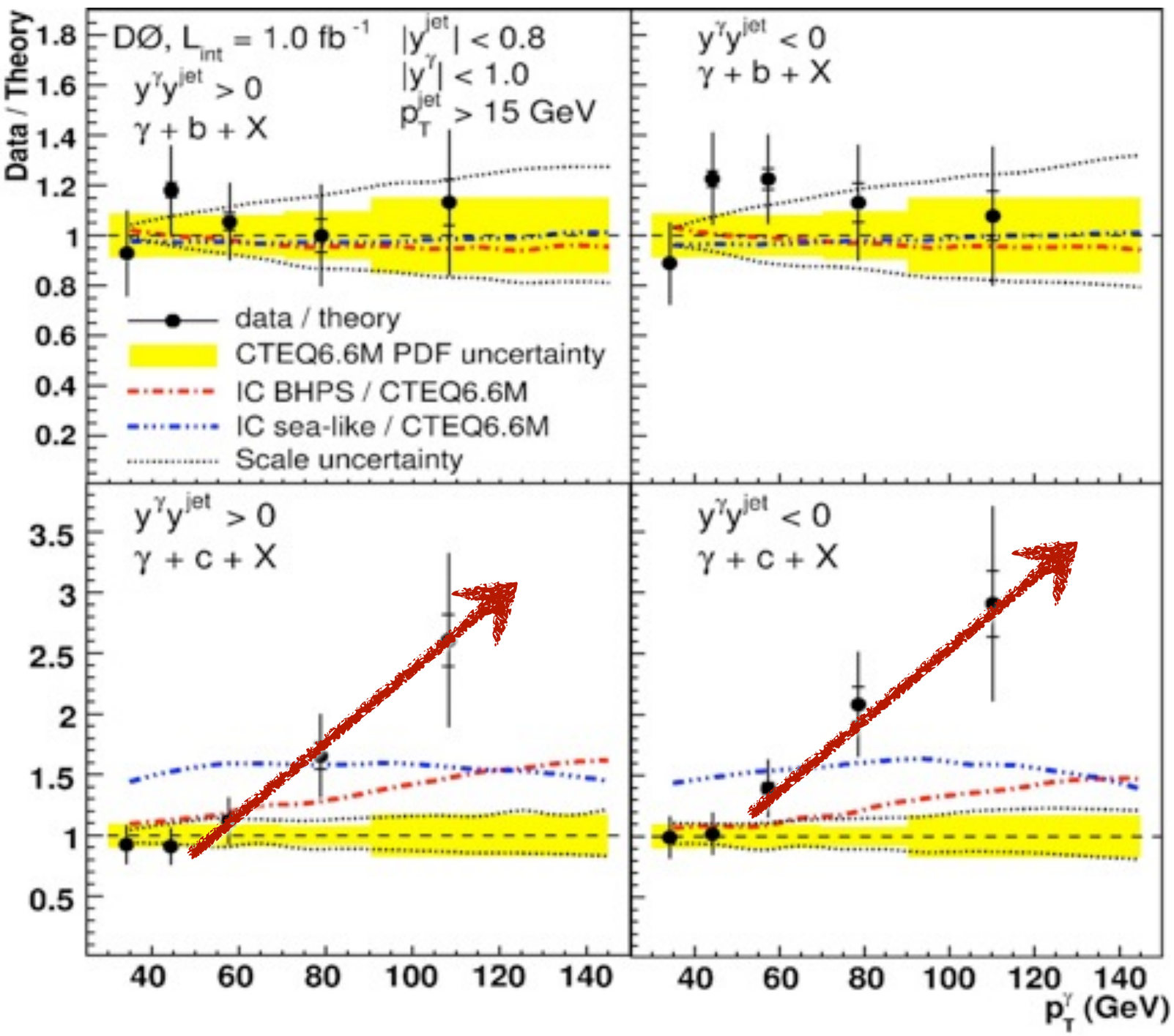
Intrinsic Heavy-Quark Fock



- **Rigorous prediction of QCD, OPE**
- **Color-Octet Color-Octet Fock State**
- **Probability** $P_{Q\bar{Q}} \propto \frac{1}{M_Q^2}$ $P_{Q\bar{Q}Q\bar{Q}} \sim \alpha_s^2 P_{Q\bar{Q}}$ $P_{c\bar{c}/p} \simeq 1\%$
- **Large Effect at high x**
- **Greatly increases kinematics of colliders such as Higgs production**
- **Underestimated in conventional parameterizations of heavy quark distributions**
- **Many EIC, LHC tests (LHCb -SMOG)**

D0

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



$$p\bar{p} \to \gamma + Q + X$$

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

Ratio is insensitive to gluon PDF, scales

$$gc \to \gamma c$$

Signal for significant intrinsic charm

Mesropian, Bandurin

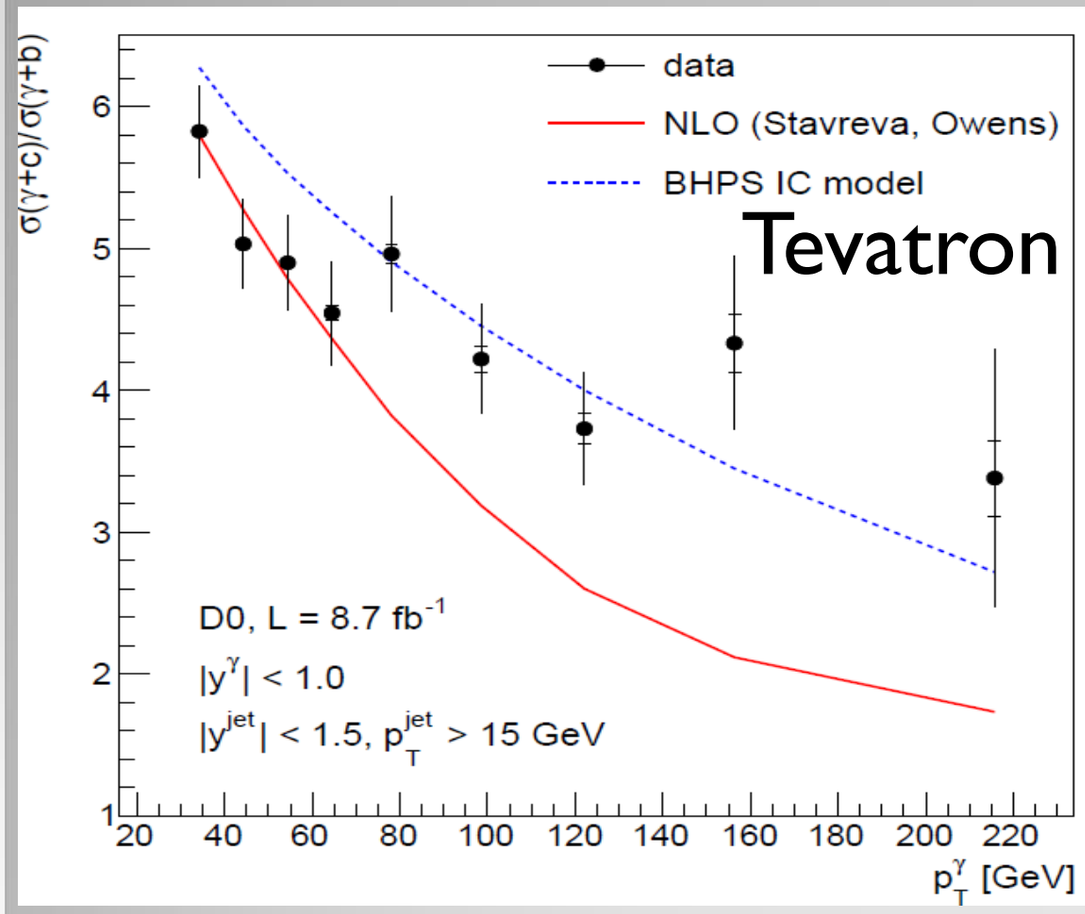
$$c(x, Q^2) = c(x, Q^2)_{\text{extrinsic}} + c(x, Q^2)_{\text{intrinsic}}$$

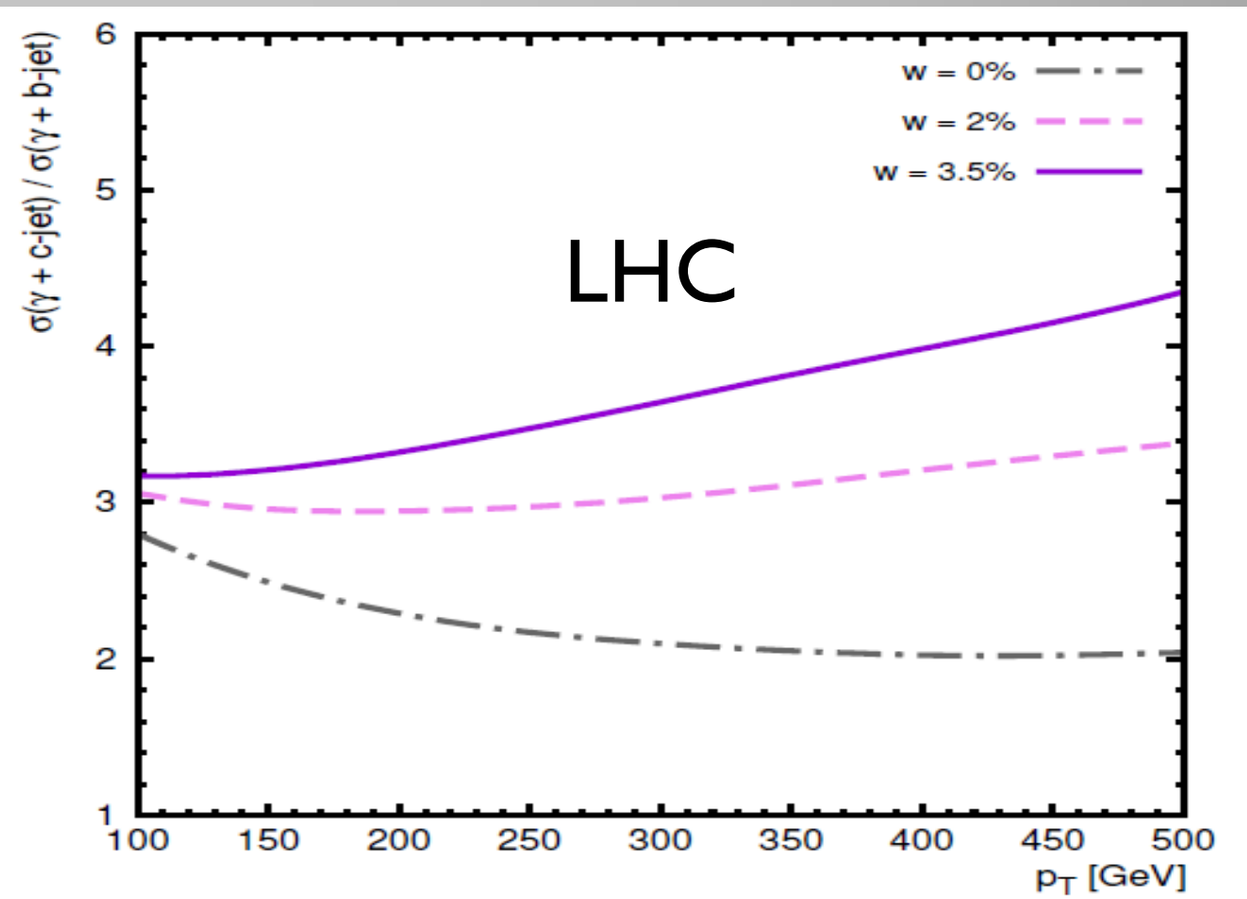
LHC: $pp \to Z^0 c X$

Boettcher, Ilten, Williams

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)





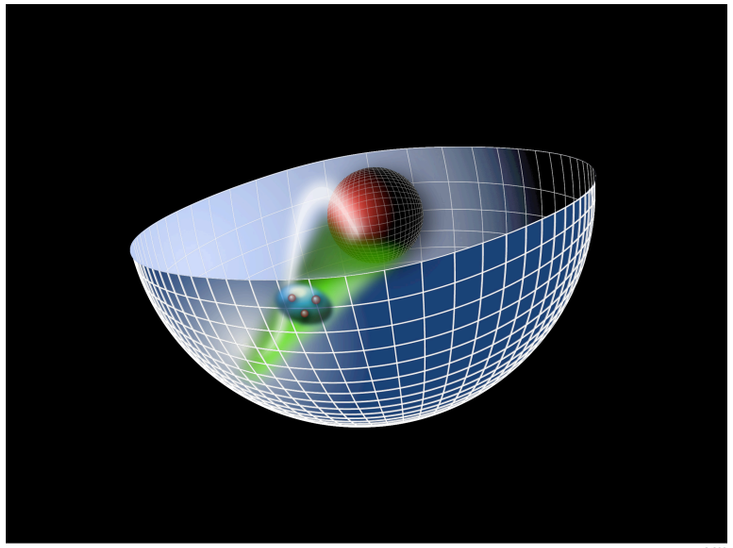
V,M,Abazov, et al. (D0) Phys.Lett. B719 (2013) 354 .

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

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

AdS5: Conformal Template for QCD

$\phi(z)$

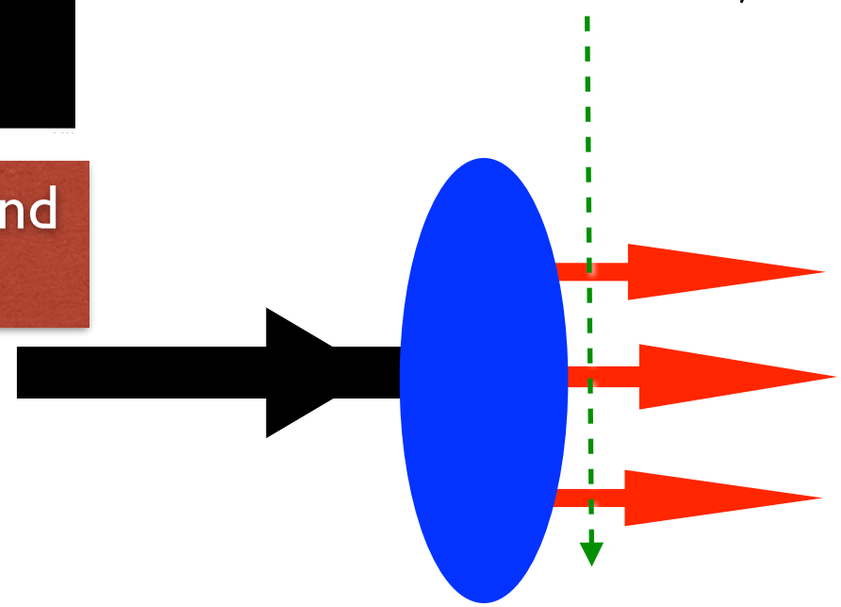


with Guy de Teramond and Hans Guenter Dosch

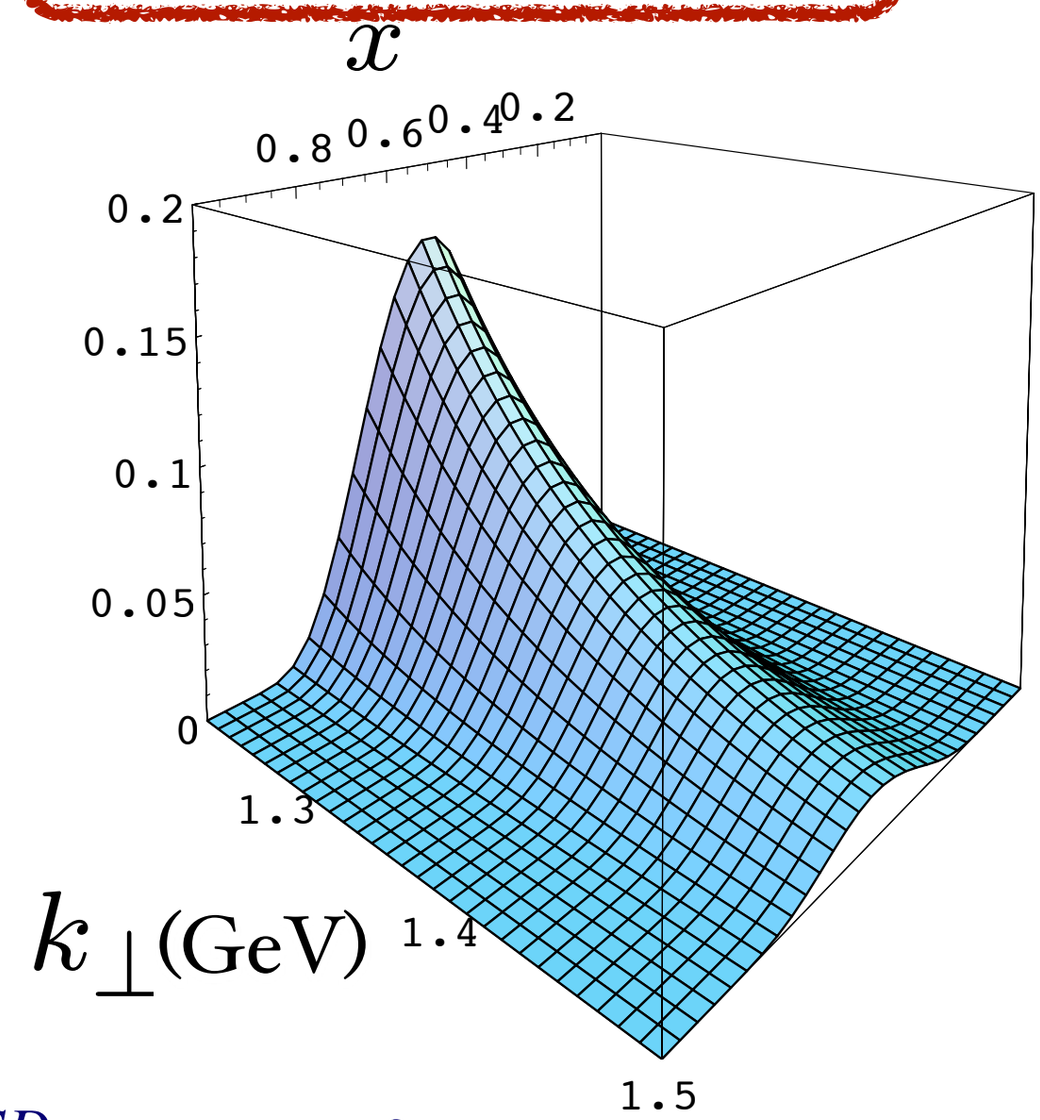
- *Light-Front Holography*

Duality of AdS$_5$ with LF Hamiltonian Theory

Fixed $\tau = t + z/c$



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



- *Light Front Wavefunctions:*

Light-Front Schrödinger Equation
Spectroscopy and Dynamics

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

JLAB-THY-18-2803
SLAC-PUB-17327

Nonperturbative strange-quark sea from lattice QCD, light-front holography, and meson-baryon fluctuation models

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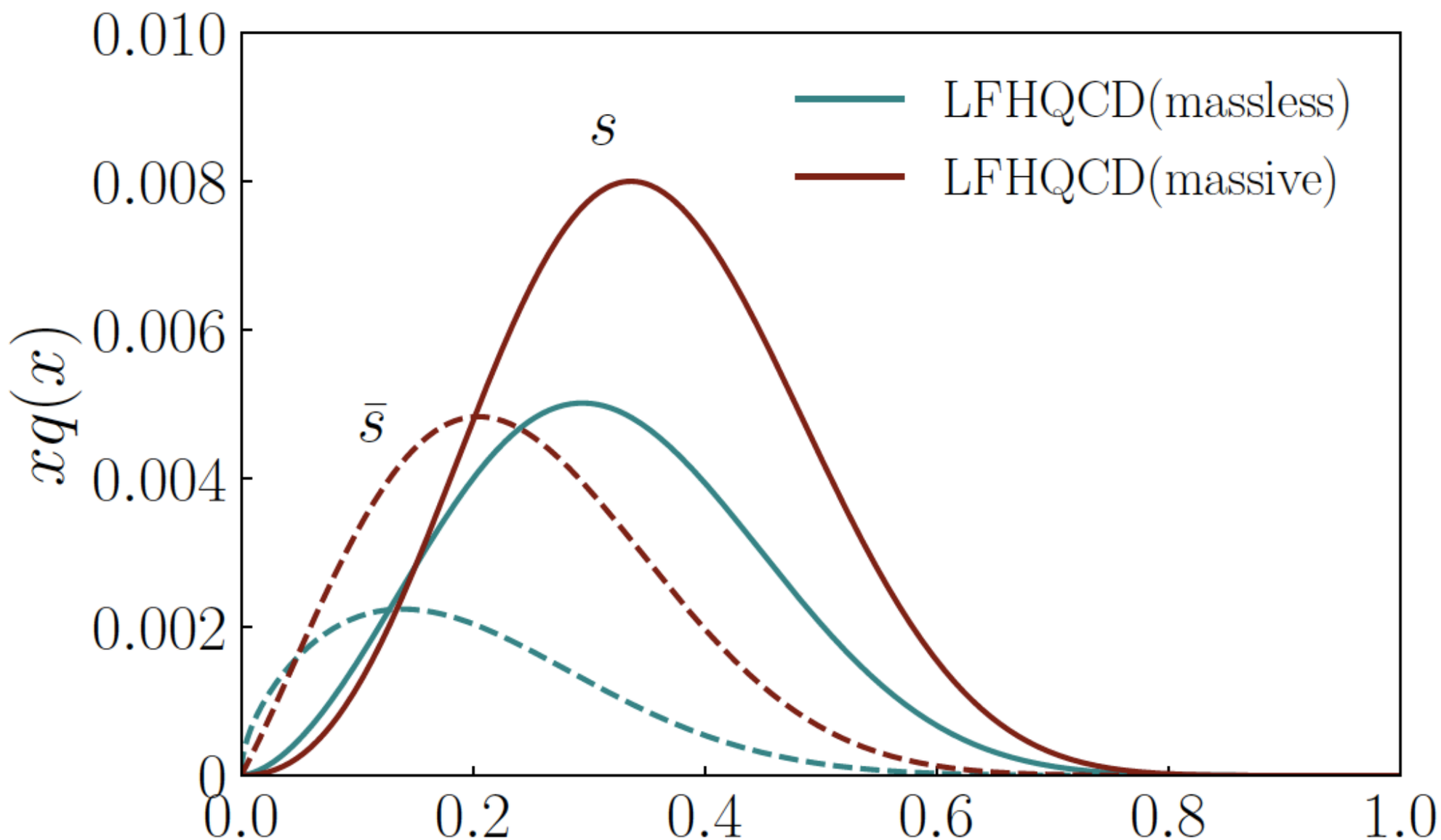
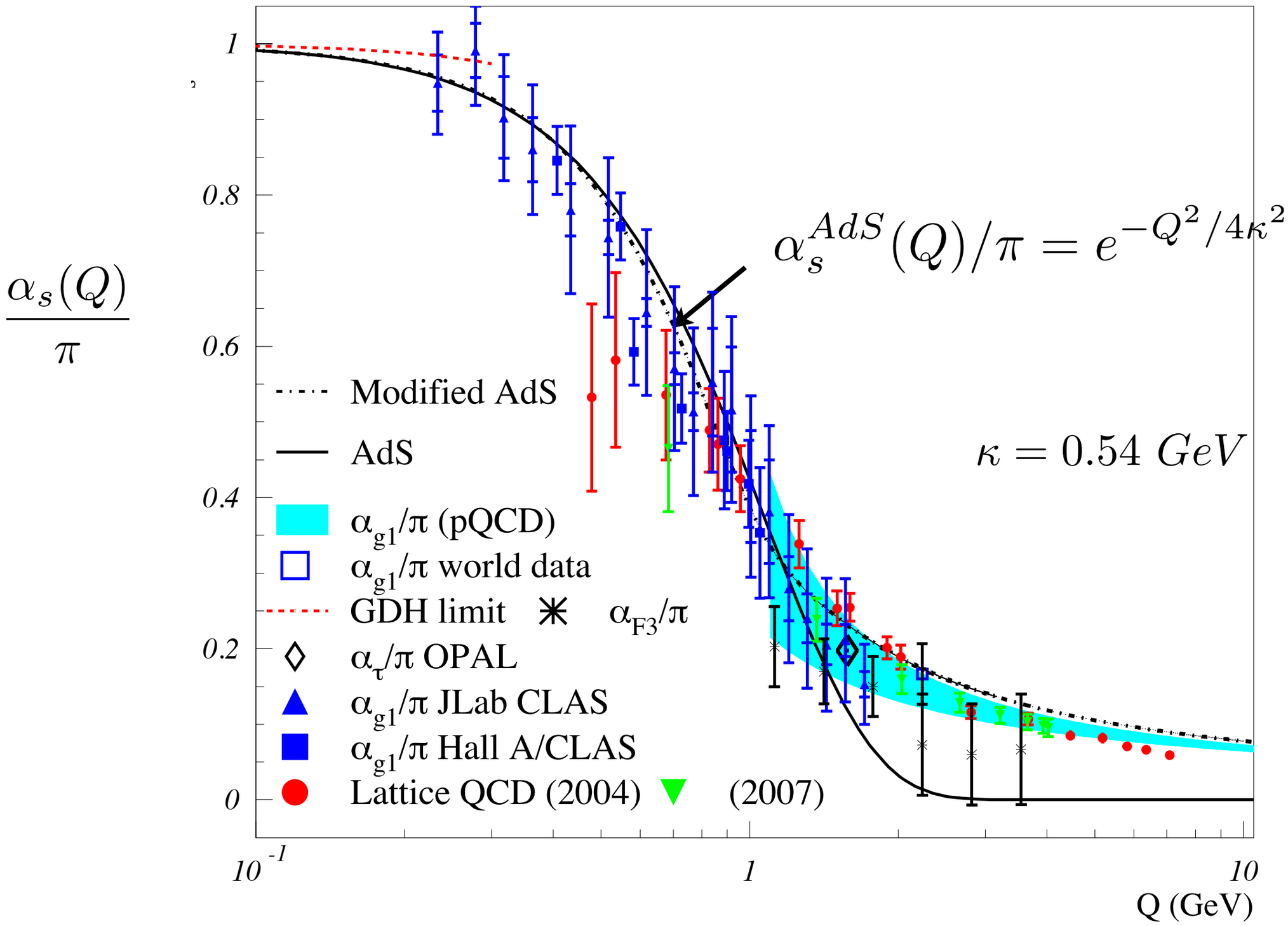


Analytic, defined at all scales, IR Fixed Point



AdS/QCD dilaton captures the higher twist corrections to effective charges for Q < 1 GeV

$$e^{\varphi} = e^{+\kappa^2 z^2}$$

Deur, de Teramond, sjb

Deur, de Tèramond, sjb

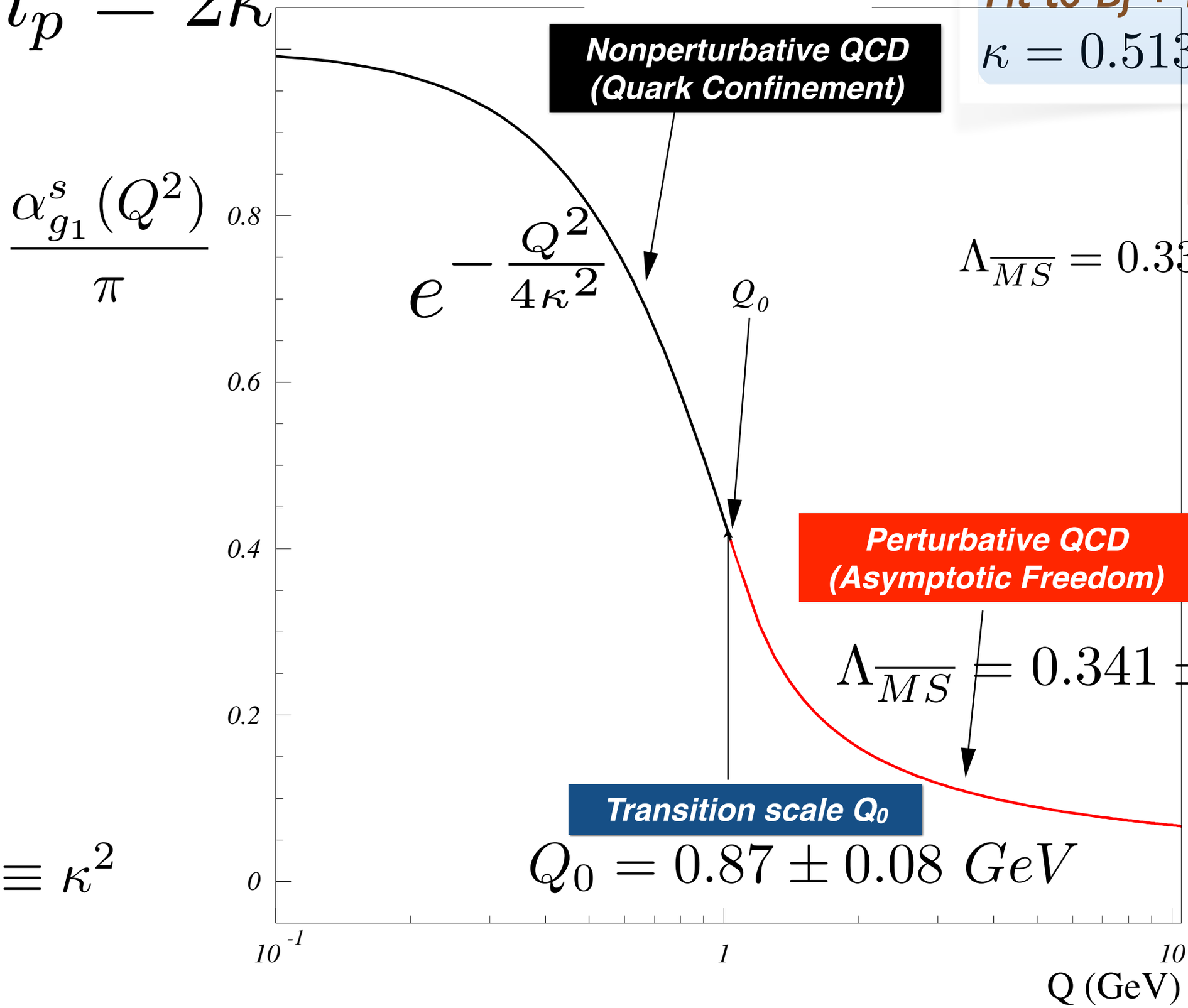
$$m_\rho = \sqrt{2}\kappa$$

$$m_p = 2\kappa$$

All-Scale QCD Coupling

Fit to Bj + DHG Sum Rules:

$$\kappa = 0.513 \pm 0.007\ GeV$$



Expt:

$$\Lambda_{\overline{MS}} = 0.339 \pm 0.016\ GeV$$

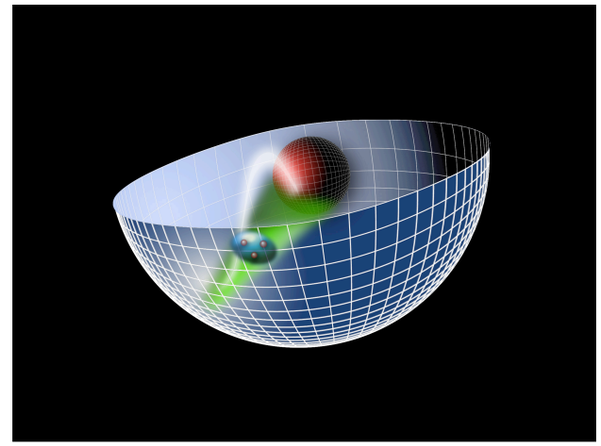
$$\lambda \equiv \kappa^2$$

$\overline{MS}$ scheme

de Tèramond, Dosch, sjb

AdS/QCD
Soft-Wall Model

Single scheme-independent fundamental mass scale
κ



Light-Front Holography

$$\zeta^2 = x(1-x)\mathbf{b}_\perp^2.$$

$$\left[-\frac{d^2}{d\zeta^2} + \frac{1-4L^2}{4\zeta^2} + U(\zeta)\right]\psi(\zeta) = \mathcal{M}^2\psi(\zeta)$$

Light-Front Schrödinger Equation

$$U(\zeta) = \kappa^4\zeta^2 + 2\kappa^2(L+S-1)$$

Unique Confinement Potential!

Conformal Symmetry of the action

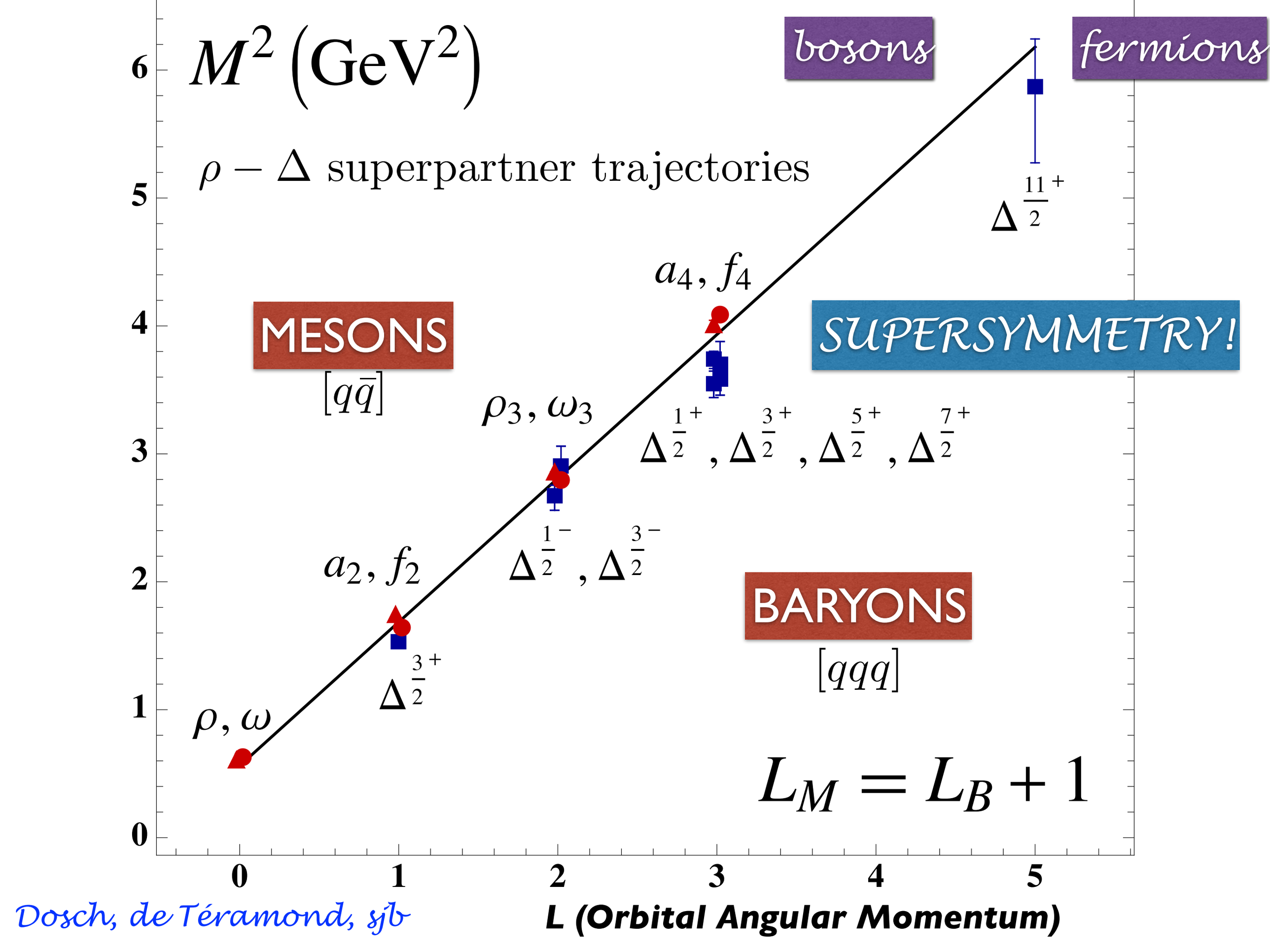
Confinement scale:
(m_q=0)

$$\kappa \simeq 0.6\ GeV$$

$$1/\kappa \simeq 1/3\ fm$$

- **de Alfaro, Fubini, Furlan:**

Scale can appear in Hamiltonian and EQM without affecting conformal invariance of action!

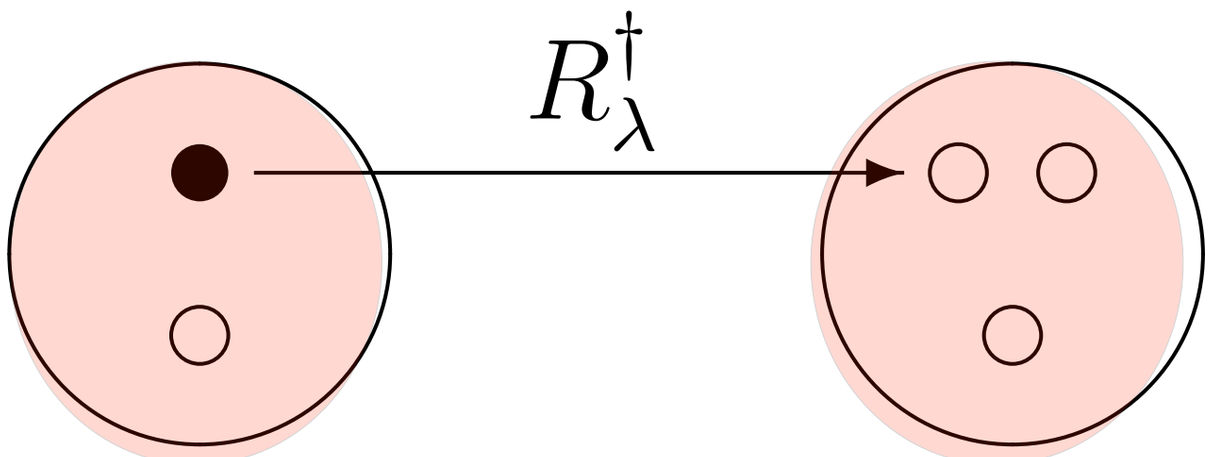


Dosch, de Téramond, sjb

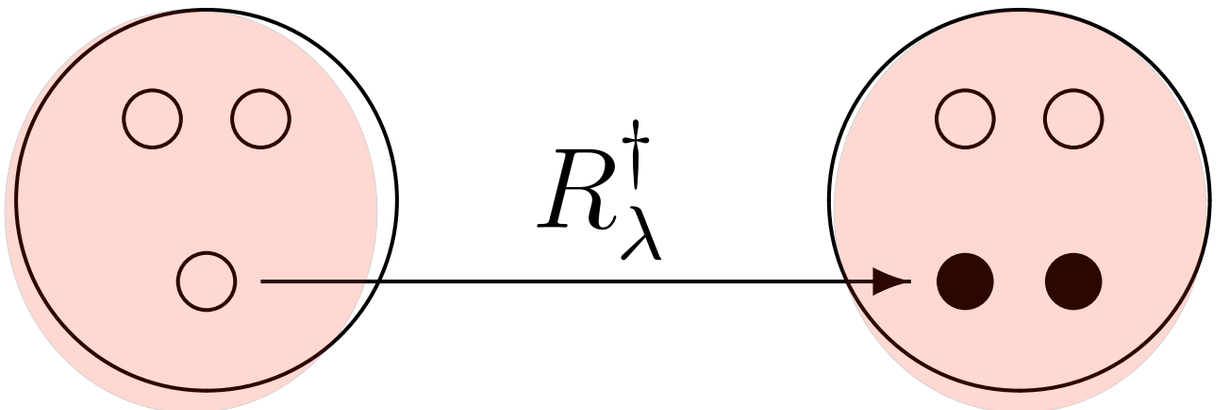
de Tèramond, Dosch, Lorce, sjb

Superconformal Algebra

2X2 Hadronic Multiplets



$\phi_M,\ L_B+1$ $\psi_{B+},\ L_B$



$\psi_{B-},\ L_B+1$ $\phi_T,\ L_B$

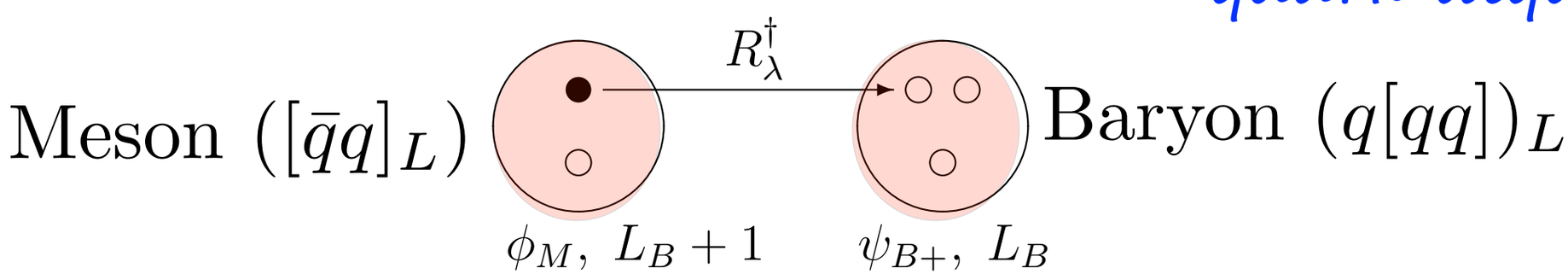
Meson | Baryon (two components) | Tetraquark

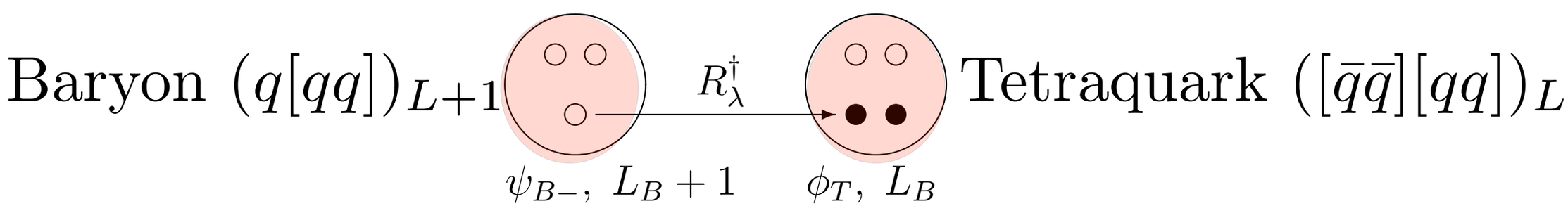
Superconformal algebra

2 X 2 Matrix Representations: Mass-Degenerate Hadronic Eigensolutions

$$\begin{pmatrix} \phi_M(L_M = L_B + 1) & \psi_{B-}(L_B + 1) \\ \psi_{B+}(L_B) & \phi_T(L_T = L_B) \end{pmatrix}$$

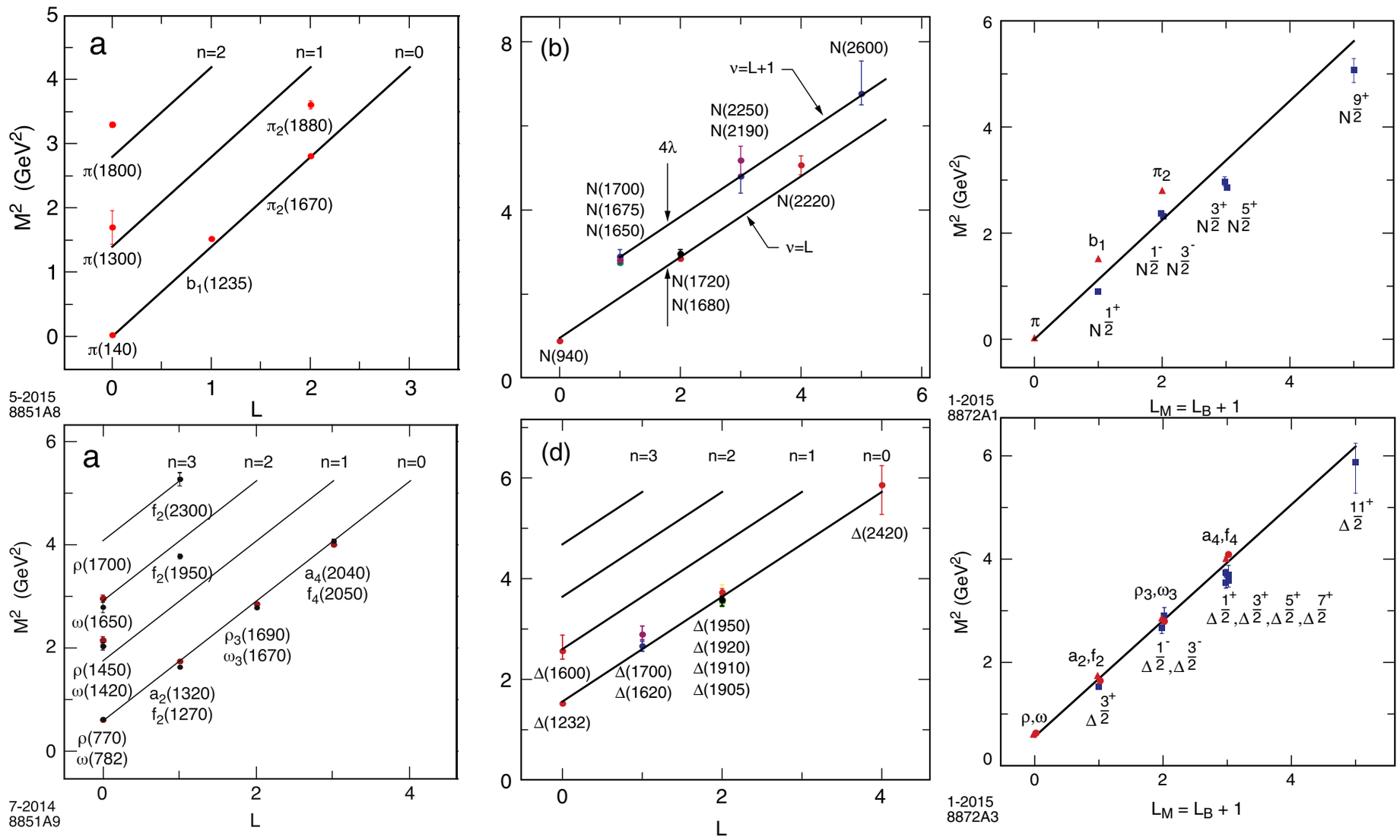
quark-diquark baryons





diquark-diquark tetraquarks

Hadron Spectrum in LF Holography



S.J. Brodsky, G.F. de Téramond, H.G. Dosch, J. Erlich, Phys. Rep. 584, 1 (2015);
H.G. Dosch, G.F. de Téramond, S.J. Brodsky, Phys. Rev. D 91, 045040 (2015); D91, 085016 (2015).

Meson			Baryon			Tetraquark		
q-cont	$J^{P(C)}$	Name	q-cont	J^P	Name	q-cont	$J^{P(C)}$	Name
$\bar{q}q$	0^{-+}	$\pi(140)$	—	—	—	—	—	—
$\bar{q}q$	1^{+-}	$b_1(1235)$	$[ud]q$	$(1/2)^+$	$N(940)$	$[ud][\bar{u}\bar{d}]$	0^{++}	$f_0(980)$
$\bar{q}q$	2^{-+}	$\pi_2(1670)$	$[ud]q$	$(1/2)^-$	$N_{\frac{1}{2}^-}(1535)$	$[ud][\bar{u}\bar{d}]$	1^{-+}	$\pi_1(1400)$
				$(3/2)^-$	$N_{\frac{3}{2}^-}(1520)$			$\pi_1(1600)$
$\bar{q}q$	1^{--}	$\rho(770)$, $\omega(780)$	—	—	—	—	—	—
$\bar{q}q$	2^{++}	$a_2(1320)$, $f_2(1270)$	$[qq]q$	$(3/2)^+$	$\Delta(1232)$	$[qq][\bar{u}\bar{d}]$	1^{++}	$a_1(1260)$
$\bar{q}q$	3^{--}	$\rho_3(1690)$, $\omega_3(1670)$	$[qq]q$	$(1/2)^-$	$\Delta_{\frac{1}{2}^-}(1620)$	$[qq][\bar{u}\bar{d}]$	2^{--}	$\rho_2(\sim 1700)$?
				$(3/2)^-$	$\Delta_{\frac{3}{2}^-}(1700)$			
$\bar{q}q$	4^{++}	$a_4(2040)$, $f_4(2050)$	$[qq]q$	$(7/2)^+$	$\Delta_{\frac{7}{2}^+}(1950)$	$[qq][\bar{u}\bar{d}]$	3^{++}	$a_3(\sim 2070)$?
$\bar{q}s$	$0^{-(+)}$	$\bar{K}(495)$	—	—	—	—	—	—
$\bar{q}s$	$1^{+(-)}$	$\bar{K}_1(1270)$	$[ud]s$	$(1/2)^+$	$\Lambda(1115)$	$[ud][\bar{s}\bar{q}]$	$0^{+(+)}$	$K_0^*(1430)$
$\bar{q}s$	$2^{-(+)}$	$K_2(1770)$	$[ud]s$	$(1/2)^-$	$\Lambda(1405)$	$[ud][\bar{s}\bar{q}]$	$1^{-(+)}$	$K_1^*(\sim 1700)$?
				$(3/2)^-$	$\Lambda(1520)$			
$\bar{s}q$	$0^{-(+)}$	$K(495)$	—	—	—	—	—	—
$\bar{s}q$	$1^{+(-)}$	$K_1(1270)$	$[sq]q$	$(1/2)^+$	$\Sigma(1190)$	$[sq][\bar{s}\bar{q}]$	0^{++}	$a_0(980)$
								$f_0(980)$
$\bar{s}q$	$1^{-(-)}$	$K^*(890)$	—	—	—	—	—	—
$\bar{s}q$	$2^{+(+)}$	$K_2^*(1430)$	$[sq]q$	$(3/2)^+$	$\Sigma(1385)$	$[sq][\bar{q}\bar{q}]$	$1^{+(+)}$	$K_1(1400)$
$\bar{s}q$	$3^{-(-)}$	$K_3^*(1780)$	$[sq]q$	$(3/2)^-$	$\Sigma(1670)$	$[sq][\bar{q}\bar{q}]$	$2^{-(-)}$	$K_2(\sim 1700)$?
$\bar{s}q$	$4^{+(+)}$	$K_4^*(2045)$	$[sq]q$	$(7/2)^+$	$\Sigma(2030)$	$[sq][\bar{q}\bar{q}]$	$3^{+(+)}$	$K_3(\sim 2070)$?
$\bar{s}s$	0^{-+}	$\eta(550)$	—	—	—	—	—	—
$\bar{s}s$	1^{+-}	$h_1(1170)$	$[sq]s$	$(1/2)^+$	$\Xi(1320)$	$[sq][\bar{s}\bar{q}]$	0^{++}	$f_0(1370)$
								$a_0(1450)$
$\bar{s}s$	2^{-+}	$\eta_2(1645)$	$[sq]s$	$(?)^?$	$\Xi(1690)$	$[sq][\bar{s}\bar{q}]$	1^{-+}	$\Phi'(1750)$?
$\bar{s}s$	1^{--}	$\Phi(1020)$	—	—	—	—	—	—
$\bar{s}s$	2^{++}	$f_2'(1525)$	$[sq]s$	$(3/2)^+$	$\Xi^*(1530)$	$[sq][\bar{s}\bar{q}]$	1^{++}	$f_1(1420)$
$\bar{s}s$	3^{--}	$\Phi_3(1850)$	$[sq]s$	$(3/2)^-$	$\Xi(1820)$	$[sq][\bar{s}\bar{q}]$	2^{--}	$\Phi_2(\sim 1800)$?
$\bar{s}s$	2^{++}	$f_2(1950)$	$[ss]s$	$(3/2)^+$	$\Omega(1672)$	$[ss][\bar{s}\bar{q}]$	$1^{+(+)}$	$K_1(\sim 1700)$?

Meson Baryon Tetraquark

New Organization of the Hadron Spectrum

M. Nielsen

Some Features of AdS/QCD

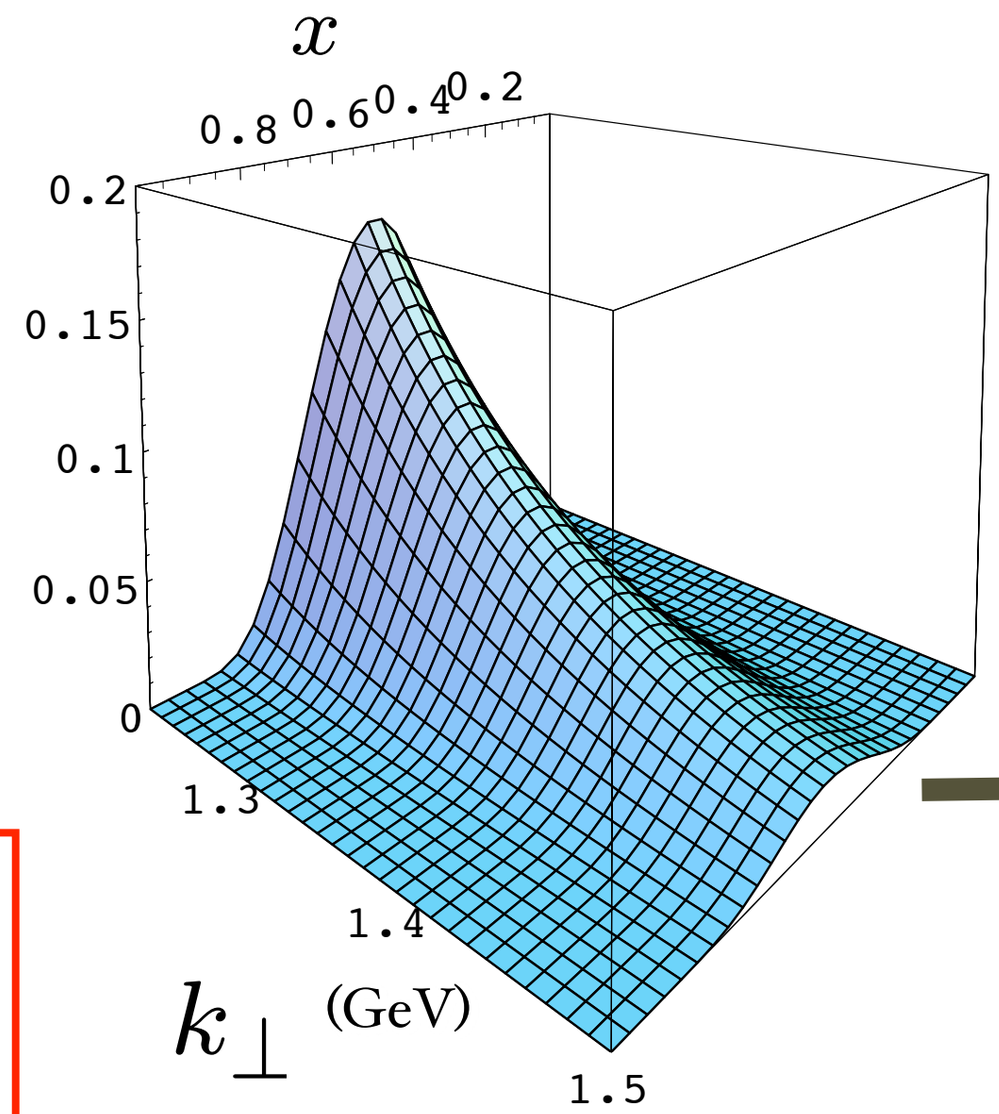
- ***Regge spectroscopy—same slope in n,L for mesons, baryons***
- ***Chiral features for m_q=0: m_π=0, chiral-invariant proton***
- ***Hadronic LFWFs***
- ***Counting Rules***
- ***Connection between hadron masses and*** $\Lambda_{\overline{MS}}$

Superconformal AdS Light-Front Holographic QCD (LFHQCD)

Meson-Baryon Mass Degeneracy for L_M=L_B+1

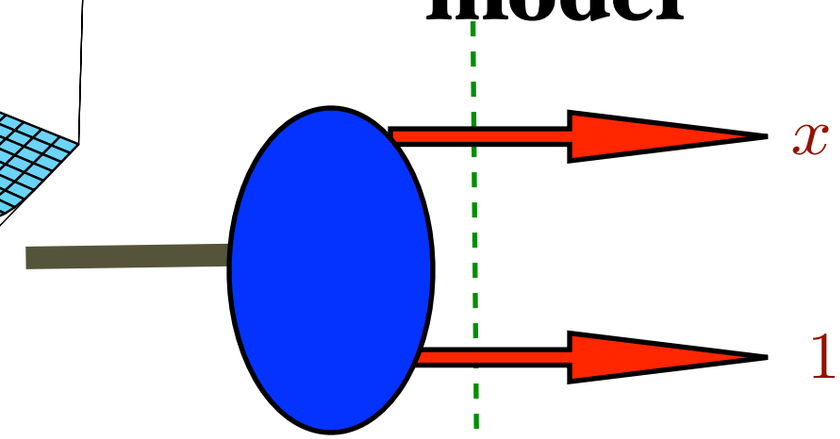
Prediction from AdS/QCD: Meson LFWF

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



de Teramond, Cao, sjb

"Soft Wall" model



massless quarks

Note coupling

$k_\perp^2, x$

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

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

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

Provides Connection of Confinement to Hadron Structure

J/ψ

LFWF peaks at

$$x_i = \frac{m_{\perp i}}{\sum_j^n m_{\perp j}}$$

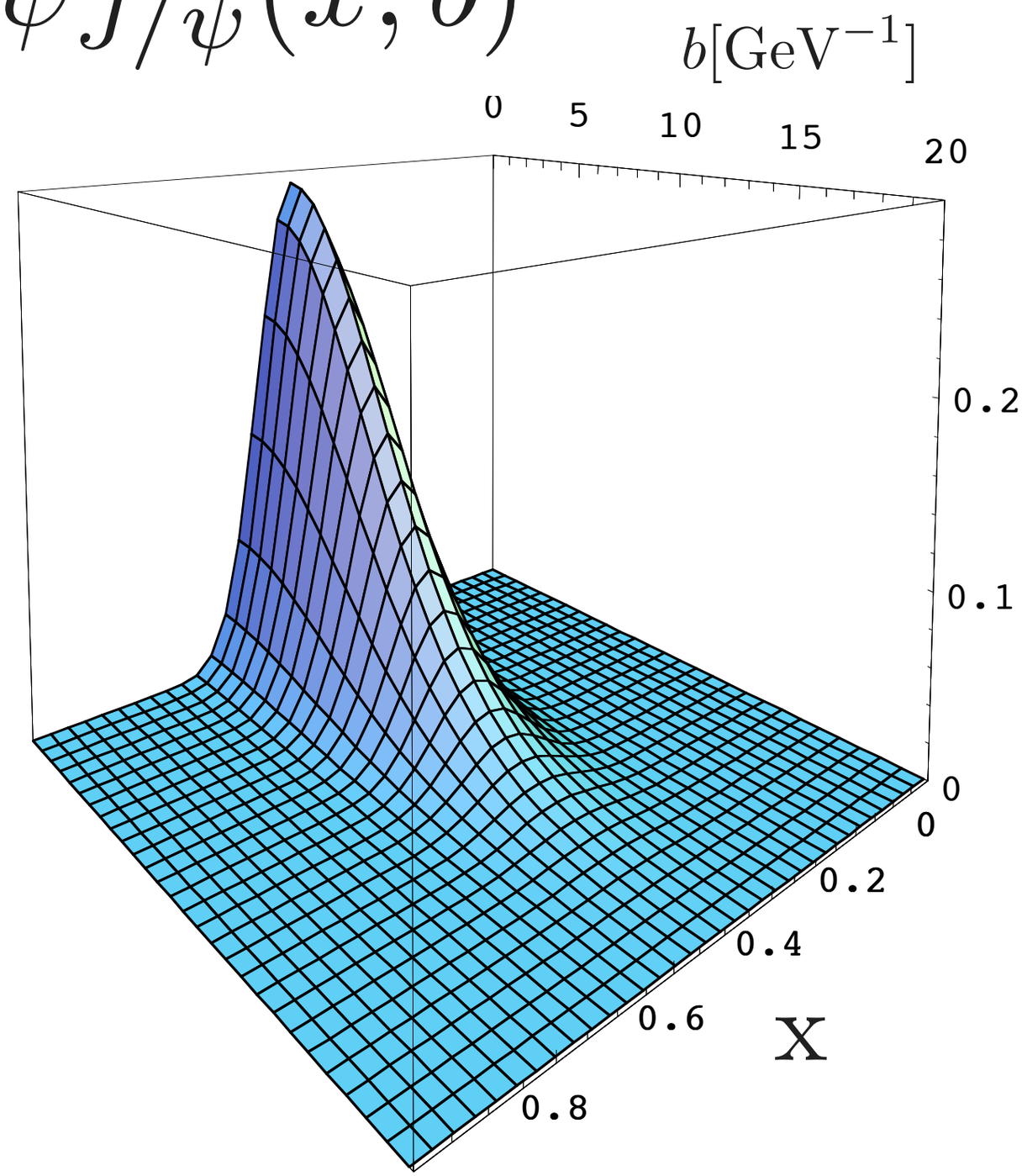
where

$$m_{\perp i} = \sqrt{m^2 + k_\perp^2}$$

minimum of LF energy denominator

$$\kappa = 0.375 \text{ GeV}$$

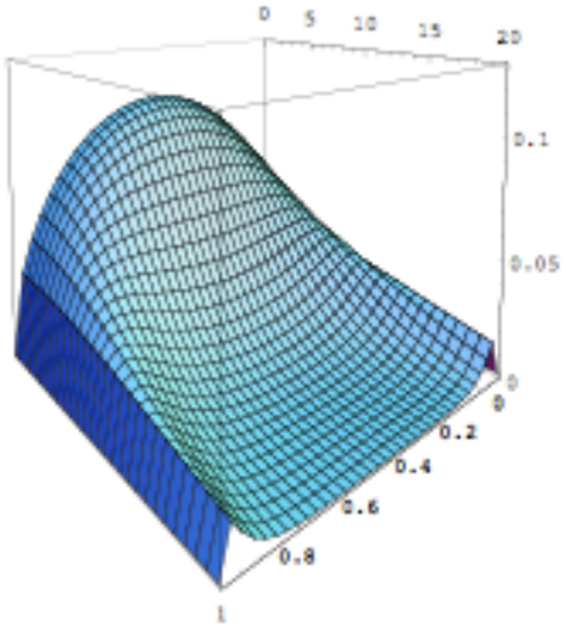
$$\psi_{J/\psi}(x, b)$$

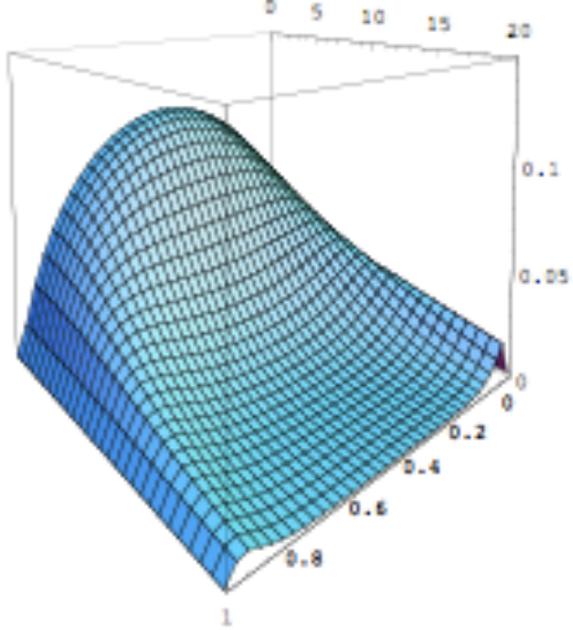


$$m_a = m_b = 1.25 \text{ GeV}$$

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

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



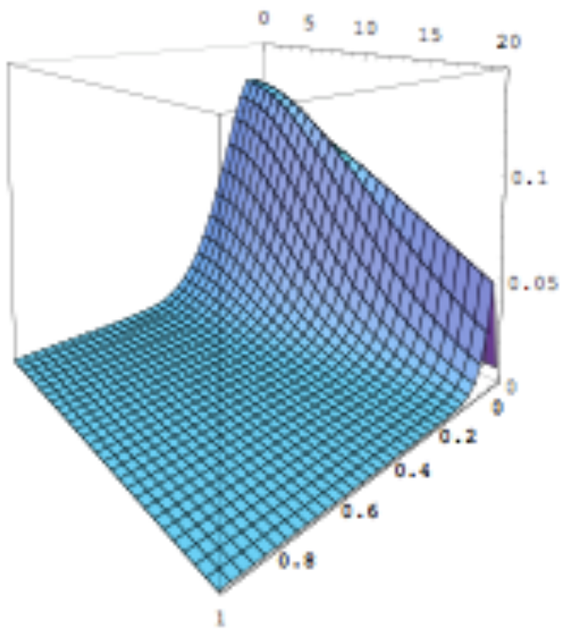


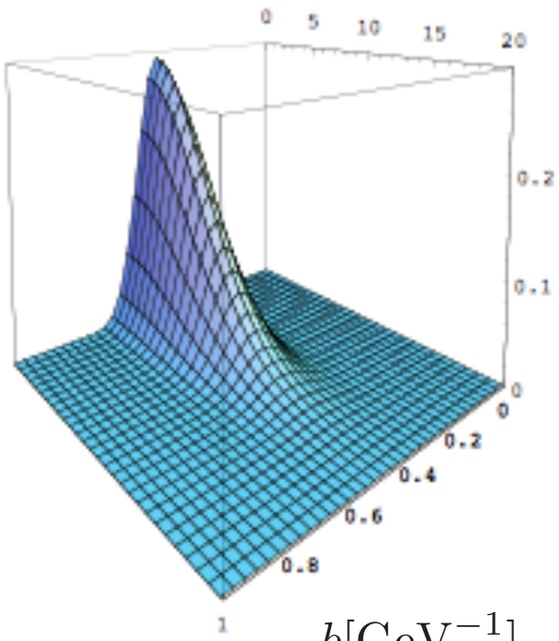
$|K^+ >= |u\bar{s} >$

$m_s = 95\ MeV$

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

$m_c = 1.25\ GeV$



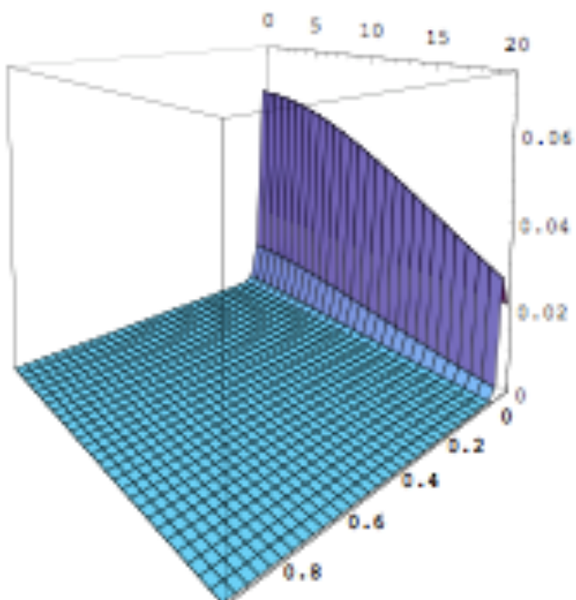


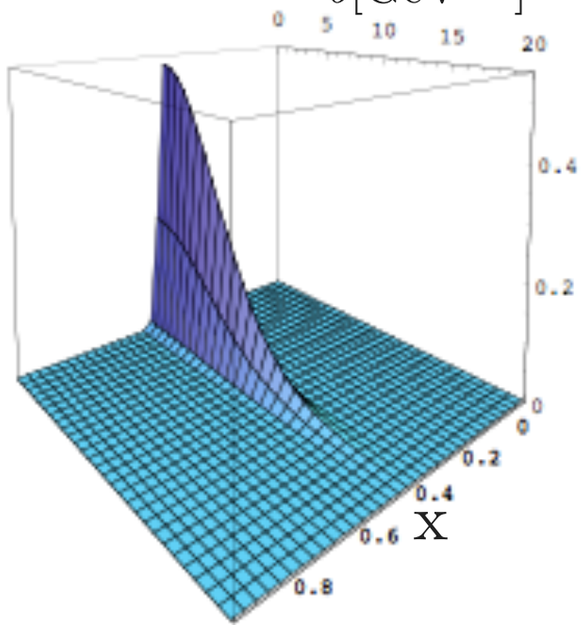
$|\eta_c >= |c\bar{c} >$

$b[\mathrm{GeV}^{-1}]$

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

$m_b = 4.2\ GeV$





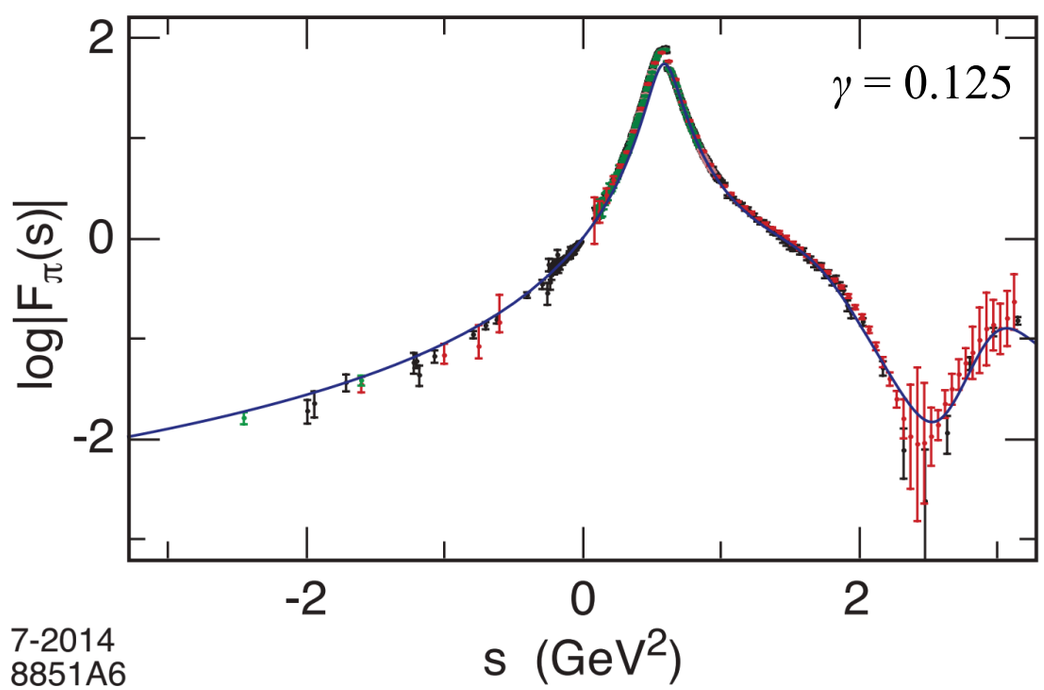
X

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

$\kappa = 375\ MeV$

Pion Form Factor

Pion form factor compared with data

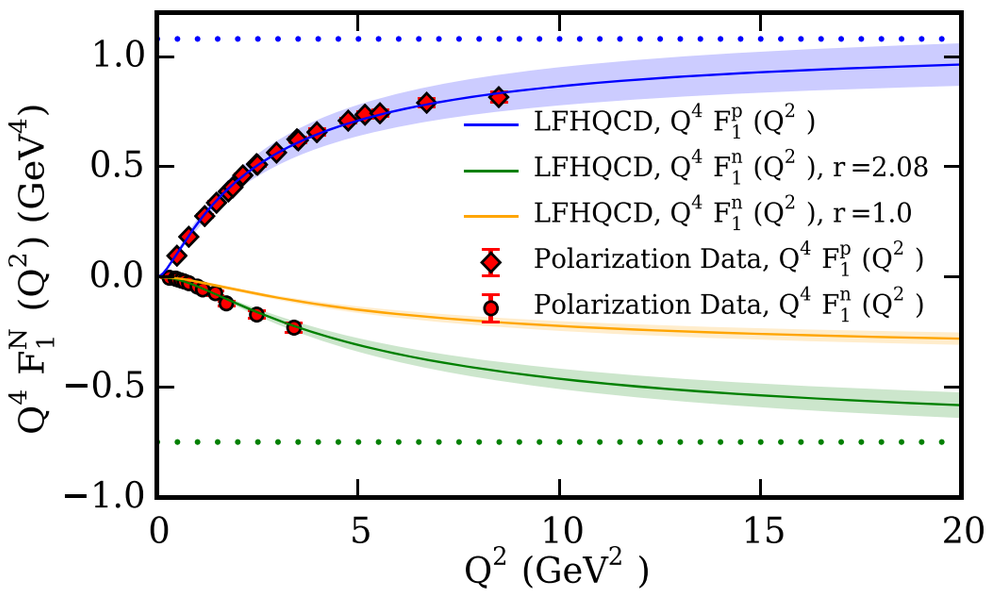


$$F_\pi(t) = \sum_\tau P_\tau F_\tau(t) \qquad \sum_\tau P_\tau = 1$$

Truncated at twist-τ = 4

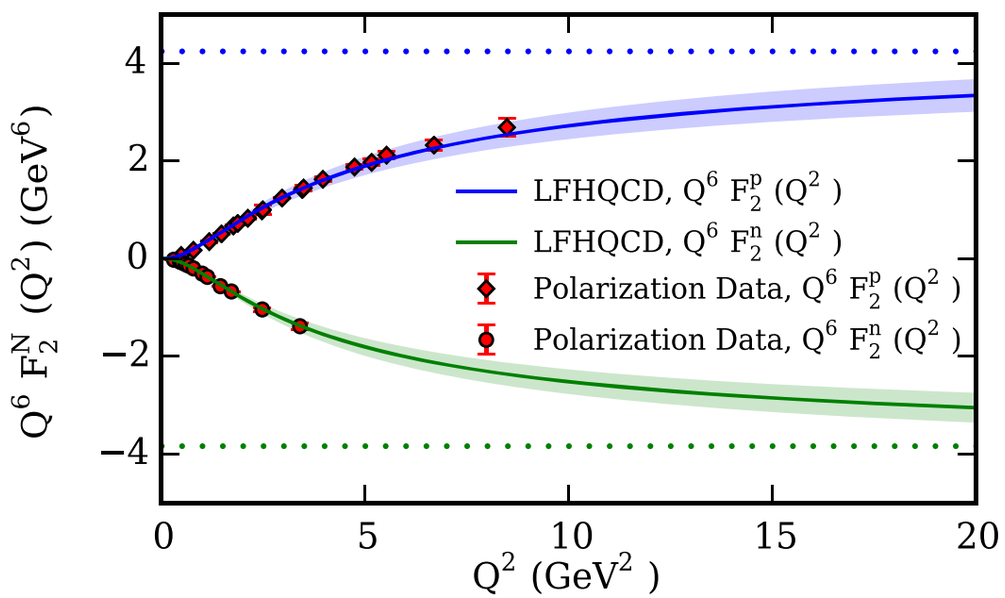
$$F_\pi(q^2) = (1-\gamma)F_{\tau=2}(q^2) + \gamma F_{\tau=4}(q^2)$$

G.F. de Téramond and S.J. Brodsky, Proc. Sci. LC2010 (2010) 029.
S.J. Brodsky, G.F. de Téramond, H.G. Dosch, J. Erlich, Phys. Rep. 584, 1 (2015). [Sec. 6.1.5]



$$F_1^p(Q^2) = F_{\tau=3}(Q^2)$$

$$F_1^n(Q^2) = -\frac{r}{3}[F_{\tau=3}(Q^2) - F_{\tau=4}(Q^2)]$$



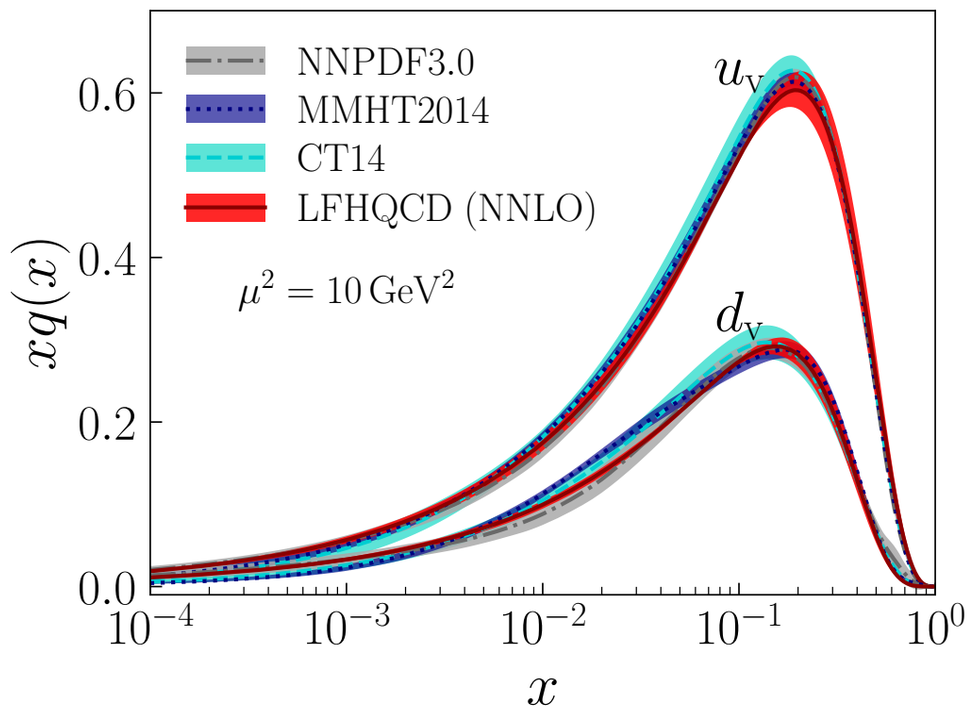
$$F_2^p(Q^2) = \chi_p[(1-\gamma_p)F_{\tau=4}(Q^2) + \gamma_p F_{\tau=6}(Q^2)]$$

$$F_2^n(Q^2) = \chi_n[(1-\gamma_n)F_{\tau=4}(Q^2) + \gamma_n F_{\tau=6}(Q^2)]$$

$$\gamma_p = 0.27 \qquad \gamma_n = 0.38$$

R.S. Sufian, G.F. de Téramond, S.J. Brodsky, A. Deur, H.G. Dosch, Phys. Rev. D 95 014011 (2017).

Nucleon PDFs in comparison with global fits



$$f(x) = \frac{1}{4\lambda}\left[(1-x)\log\left(\frac{1}{x}\right) + a(1-x)^2\right]$$

$$w(x) = x^{1-x}e^{-a(1-x)^2}$$

Parameter "a" is fixed by the first moment
$a = 0.531 \pm 0.037$

Evolved from the matching scale 1.06 ± 0.15 GeV

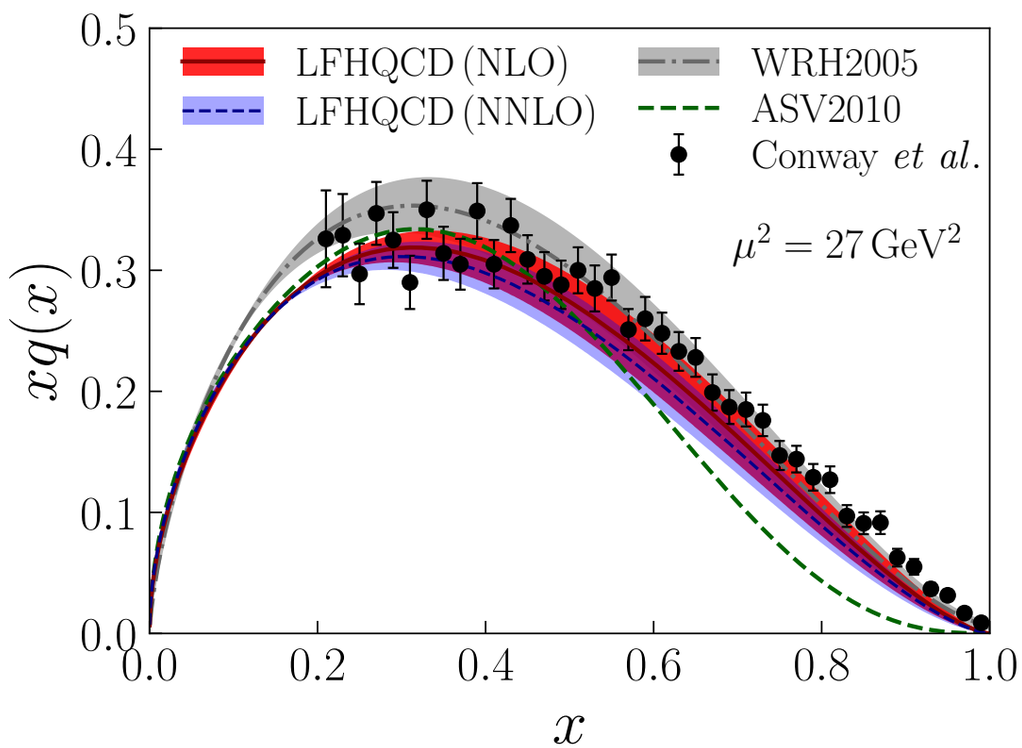
Red bands: the uncertainties of the matching scale and the parameter "a".

G.F. de Téramond, TL, R.S. Sufian, H.G. Dosch, S.J. Brodsky, A. Deur, Phys. Rev. Lett. 120, 182001 (2018).

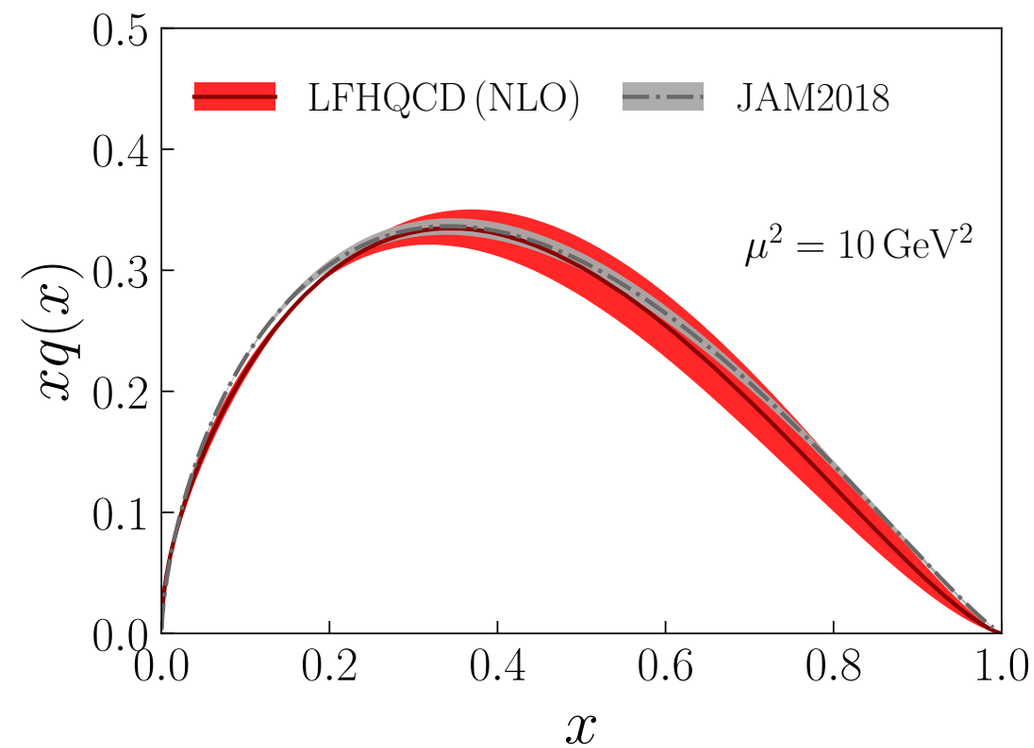
Pion PDF

Prediction for pion PDF with the same $w(x)$

$$w(x) = x^{1-x} e^{-a(1-x)^2}$$



Evolved from the matching scale
1.1 ± 0.2 GeV (NLO)



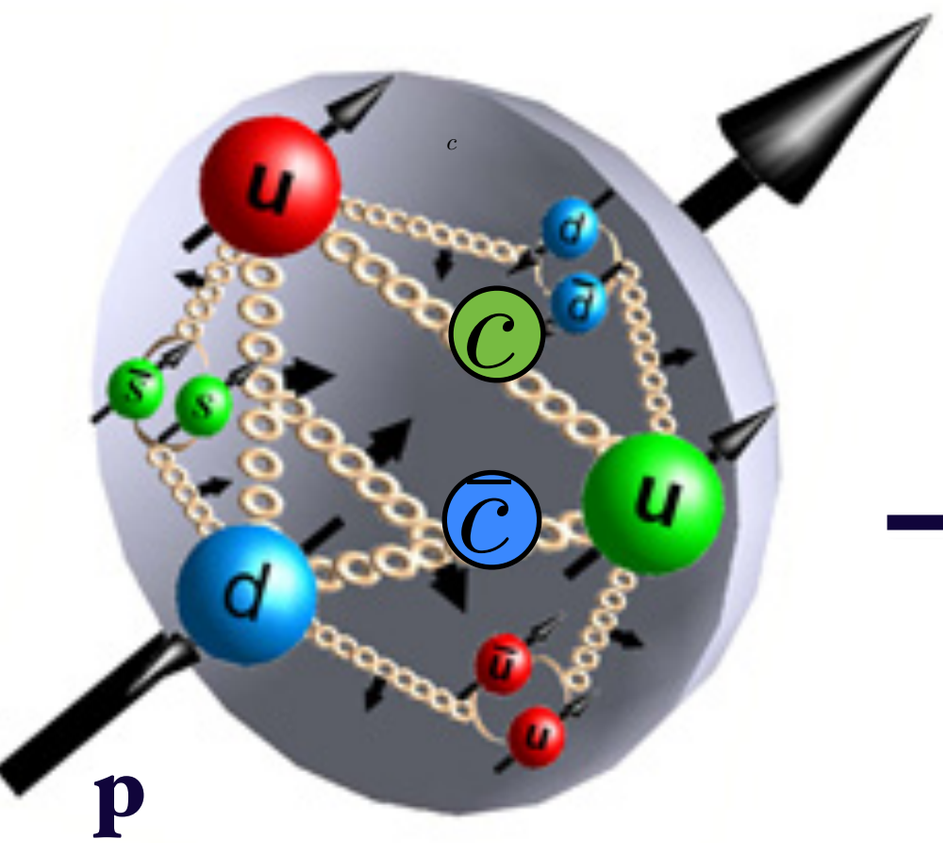
Comparison with a new global fit
by JAM [arXiv:1804.01965]

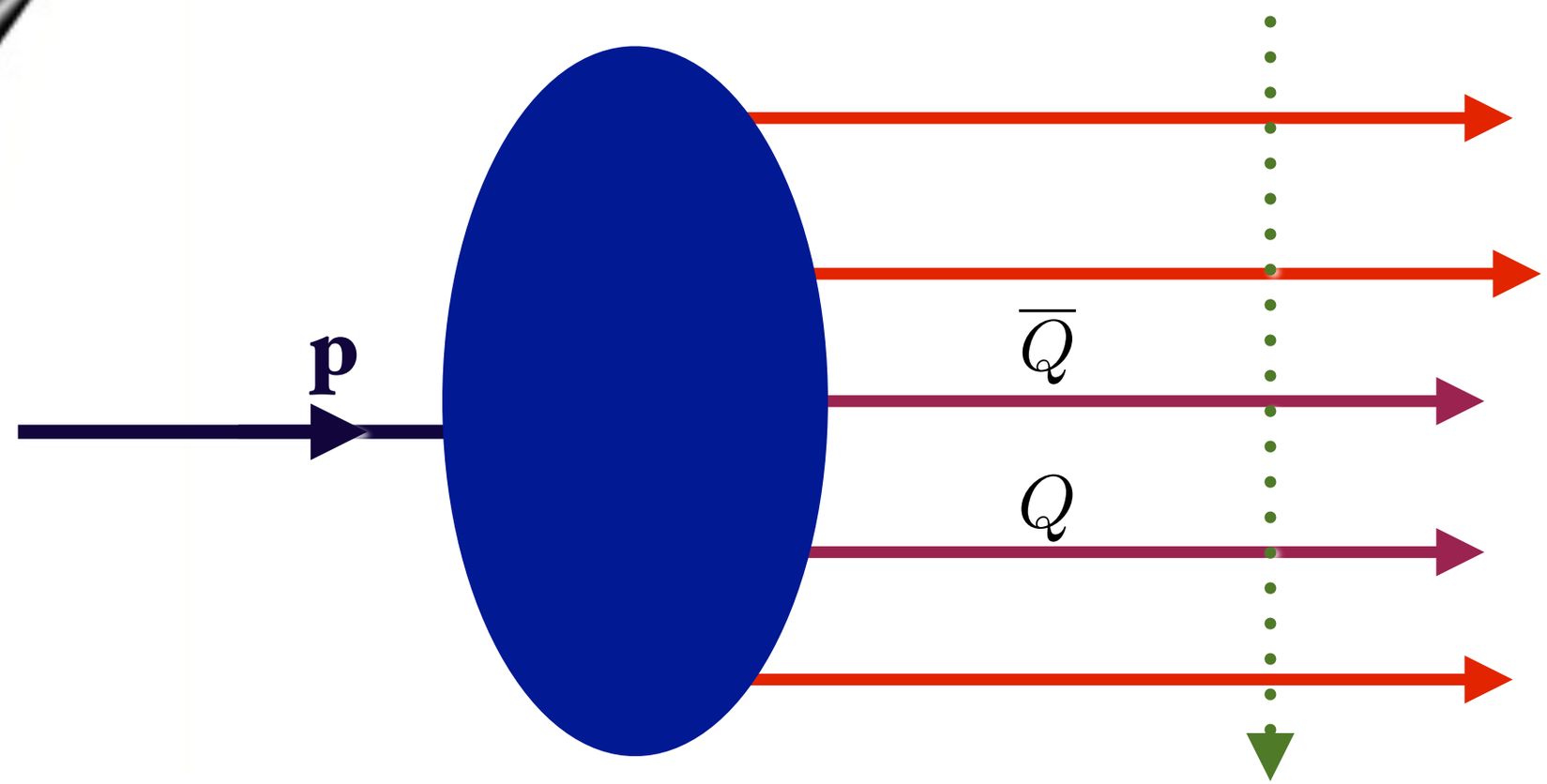
Universal gluon, extrinsic sea distibutions

Color confinement potential from AdS/QCD

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

Fixed $\tau = t + z/c$





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

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

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

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

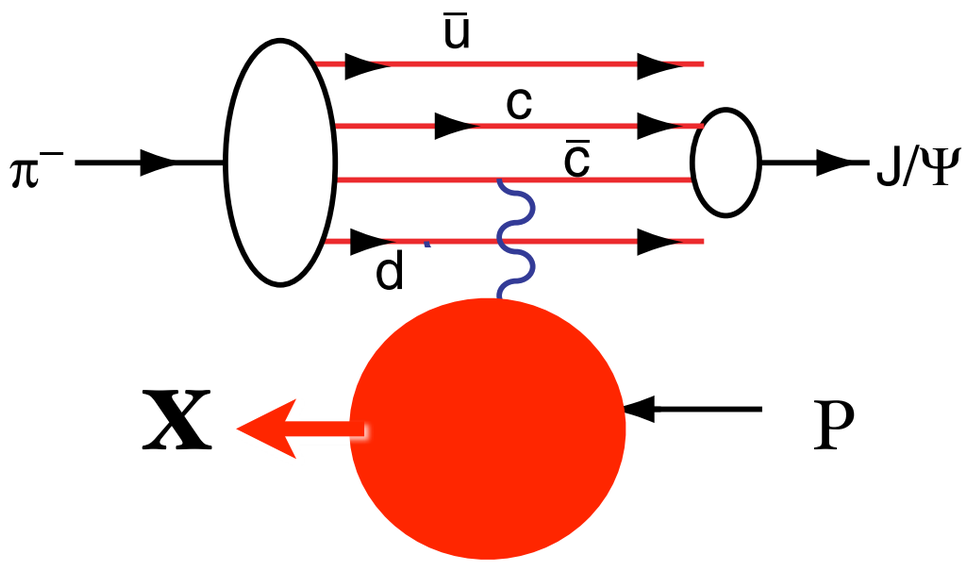
$$y = \frac{1}{2} \log \frac{k^+}{k^-} = \log \frac{xP^+}{m_\perp}$$

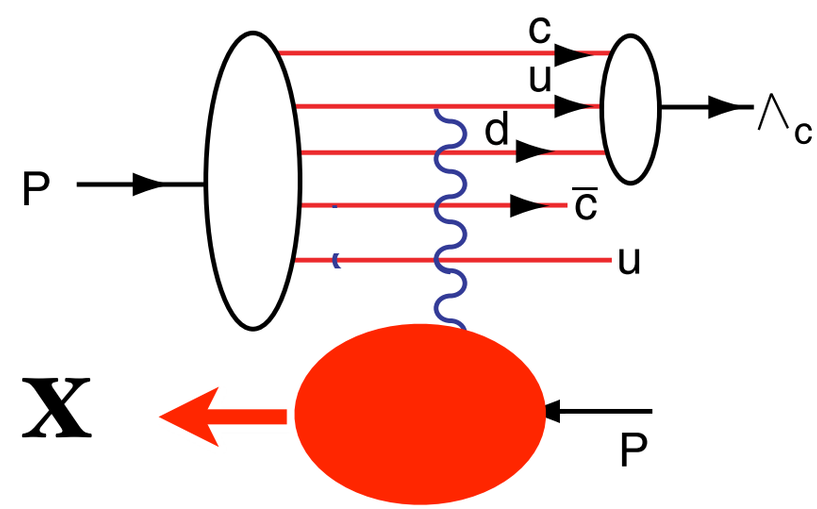
Frame independent $$\Delta y = y_a - y_b = \log \frac{x_a}{m_{\perp a}} - \log \frac{x_b}{m_{\perp b}}$$

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

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

Coalesece of comovers produces high x_F heavy hadrons





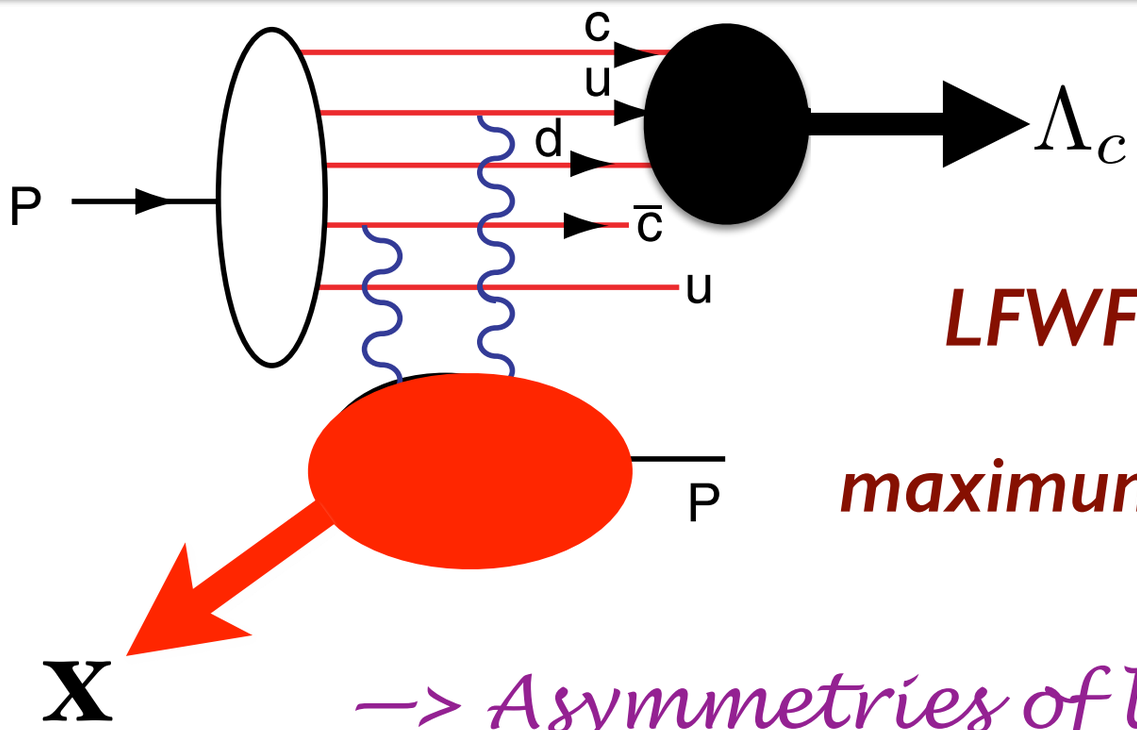
Spectator counting rules

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

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

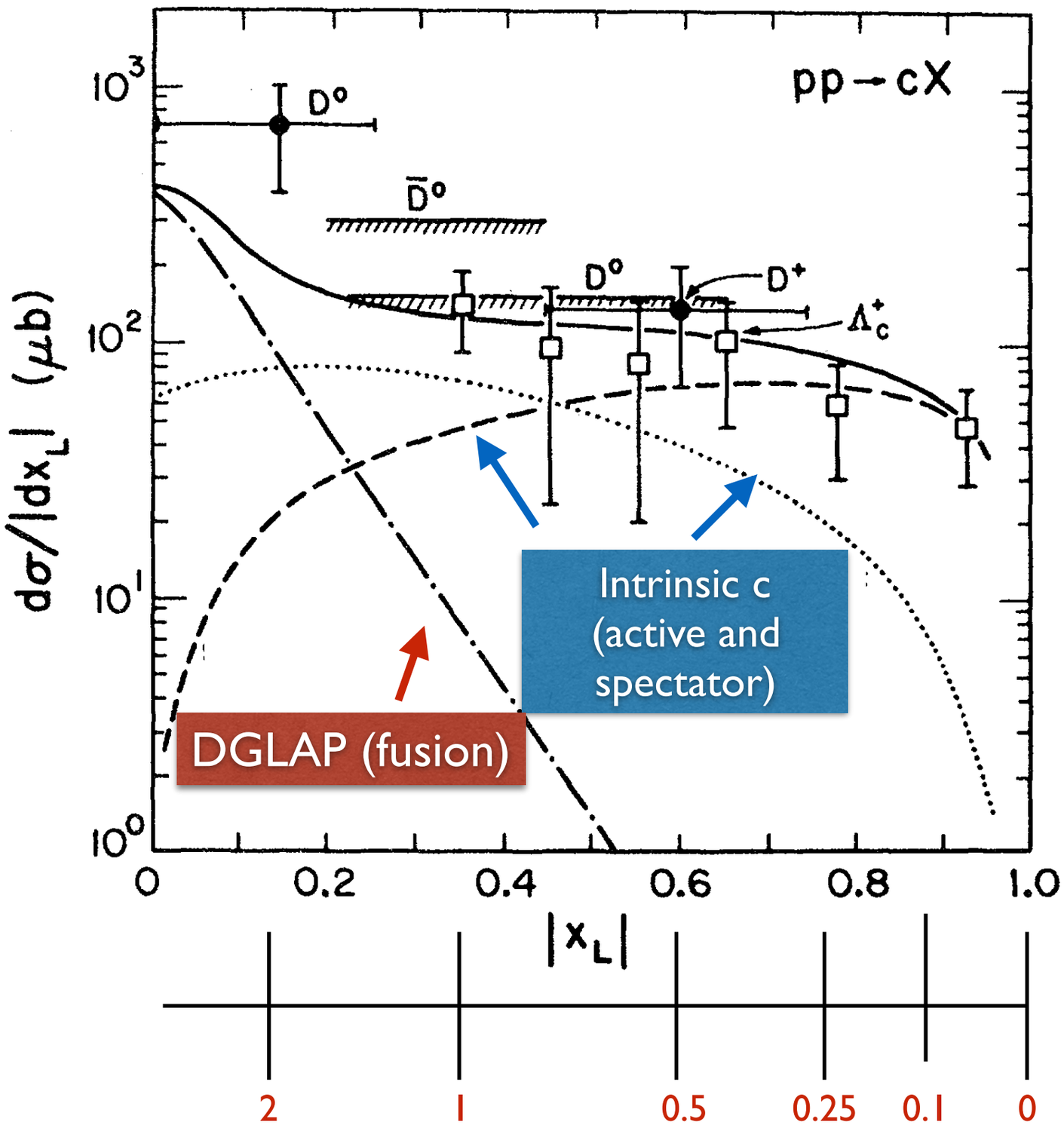
$$\frac{dN}{dx_F} \propto (1 - x_F)^{2n_{spect}-1}$$

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

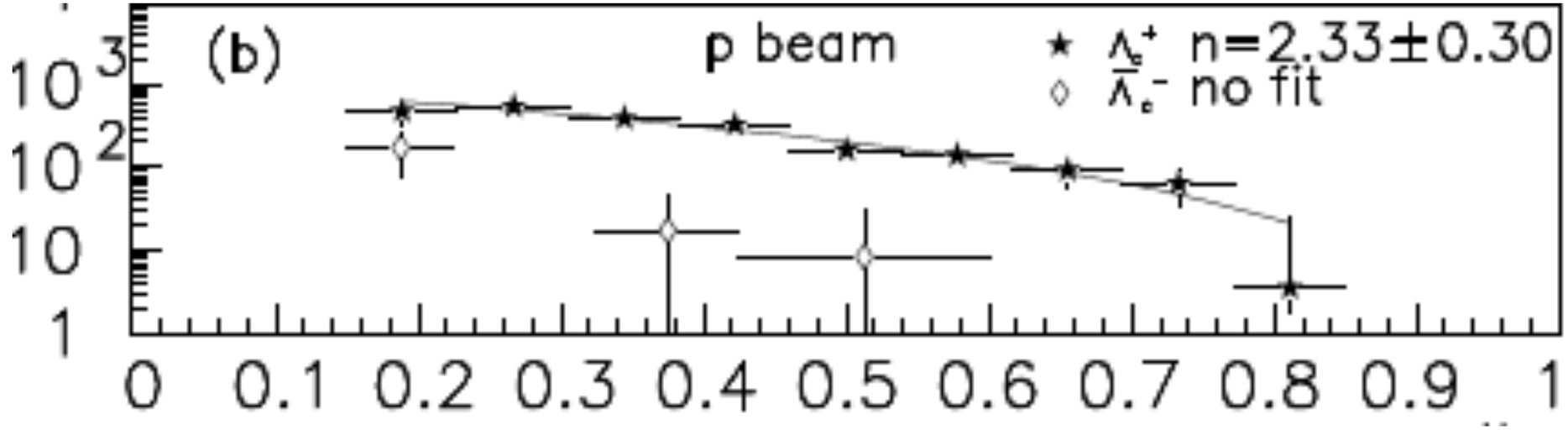
Vogt, sjb

Barger, Halzen, Keung

PRD 25 (1981)



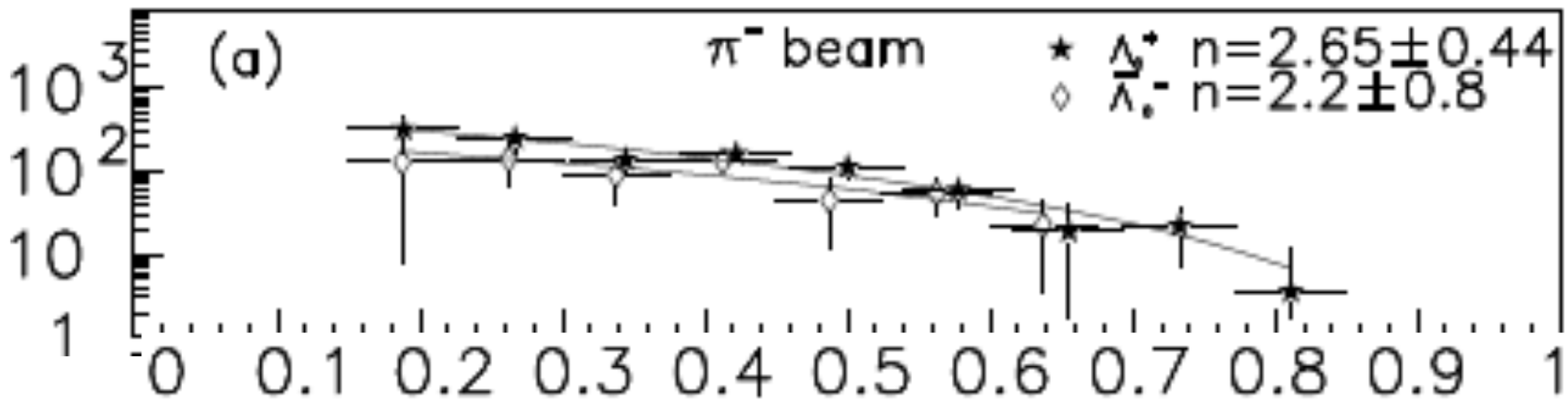
$\Delta y = \log x$



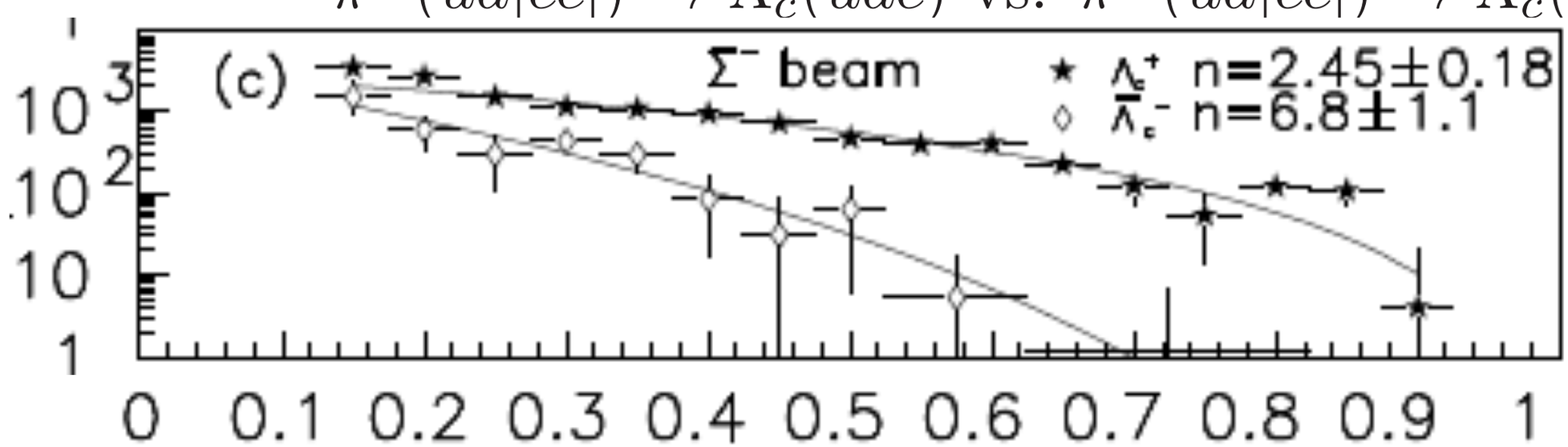
Large xF production rate close to the maximum allowed by phase space!

SELEX

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

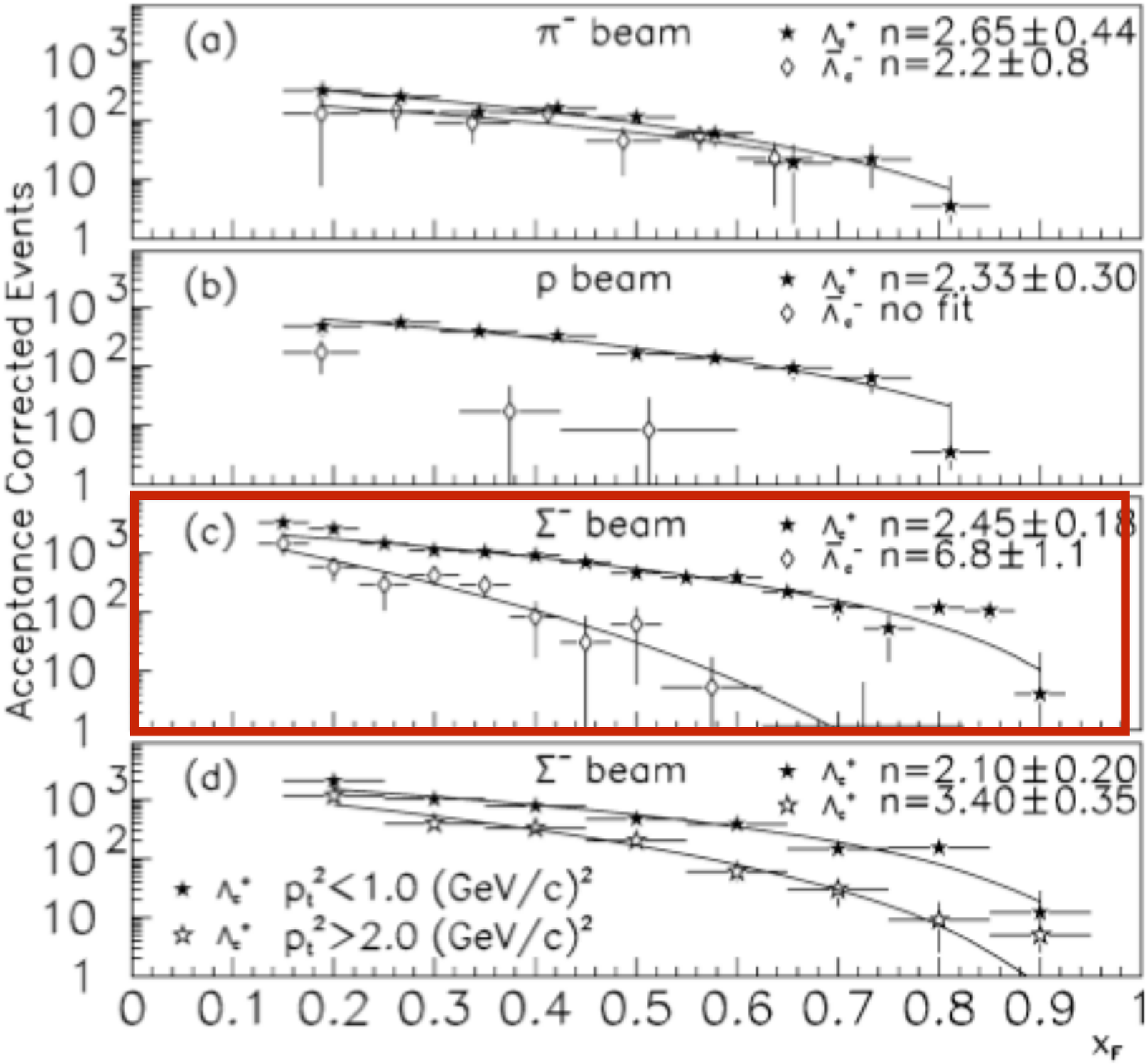


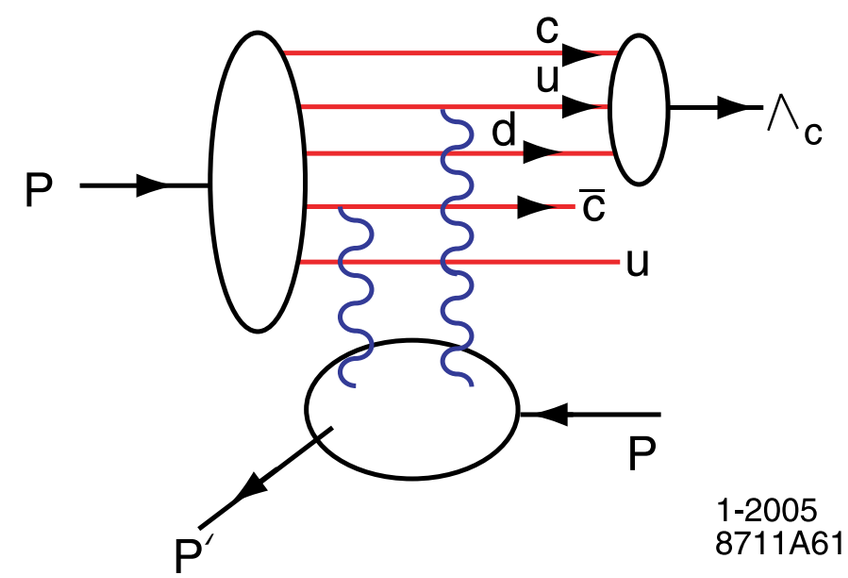
$\pi^-(\bar{u}d[c\bar{c}]) \to \Lambda_c(udc)$ vs. $\pi^-(\bar{u}d[c\bar{c}]) \to \bar{\Lambda}_c(\bar{u}\bar{d}\bar{c})$



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

SELEX





$$p(uudc\bar{c}) \rightarrow \Lambda_c(cud)$$

$$n_s = 2$$

$$(1 - x_F)^{n_{spectators}}$$

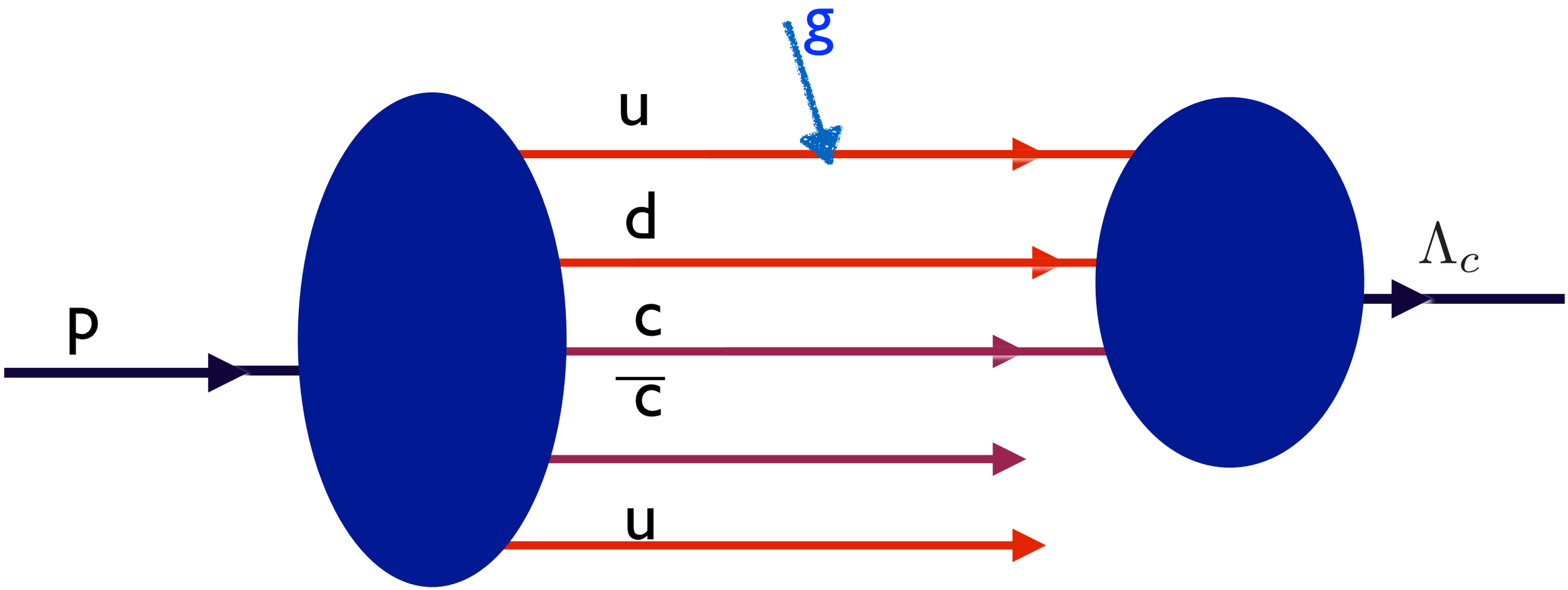
Phase space gives minimum power fall-off

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

$$pp \to \Lambda_c X$$

$$\Delta y = y_p - y_{\Lambda_c} < 2$$

$$x_{\Lambda_c} = x_c + x_u + x_d$$

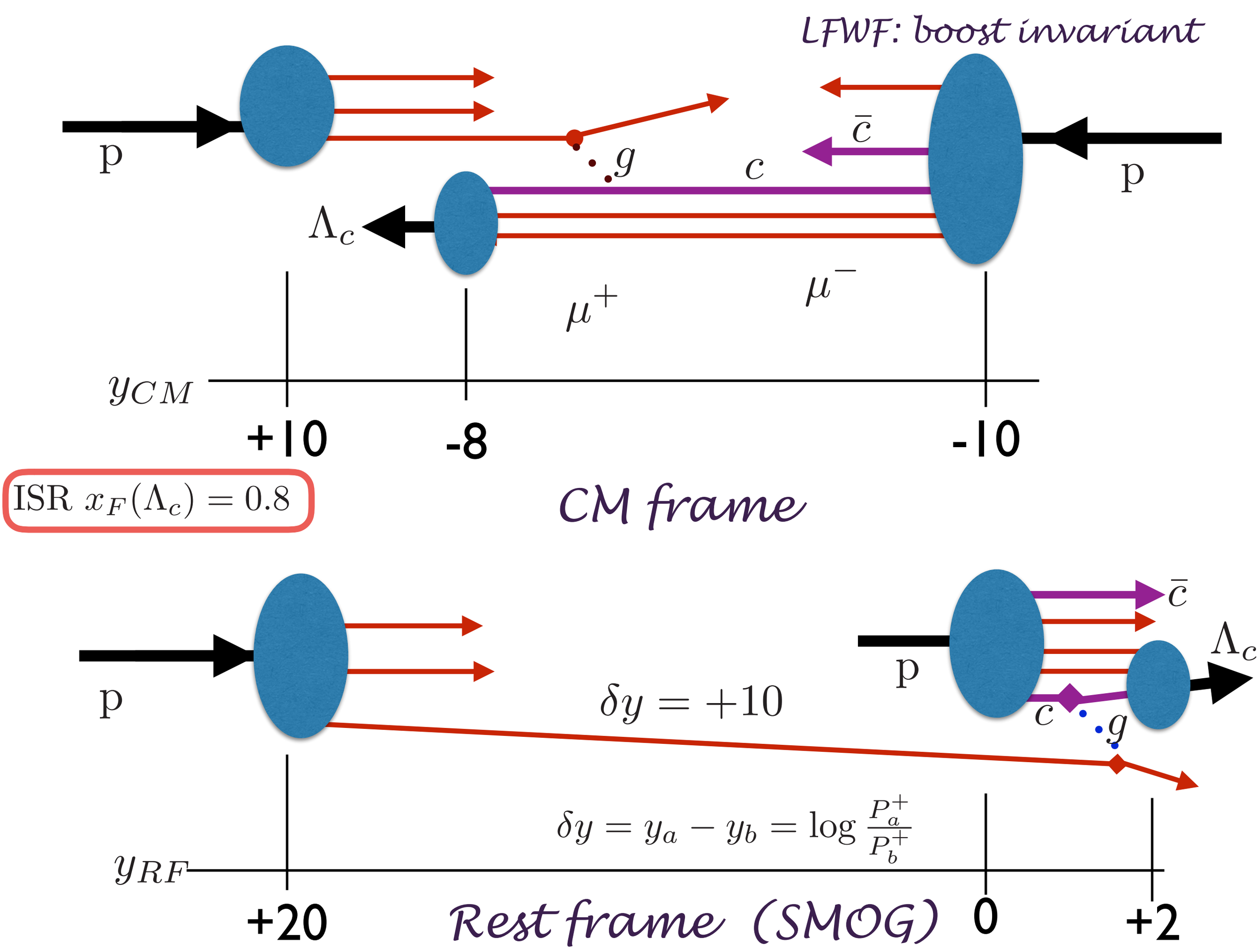


Coalescence maximal at matching rapidities

Fast proton:

High $x^F_{\Lambda_c}$

Rest frame proton:
low momentum Λ_c


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

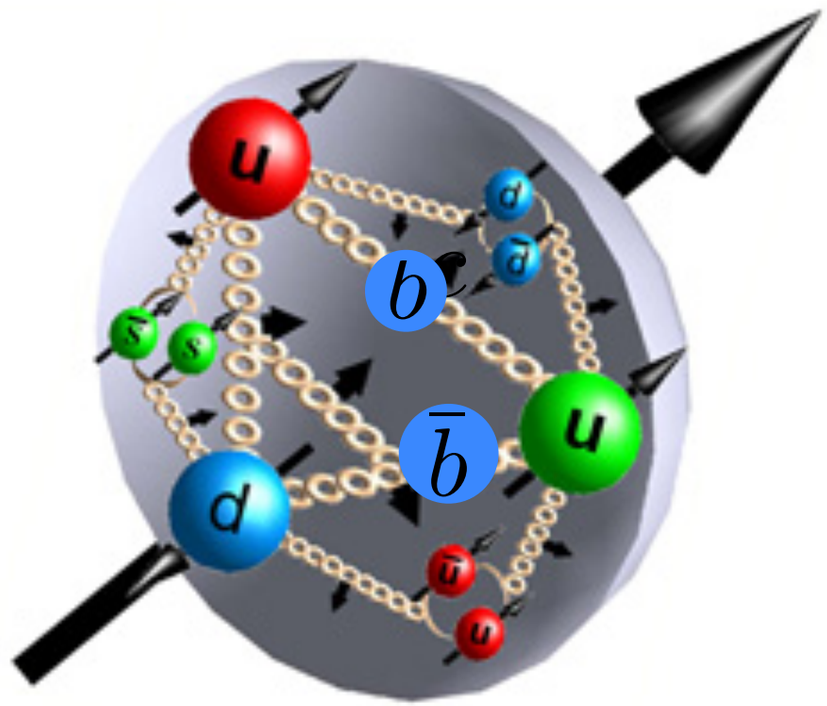
27 May 1991

CM-P00063074

THE Λ_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



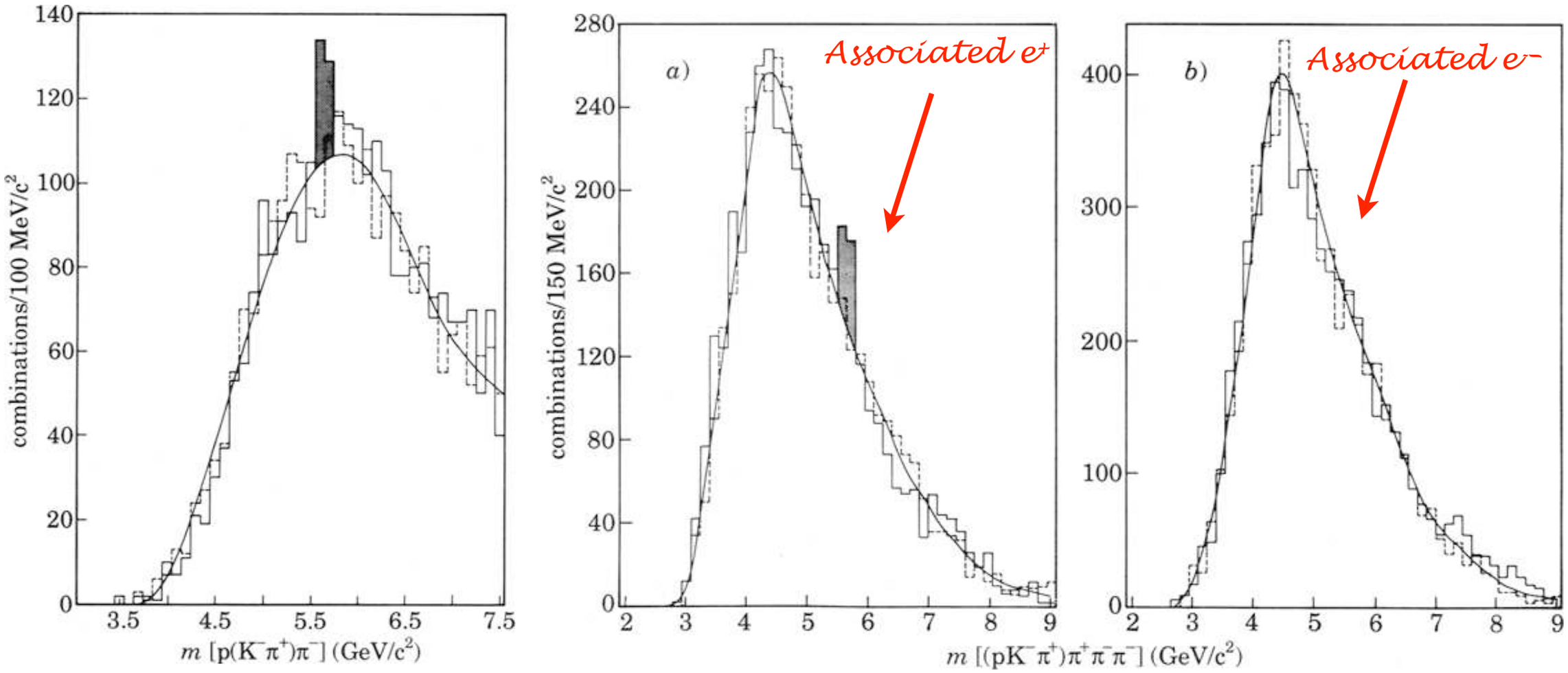
Abstract

Another decay mode of the Λ_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 Λ_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!

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

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



$$\Lambda_b^0 \to pD^0\pi^-$$

$$m_{\Lambda_b} = 5.6 \text{ GeV}$$

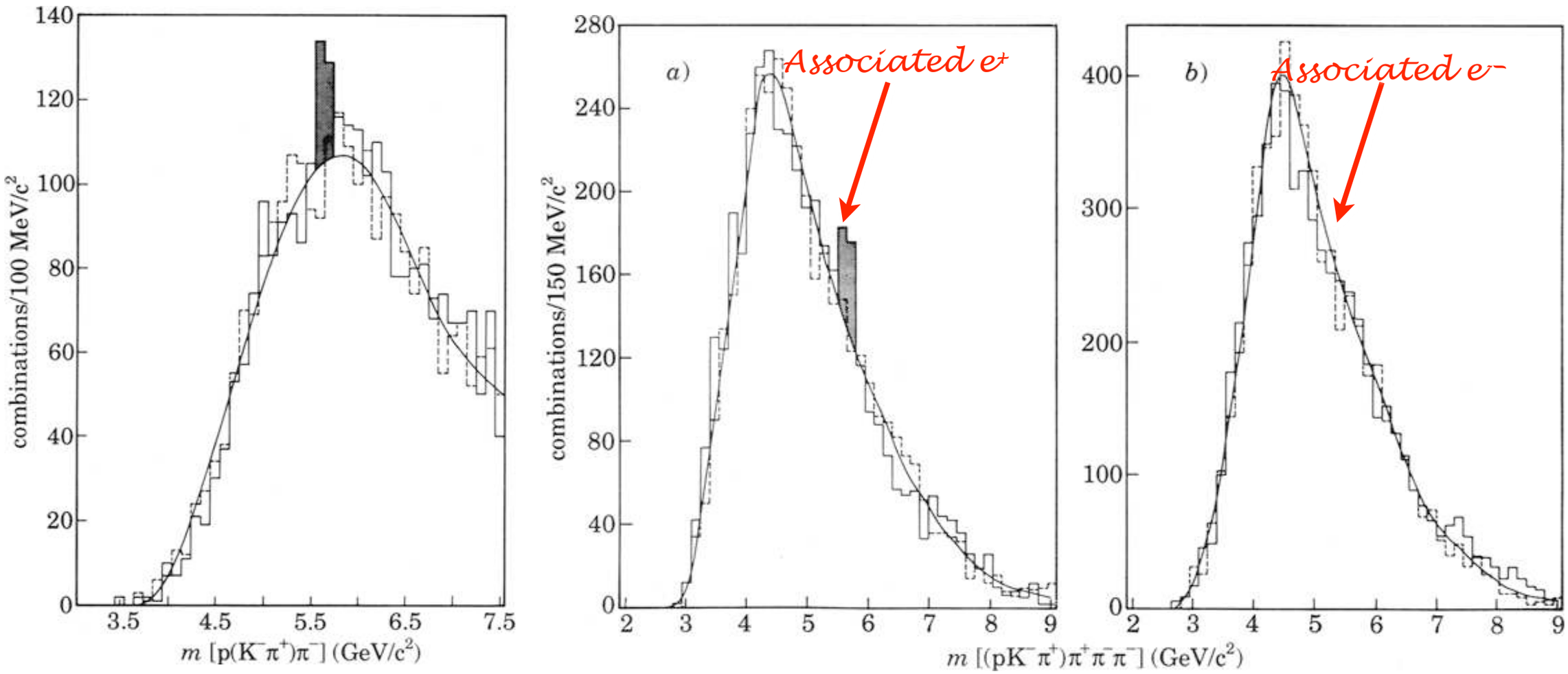
$$\Lambda_b^0 \to \Lambda_c^+\pi^+\pi^-\pi^-$$

Il Nuovo Cimento 104, 1787

First Evidence for Intrinsic Bottom!

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

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



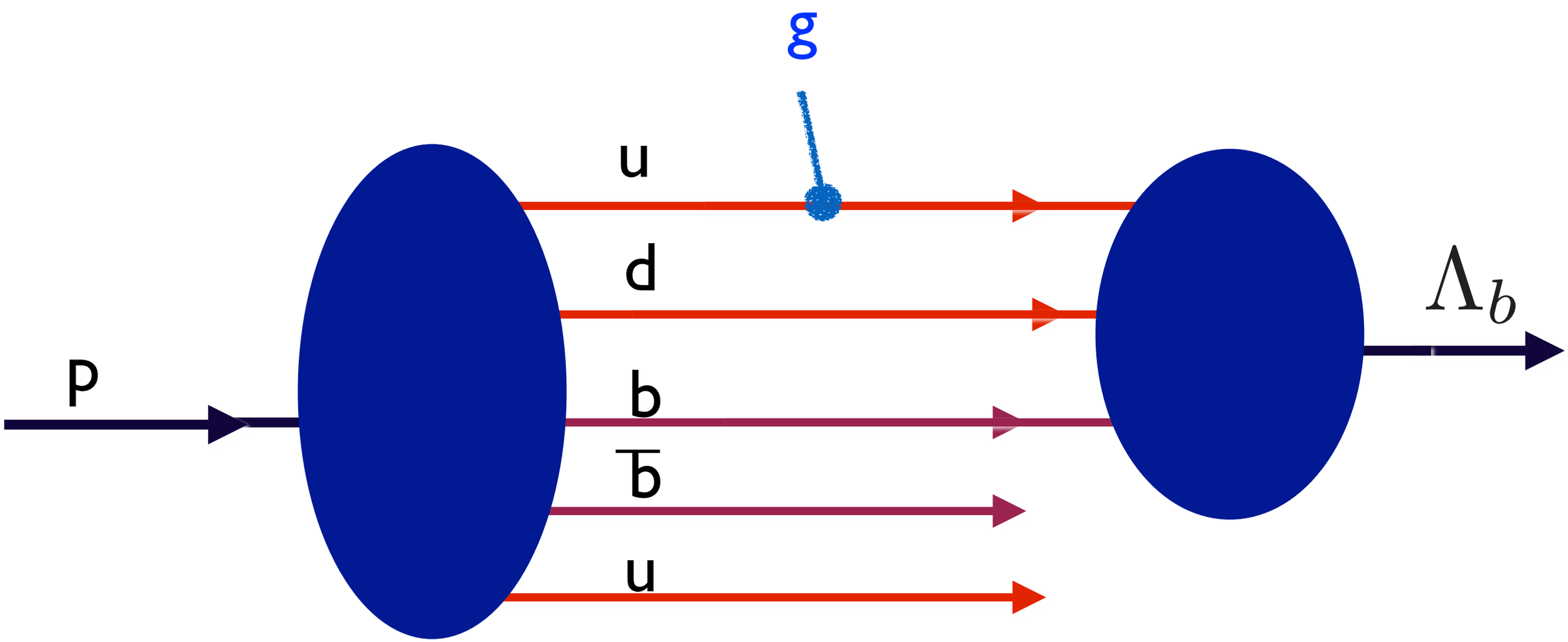
$\Lambda_b^0 \to pD^0\pi^-$ $\qquad\qquad$ $\Lambda_b^0 \to \Lambda_c^+\pi^+\pi^-\pi^-$

Il Nuovo Cimento 104, 1787

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

$$pp \to \Lambda_b X$$

$$\Delta y = y_p - y_{\Lambda_b} < 2$$



Coalescence maximal at matching rapidities

$$x_{\Lambda_b} = x_b + x_u + x_d$$

2016 Review of Particle Physics.
Please use this CITATION: C. Patrignani *et al.*(Particle Data Group), Chin. Phys. C, **40**, 100001 (2016).

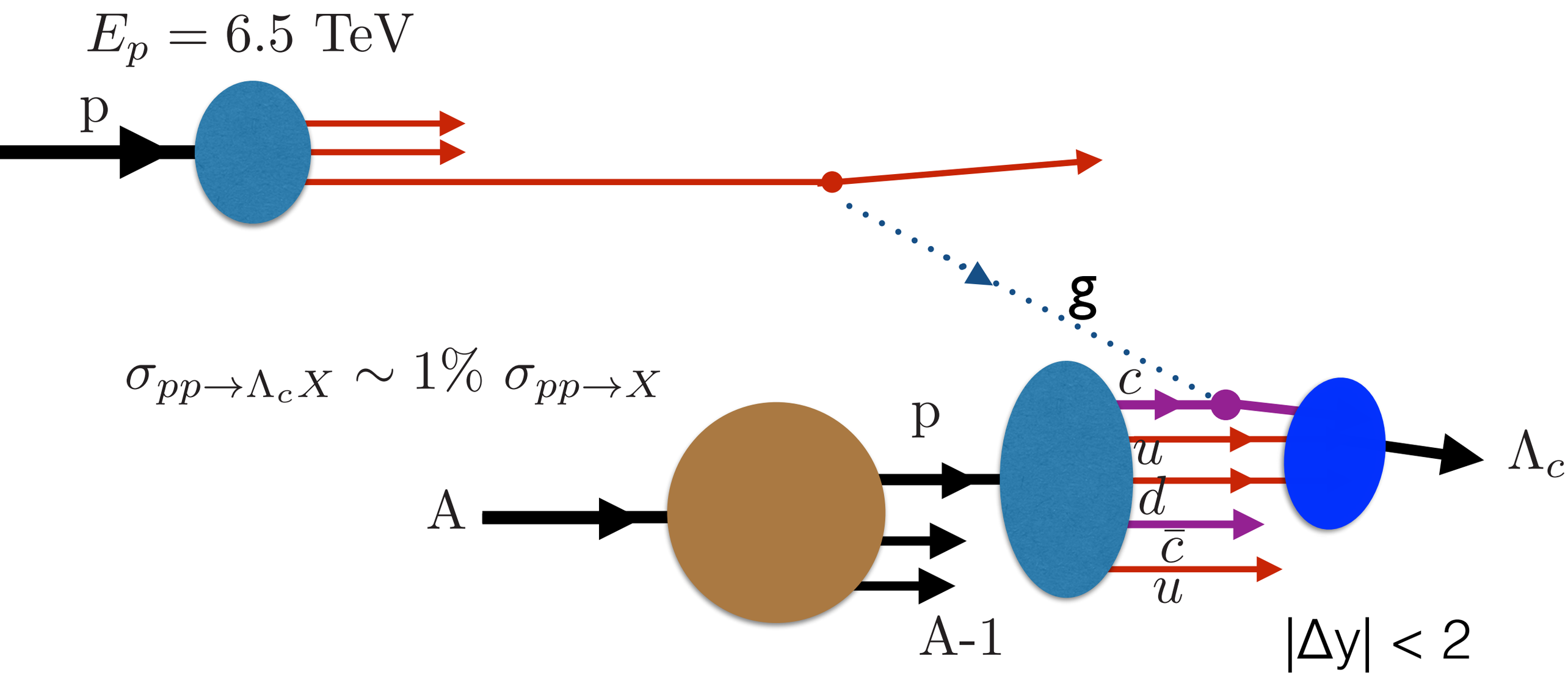
Λ_b^0 MASS

$m_{\Lambda_b^0}$

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

$$pA \to \Lambda_c X$$

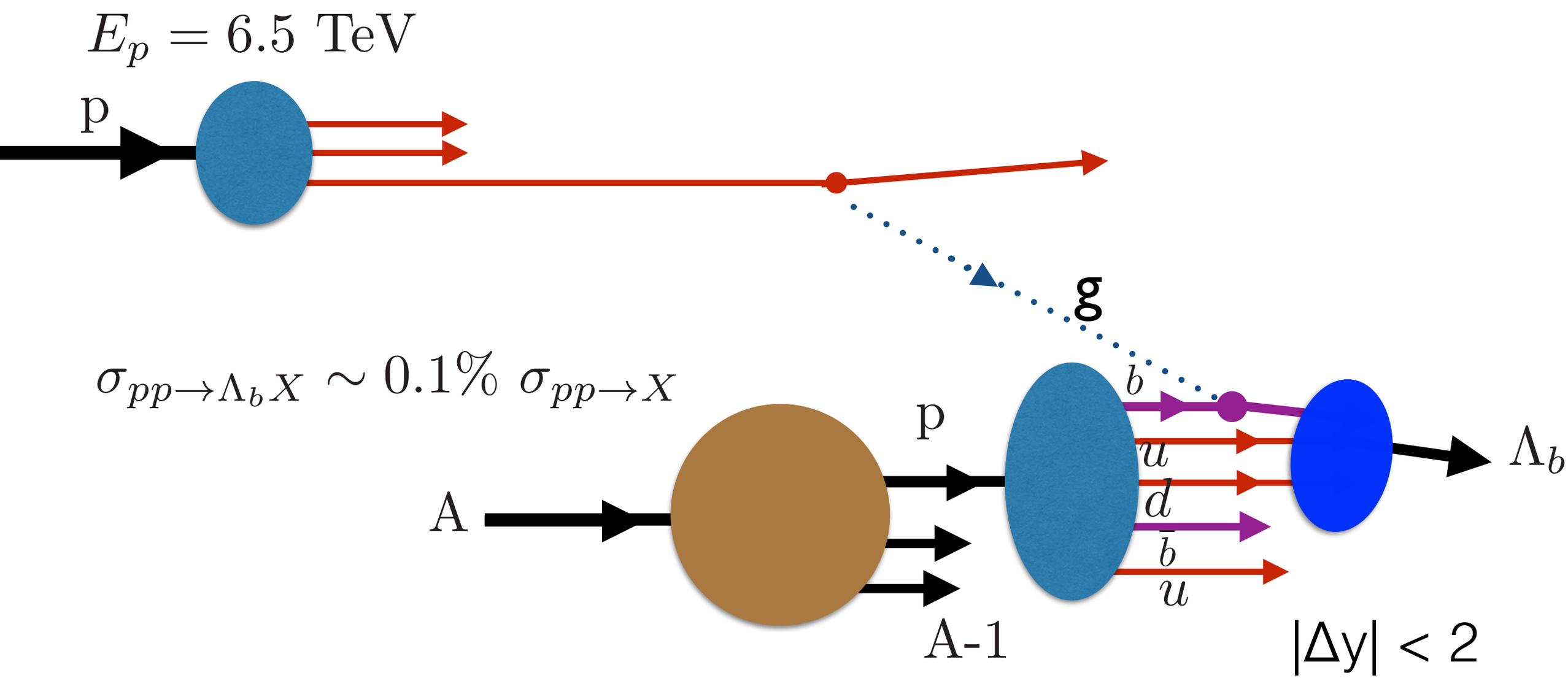


SMOG target at rest

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

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

$$pA \to \Lambda_b X$$



SMOG target at rest

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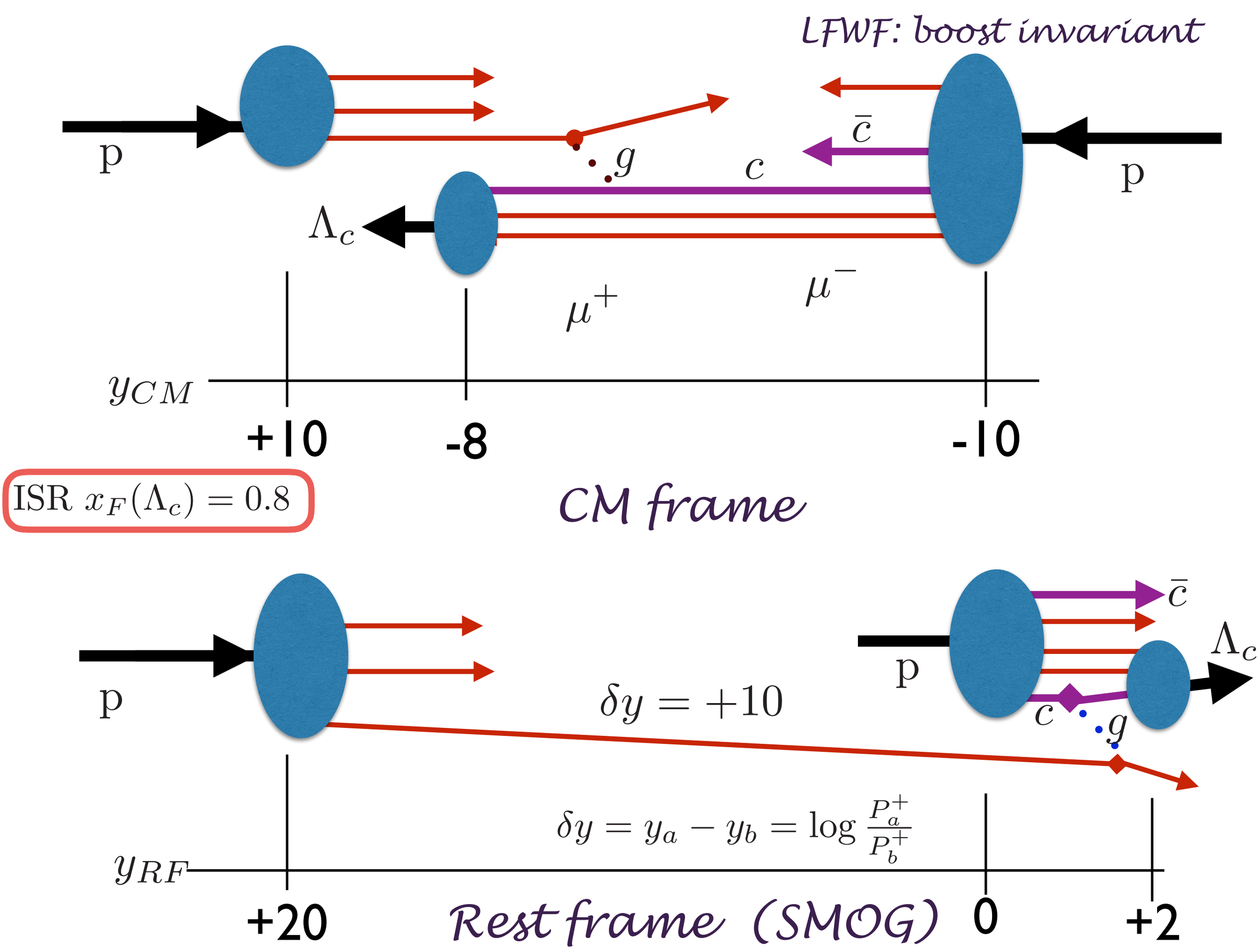
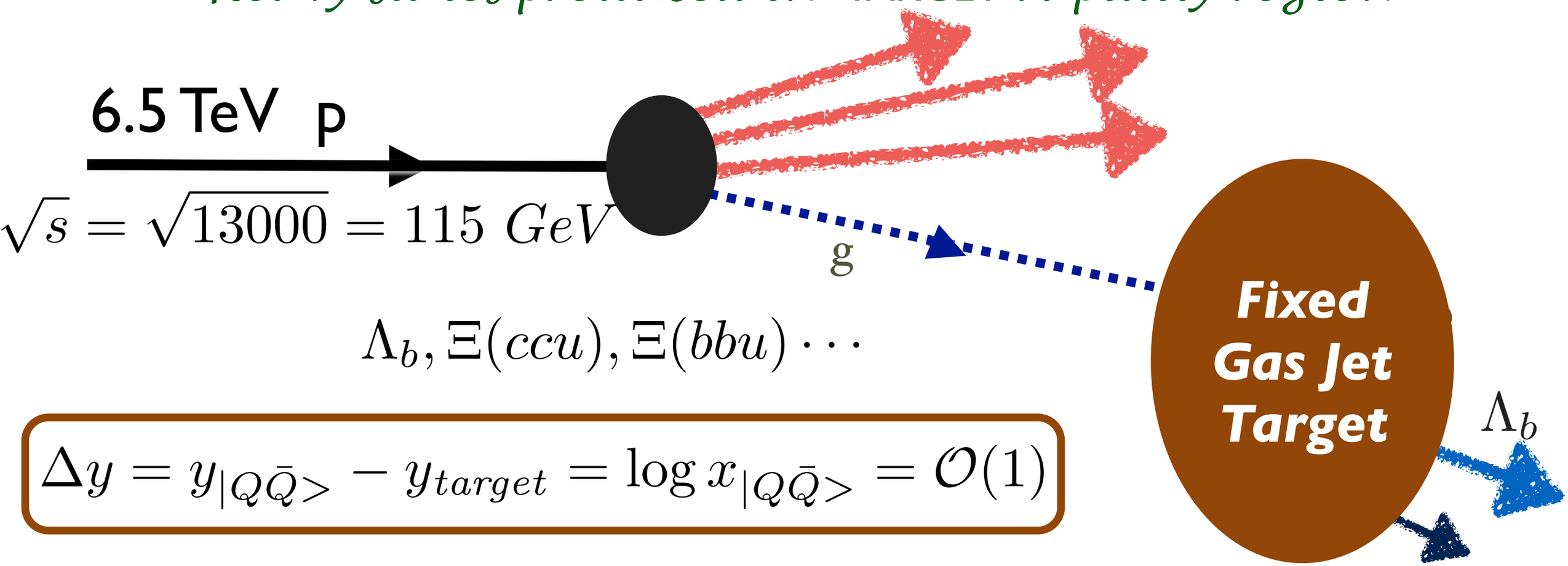

LFWF: boost invariant
p
p
g
c
$\bar{c}$
Λ_c
μ^+
μ^-
y_{CM}
+10
-8
-10
ISR $x_F(\Lambda_c) = 0.8$
CM frame
p
p
$\bar{c}$
Λ_c
c
g
$\delta y = +10$
$\delta y = y_a - y_b = \log \frac{P_a^+}{P_b^+}$
y_{RF}
+20
Rest frame (SMOG)
0
+2

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*

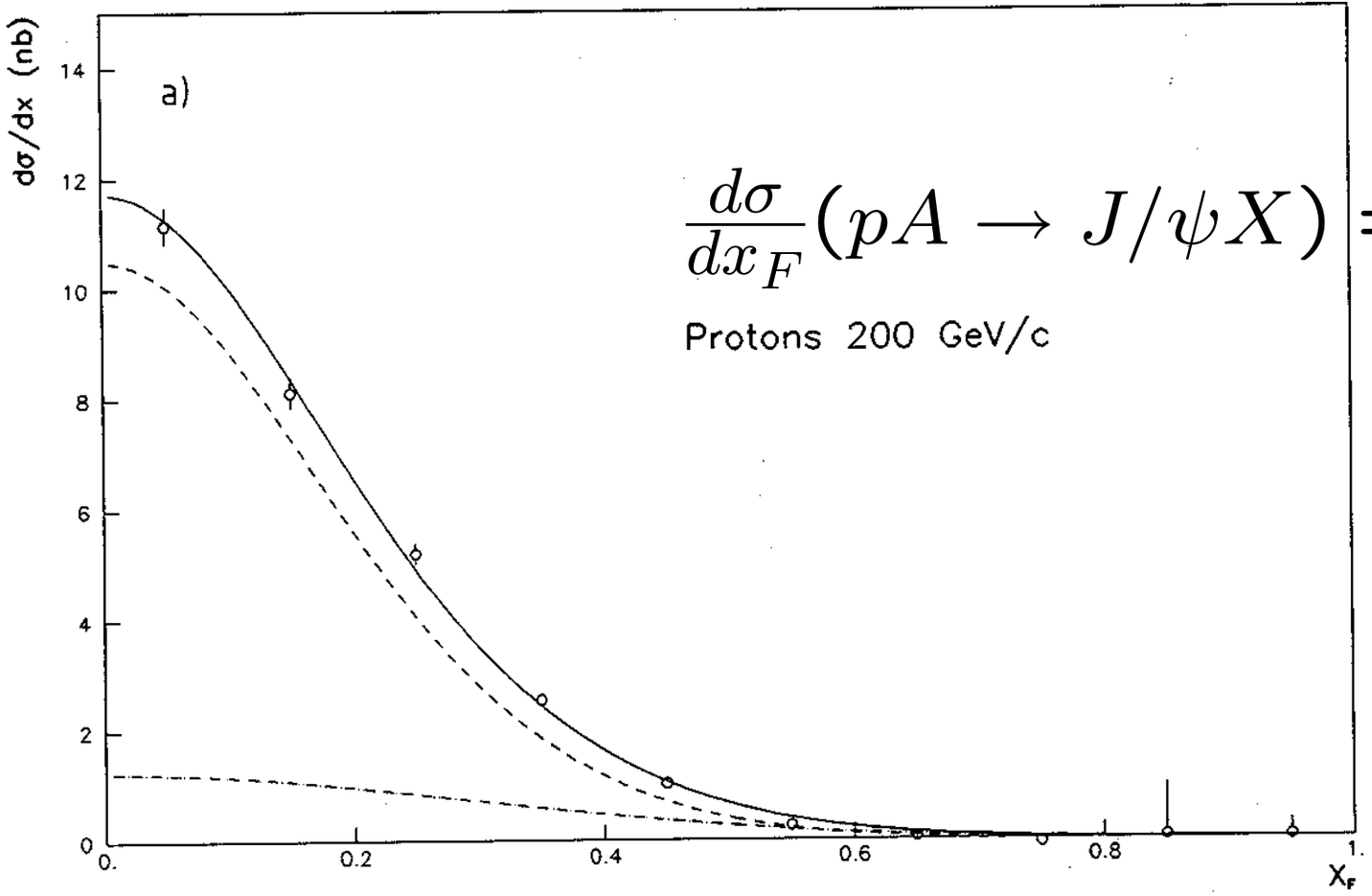


$$\Lambda_b, \Xi(ccu), \Xi(bbu) \cdots$$

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

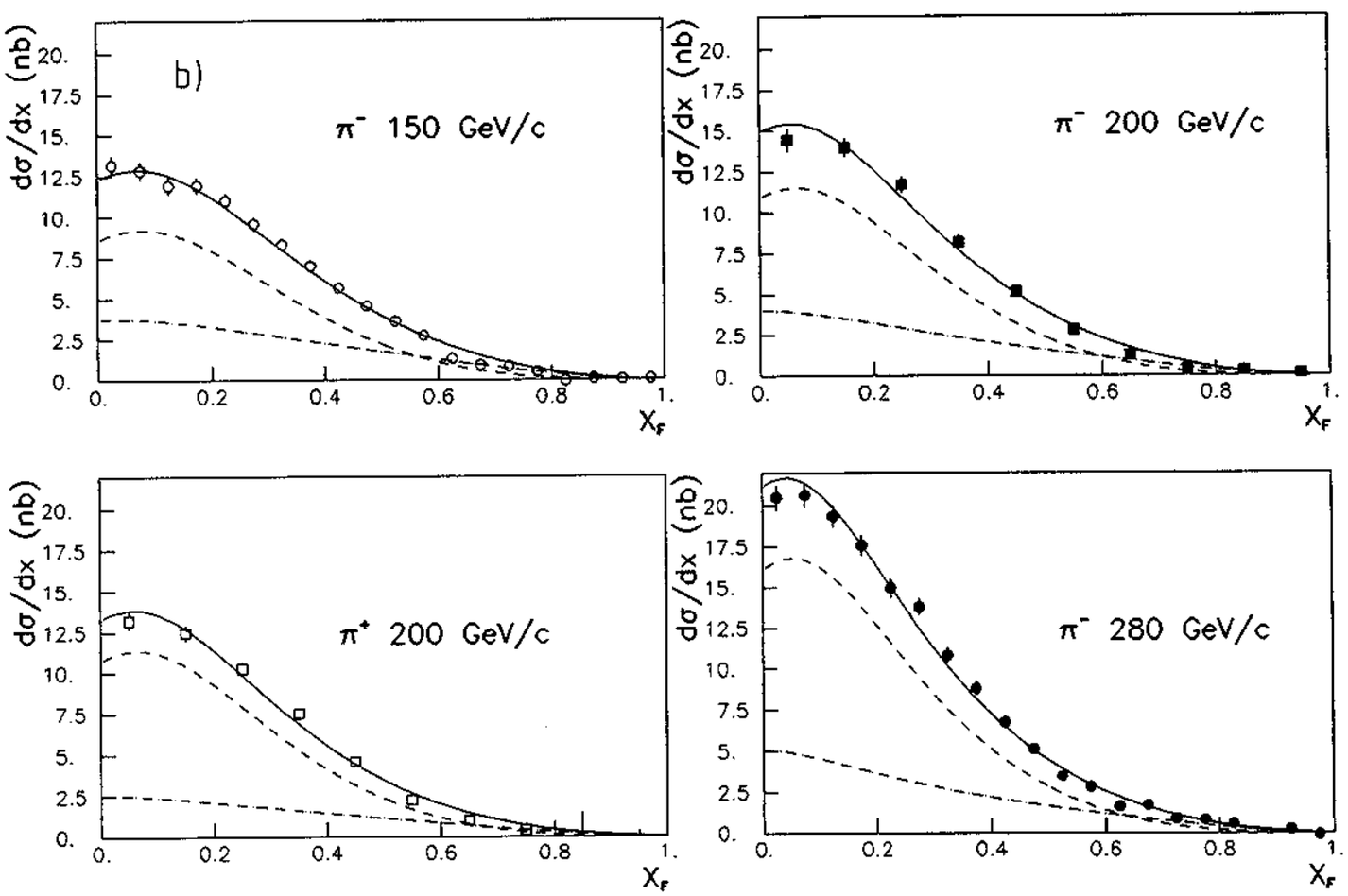
Produce $J/\psi, \Upsilon, \Lambda_c, \Lambda_b, |ccu>, |cud\bar{c}>, |cuuddd u\bar{c}>, \cdots$

Test at Smog@LHCb



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

NA3: Badier et al.

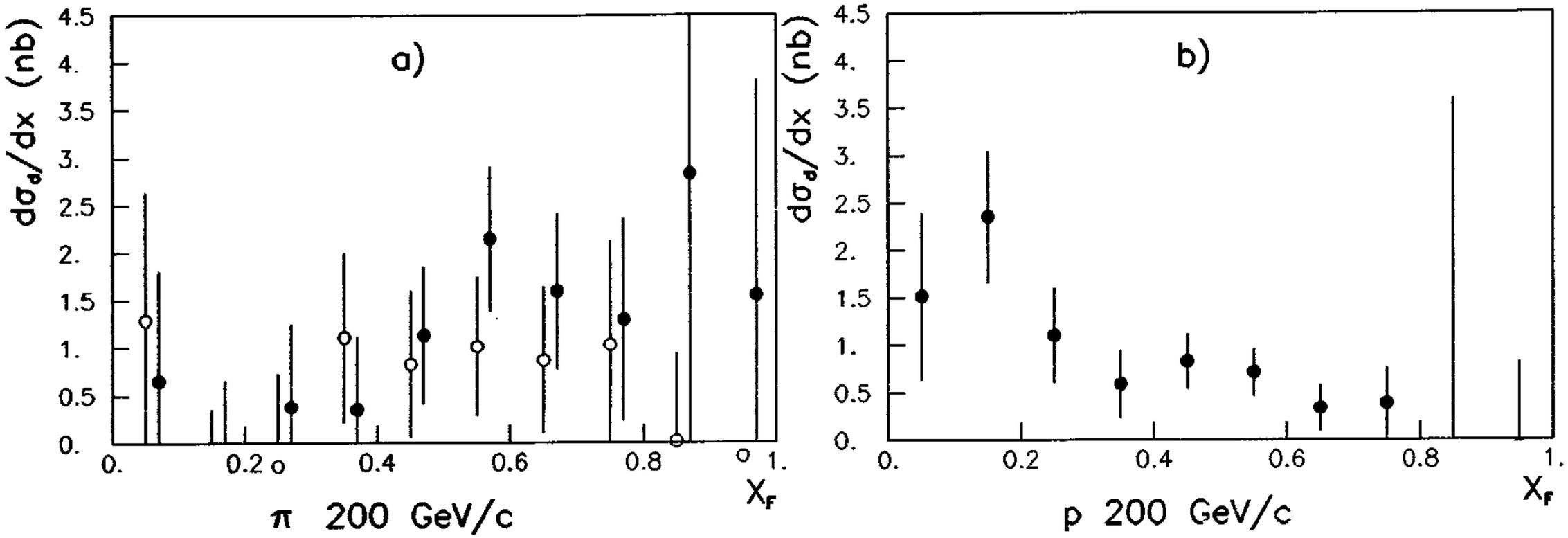


A^1 component consistent with sum of gg and $\bar{q}q$ fusion

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).

$$\frac{d\sigma}{dx_F}(\pi A \to J/\psi X) \propto A^{2/3}$$

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



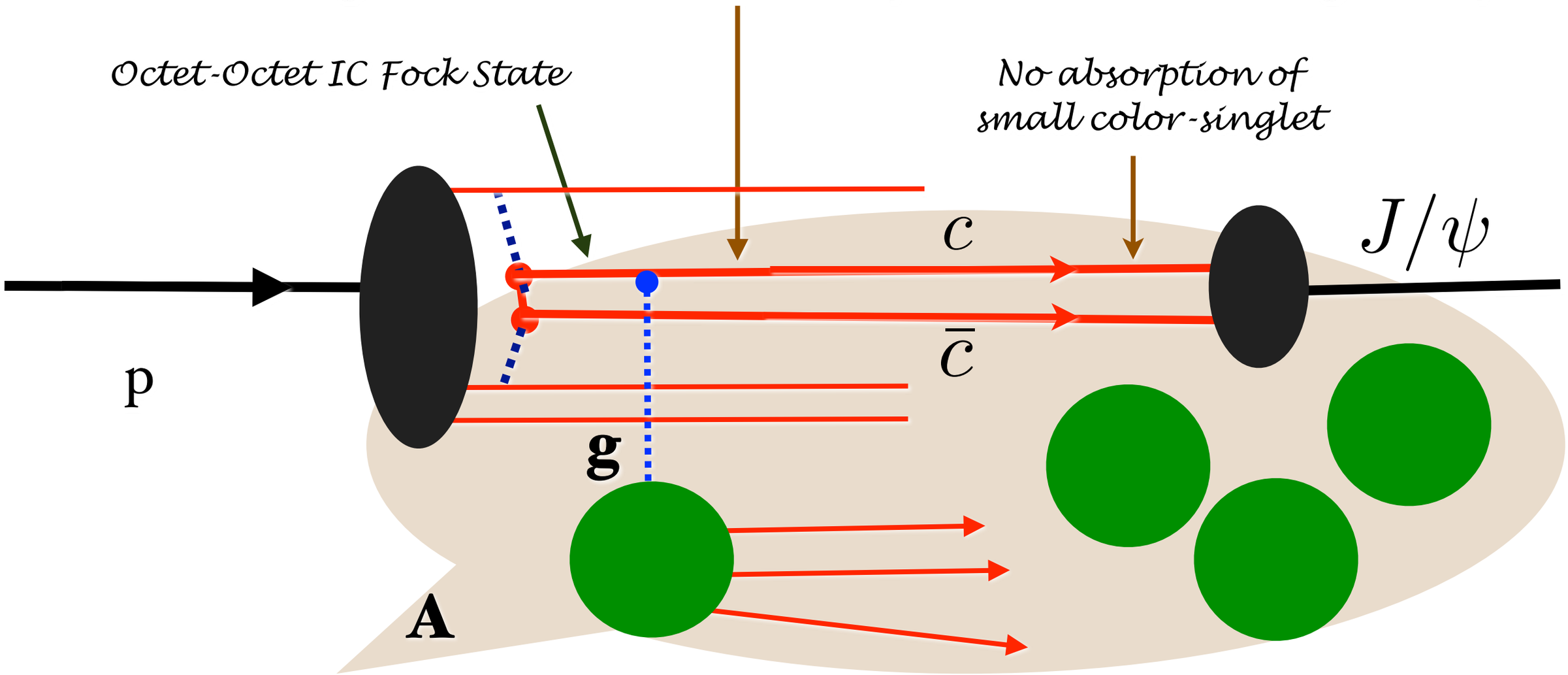
Flat x_F distribution explained by IC

NA3: Badier et al.

Color-Opaque IC Fock state interacts on nuclear front surface

Kopeliovich, Schmidt, Soffer, sjb

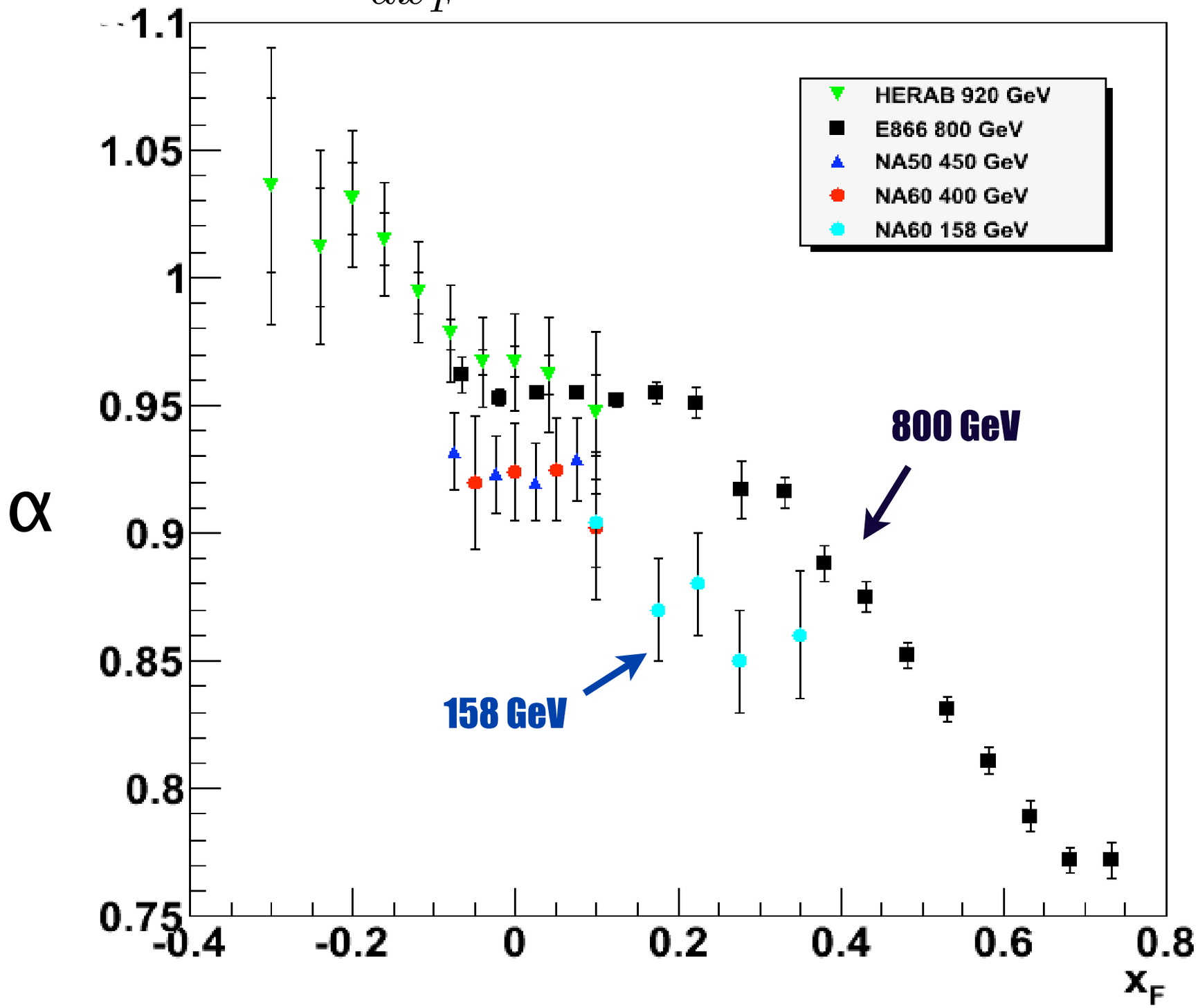
Scattering on front-face nucleon produces color-singlet $c\bar{c}$ pair



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

NA60 pA data @ 158GeV

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



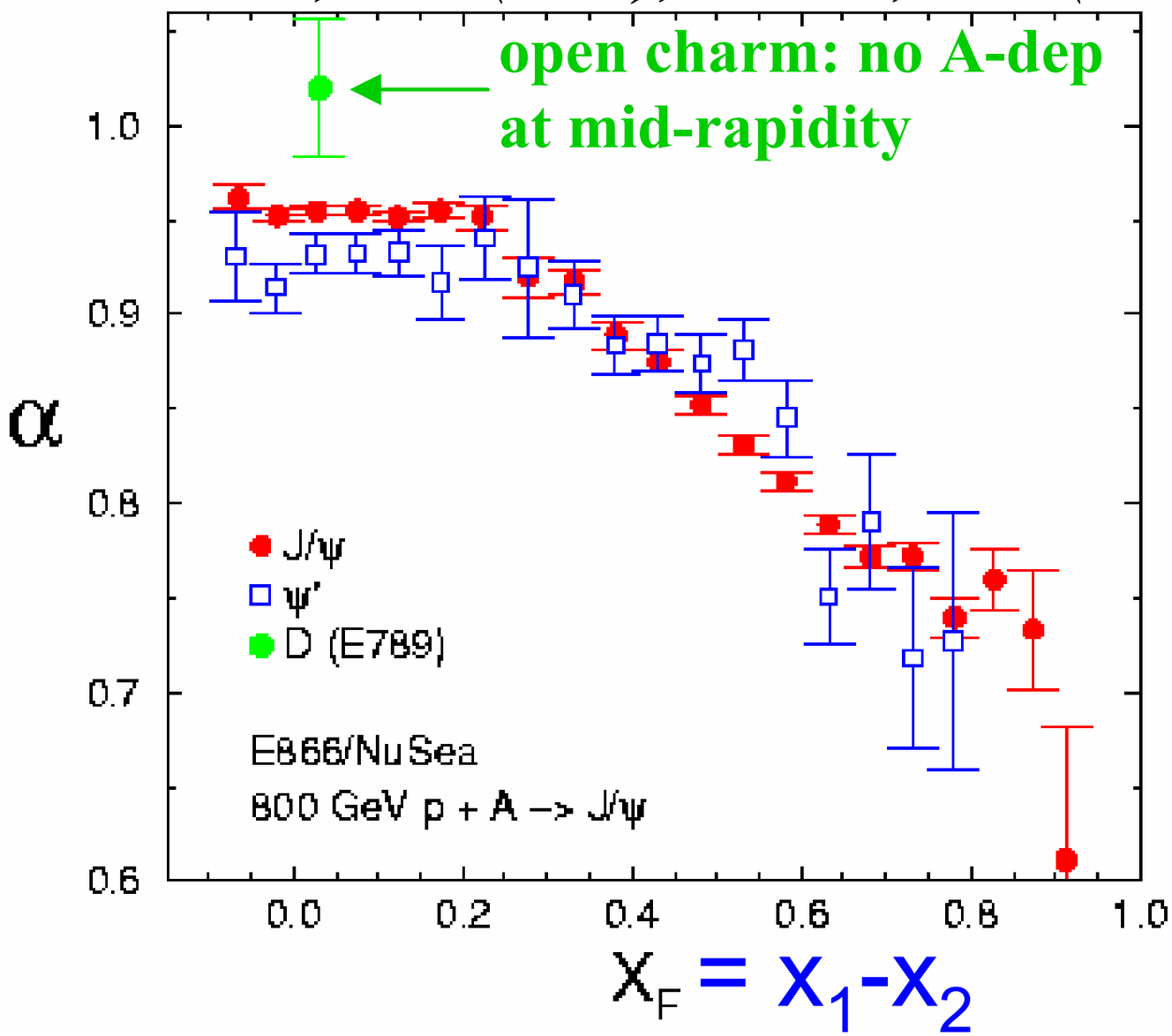
Clear dependence on x_F and beam energy

Dramatic change in nuclear dependence

M. Leitch

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

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



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

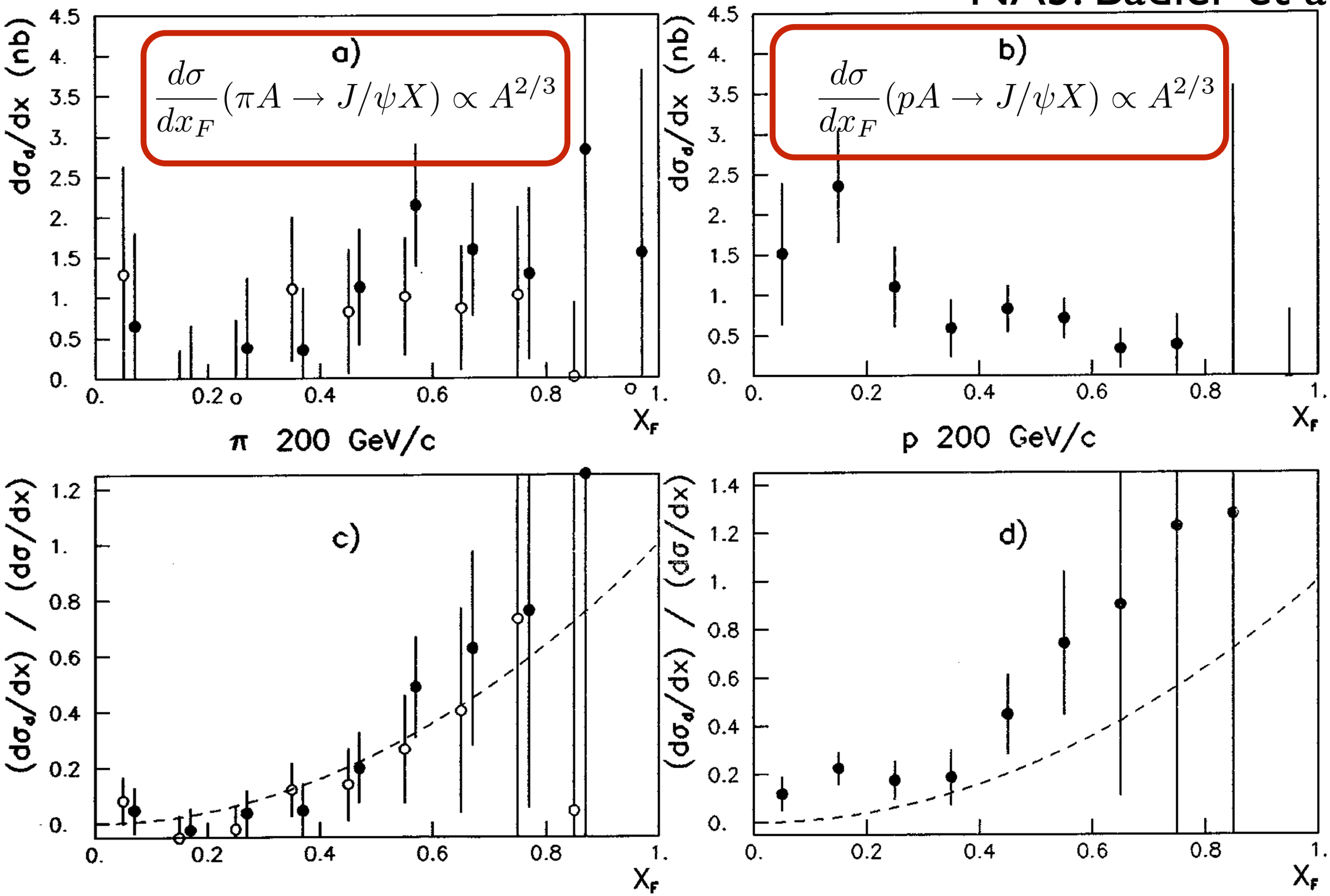
Remarkably Strong Nuclear Dependence for Fast Charmonium

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

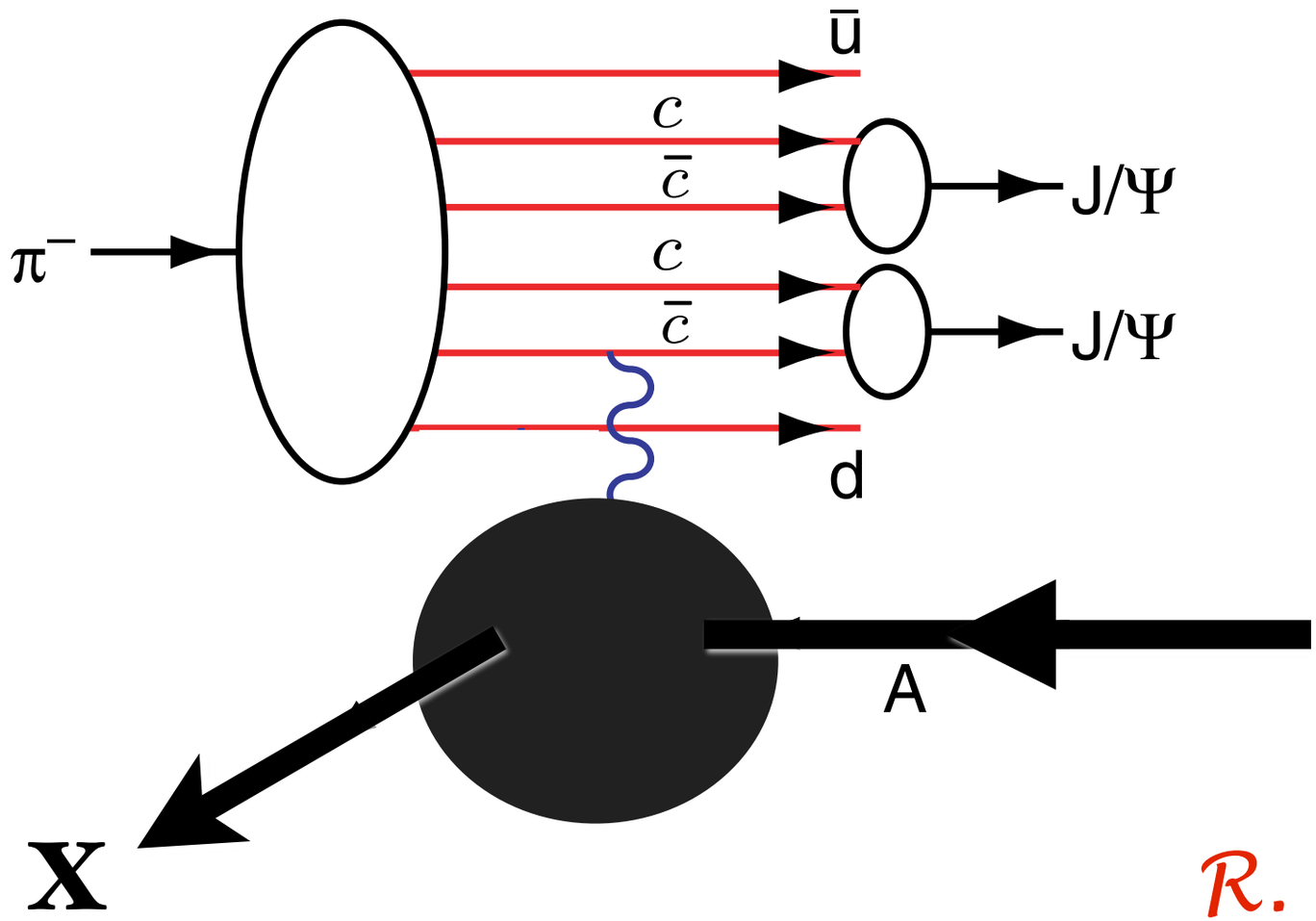
IC Explains large excess of quarkonia at large x_F, A-dependence

NA3: Badier et al.



Flat x_F distribution explained by IC

Double Quarkonium Production at High x_F



R. Vogt, sjb

Cannot be explained
by Color Drag Model

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

Excludes `color drag' model

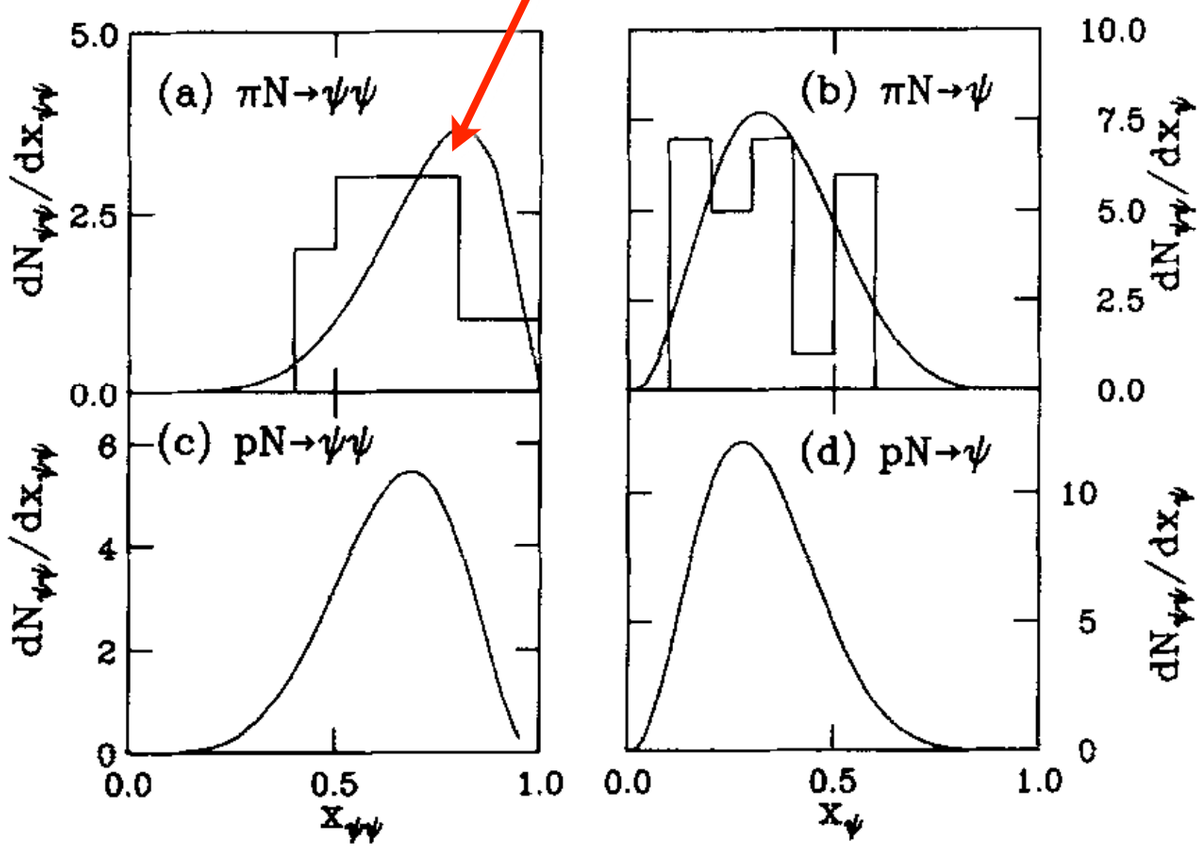


Fig. 3. The $\psi\psi$ pair distributions are shown in (a) and (c) for the pion and proton projectiles. Similarly, the distributions of J/ψ's from the pairs are shown in (b) and (d). Our calculations are compared with the $\pi^- N$ data at 150 and 280 GeV/c [1]. The $x_{\psi\psi}$ distributions are normalized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

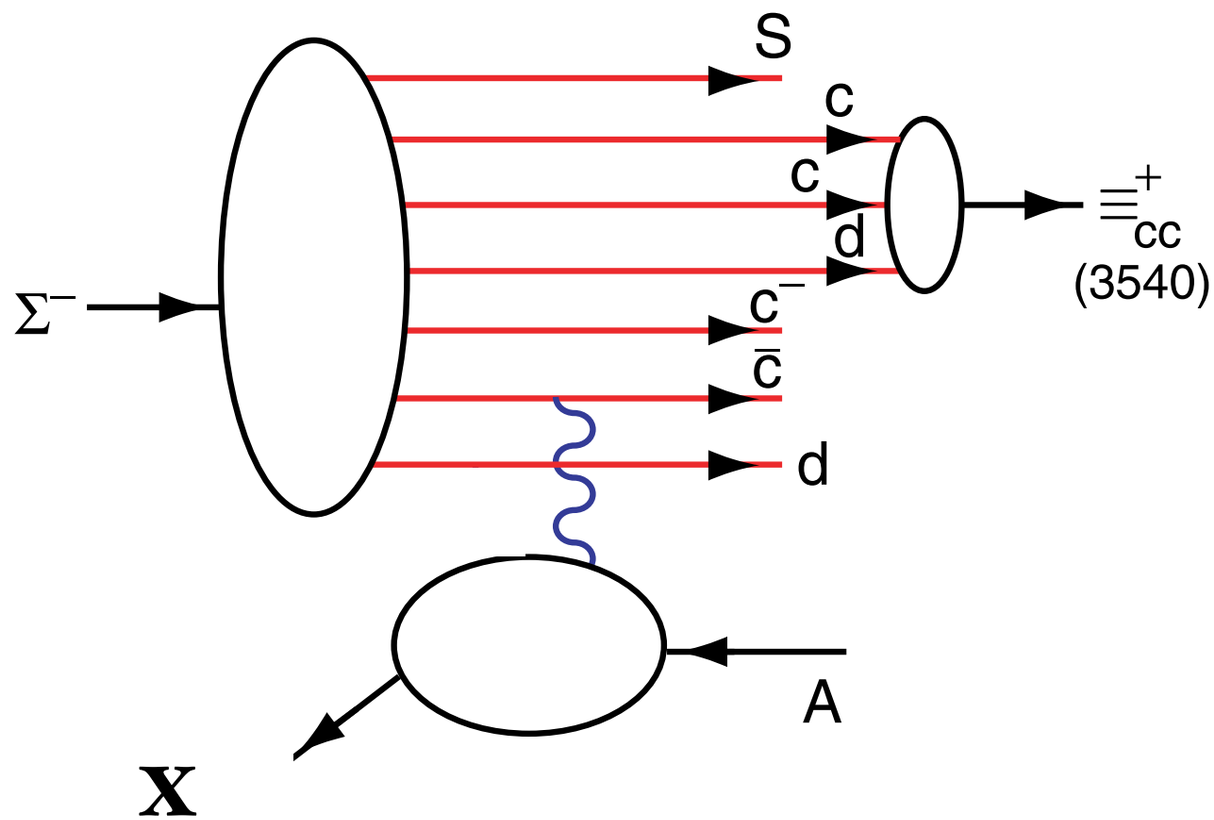
NA3 Data

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

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

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



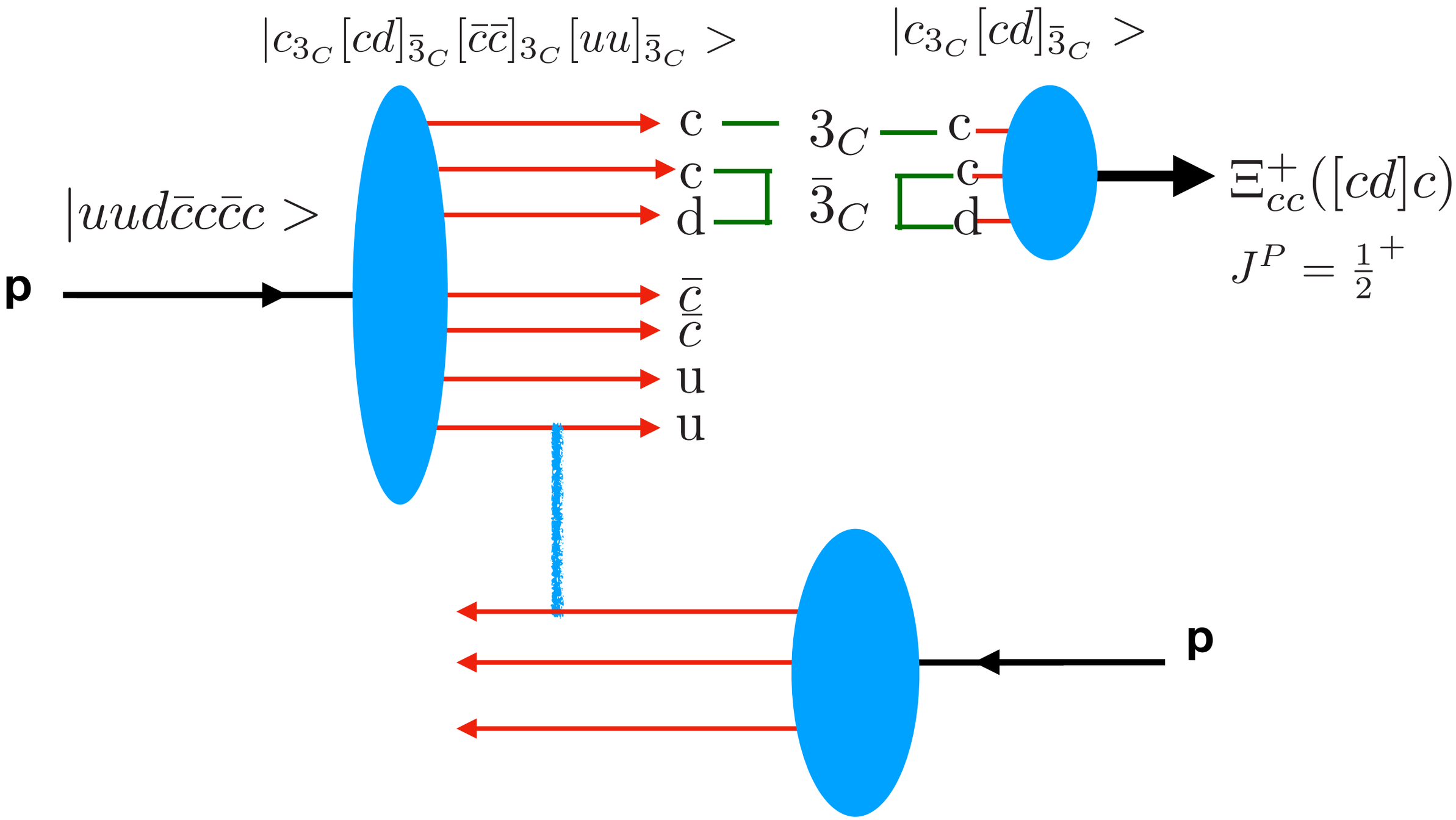
Production of a Double-Charm Baryon

SELEX high x_F $< x_F >= 0.33$

Hadroproduction of the Double-Charm Baryon at High x_F

$$p + A \to \Xi(ccd)^+ + X$$

Double Intrinsic Charm Fock State of proton



SELEX: $\Xi(ccd)^+(3510 \pm 2) \to \Lambda_c^+ K^- \pi^+$

SLAC-PUB-17156

arXiv:1709.09903v2 [hep-ph] 27 Jan 2018

Resolving the SELEX–LHCb Double-Charm Baryon Conflict: The Impact of Intrinsic Heavy-Quark Hadroproduction and Supersymmetric Light-Front Holographic QCD

S.J. Brodsky[1], S. Groote[2] and S. Koshkarev[2]

[1] SLAC National Accelerator Laboratory, Stanford University, Stanford, California 94309, USA

[2] Institute of Physics, University of Tartu, 51010 Tartu, Estonia

Abstract

In this paper we show that the intrinsic heavy-quark QCD mechanism for the hadroproduction of heavy hadrons at large x_F can resolve the apparent conflict between measurements of double-charm baryons by the SELEX fixed-target experiment and the LHCb experiment at the LHC collider. We show that both experiments are compatible, and that both results can be correct. The observed spectroscopy of double-charm hadrons is in agreement with the predictions of supersymmetric light front holographic QCD.

- 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)

Rules out color drag (Pythia)

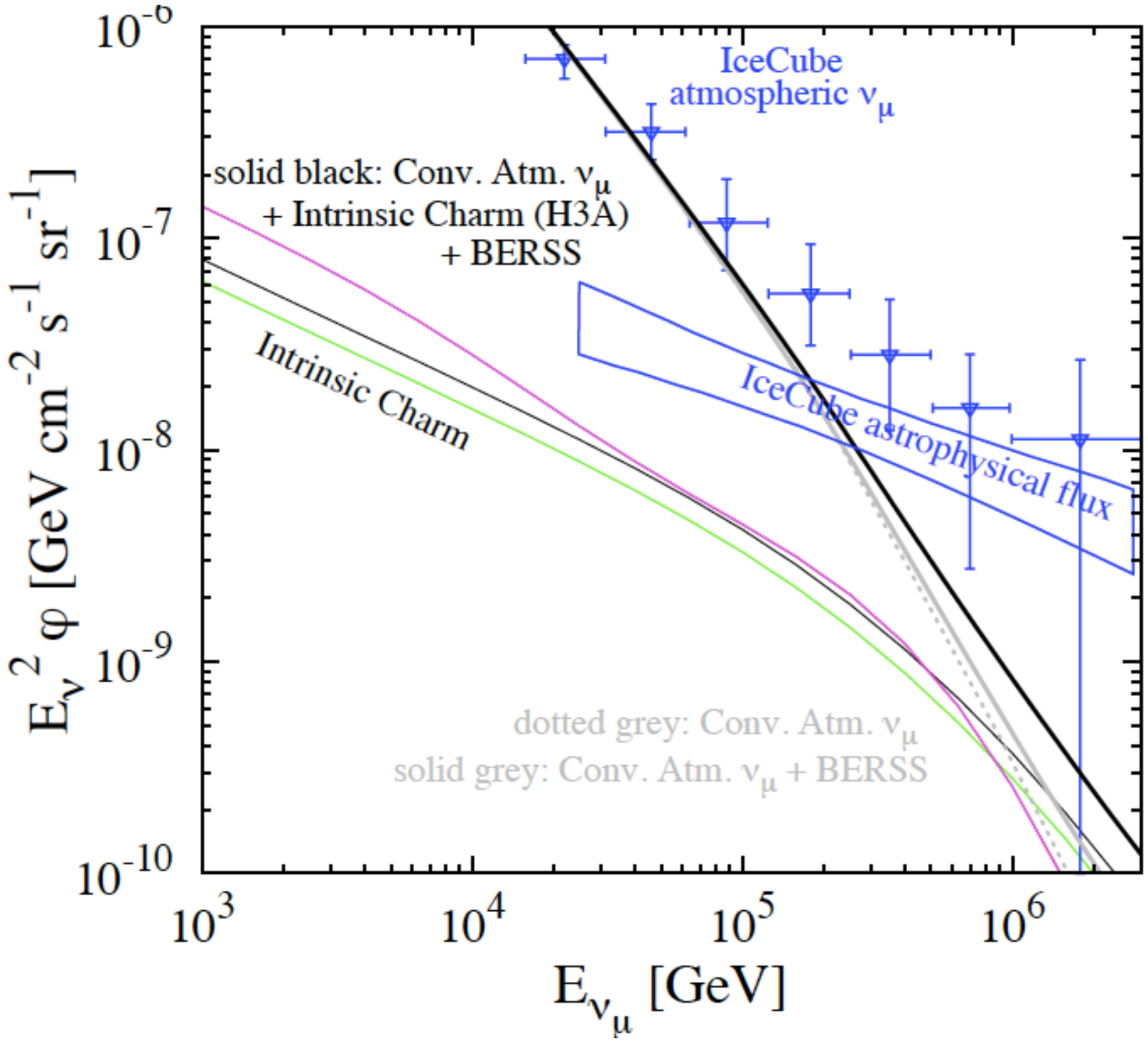
Evidence for IQ

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


IceCube
atmospheric ν_μ
solid black: Conv. Atm. ν_μ
+ Intrinsic Charm (H3A)
+ BERSS
Intrinsic Charm
IceCube astrophysical flux
dotted grey: Conv. Atm. ν_μ
solid grey: Conv. Atm. ν_μ + BERSS
$E_\nu^2\,\varphi$ [GeV cm^{-2} s^{-1} sr^{-1}]
E_{ν_μ} [GeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^3
10^4
10^5
10^6

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***

- 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

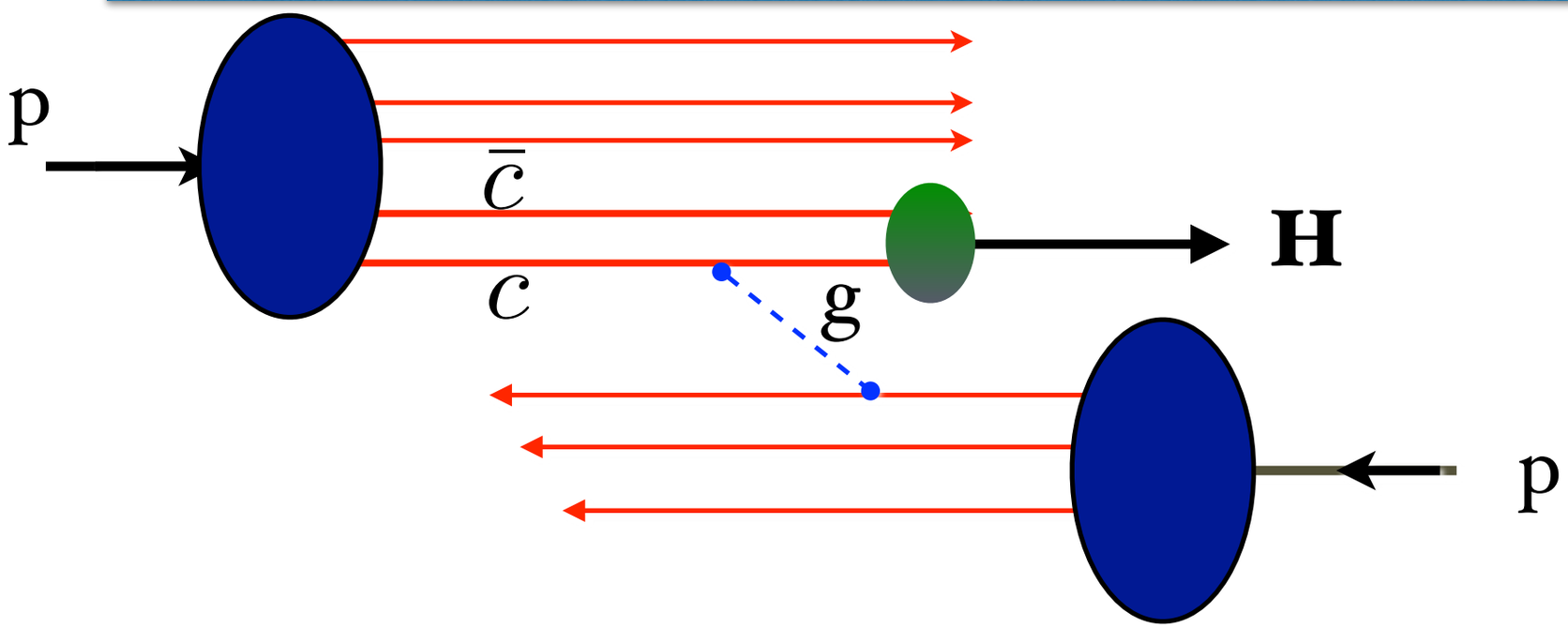
- IC Explains $J/\psi \to \rho\pi$ puzzle (Karliner, SJB)

- 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



$$pp \to HX$$

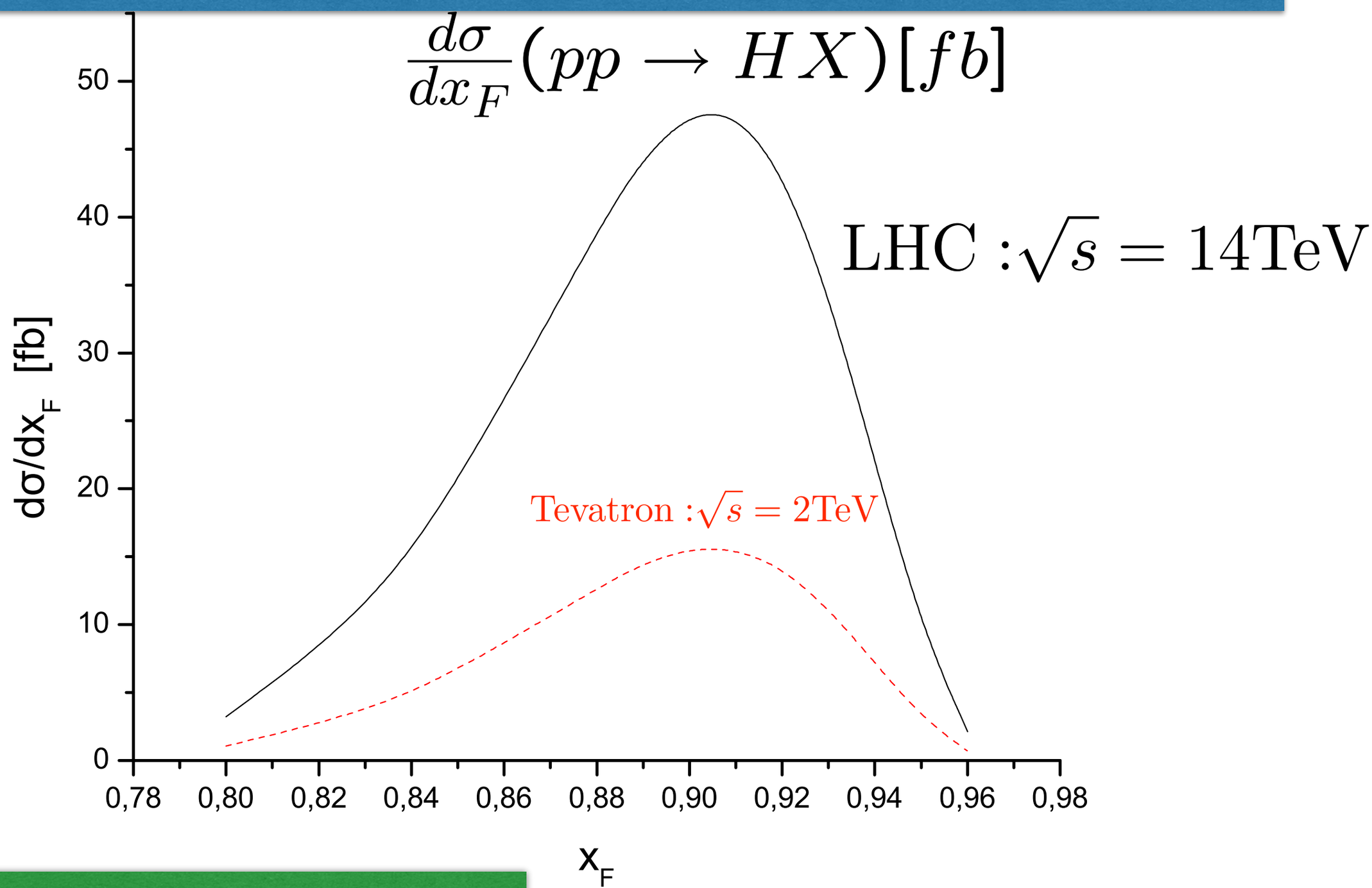
Also: intrinsic strangeness, bottom, top

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



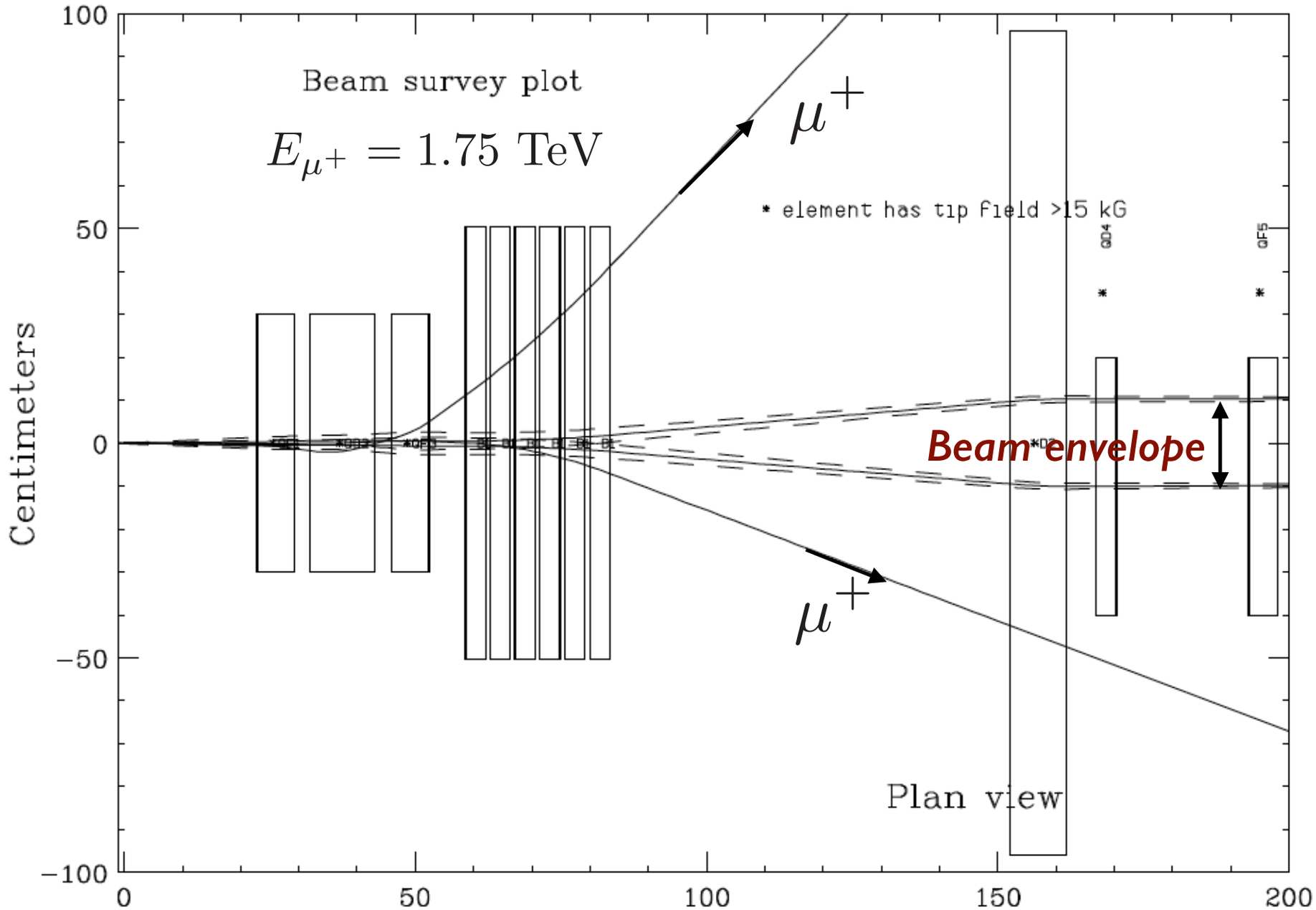
Need High x_F Acceptance

Most practical: Higgs to 4 muons

Goldhaber, Kopeliovich, Schmidt, Soffer, sjb

Use LHC Magnetic Field as Downstream Muon Spectrometer

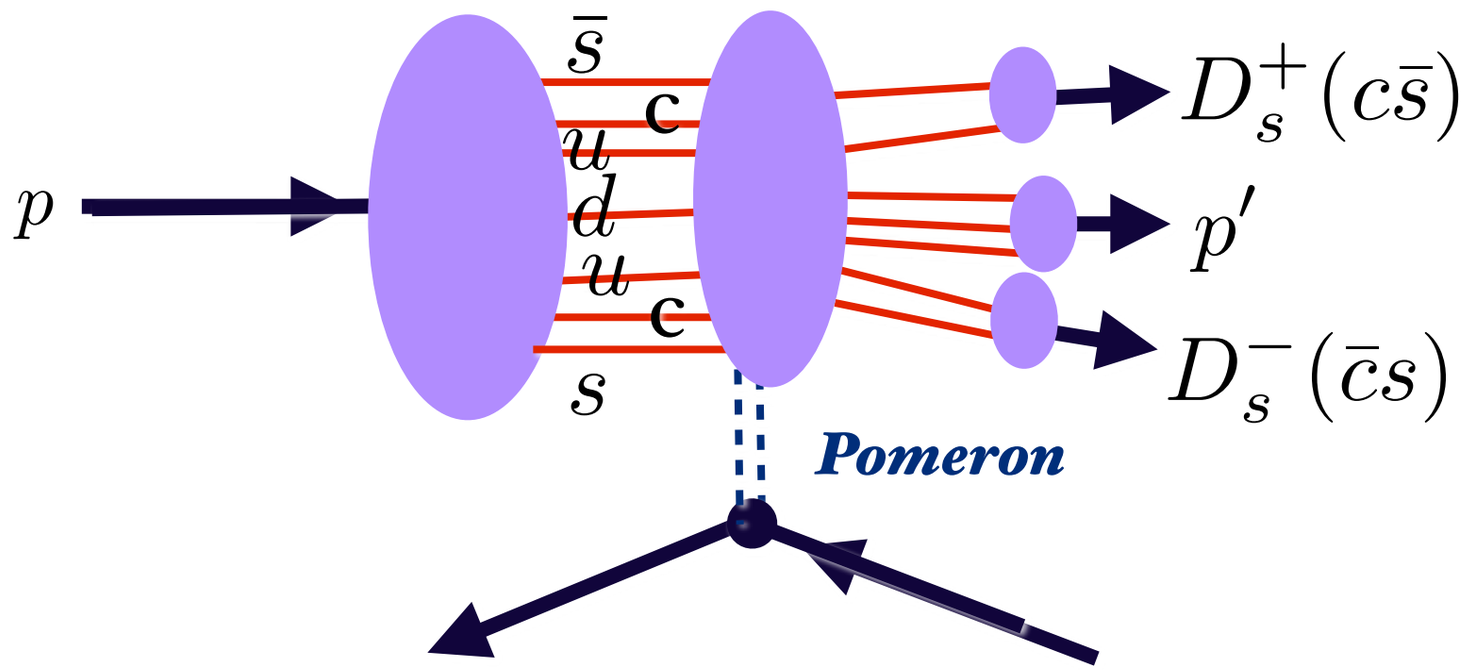
$$pp \to HX \to \mu^+\mu^-\mu^+\mu^- X$$



M.Sullivan (preliminary)

Measure exotic events at SMOG@LHCb such as

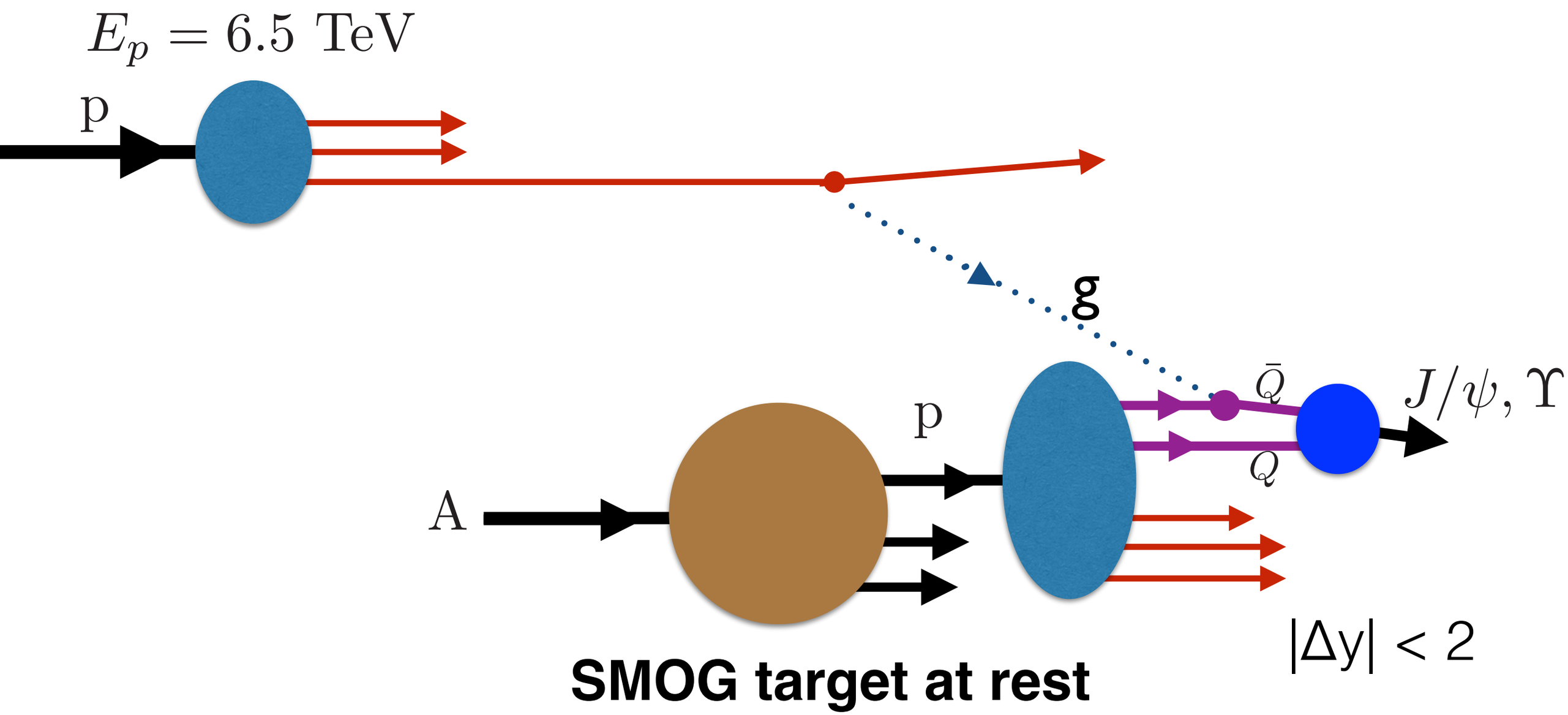
$$pA \to \Upsilon + J/\psi X \to \mu^+\mu^-\mu^+\mu^- X$$



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.

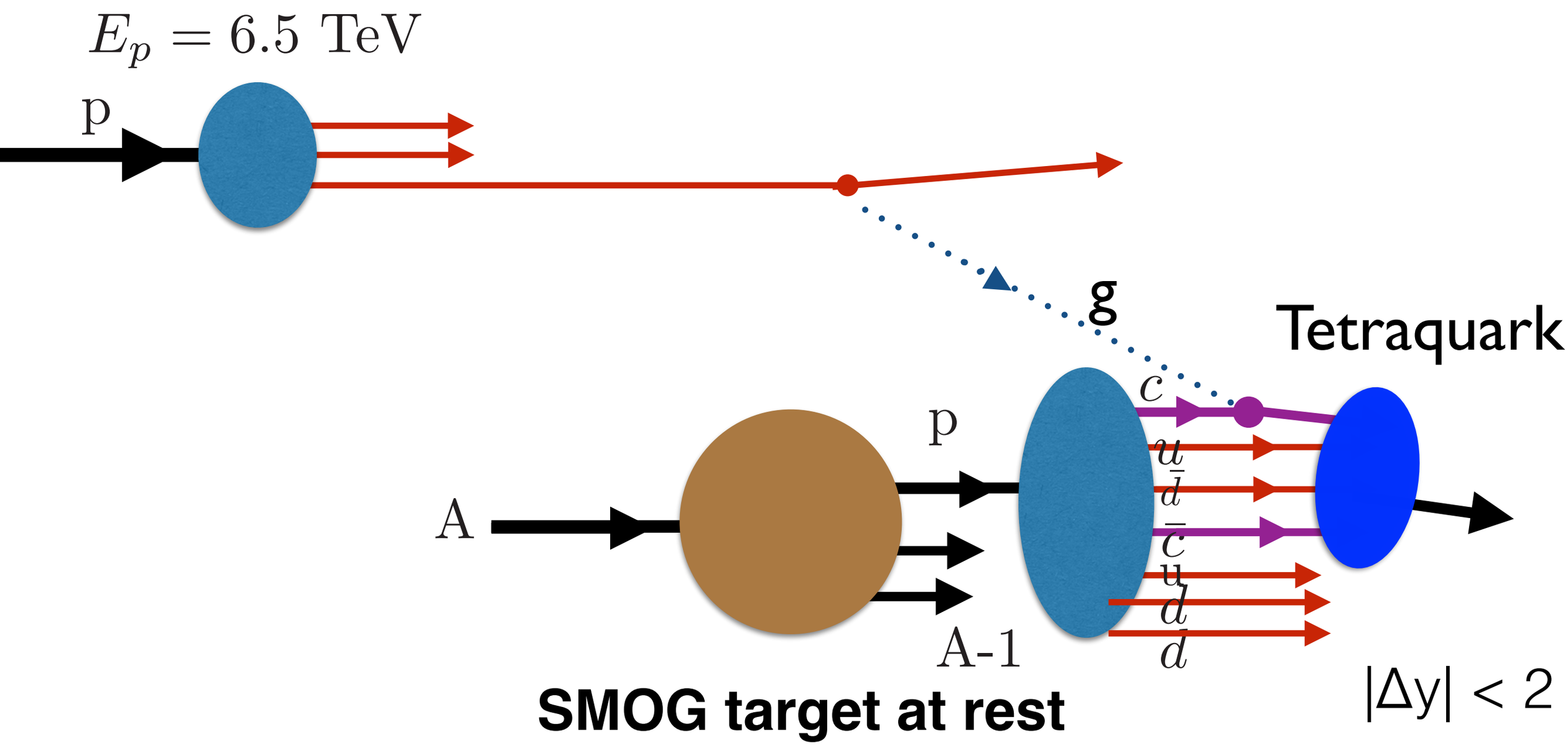
$$pA \to J/\psi X$$



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

Quarkonium produced nearly at rest — has small rapidity y < 2 in target rest frame

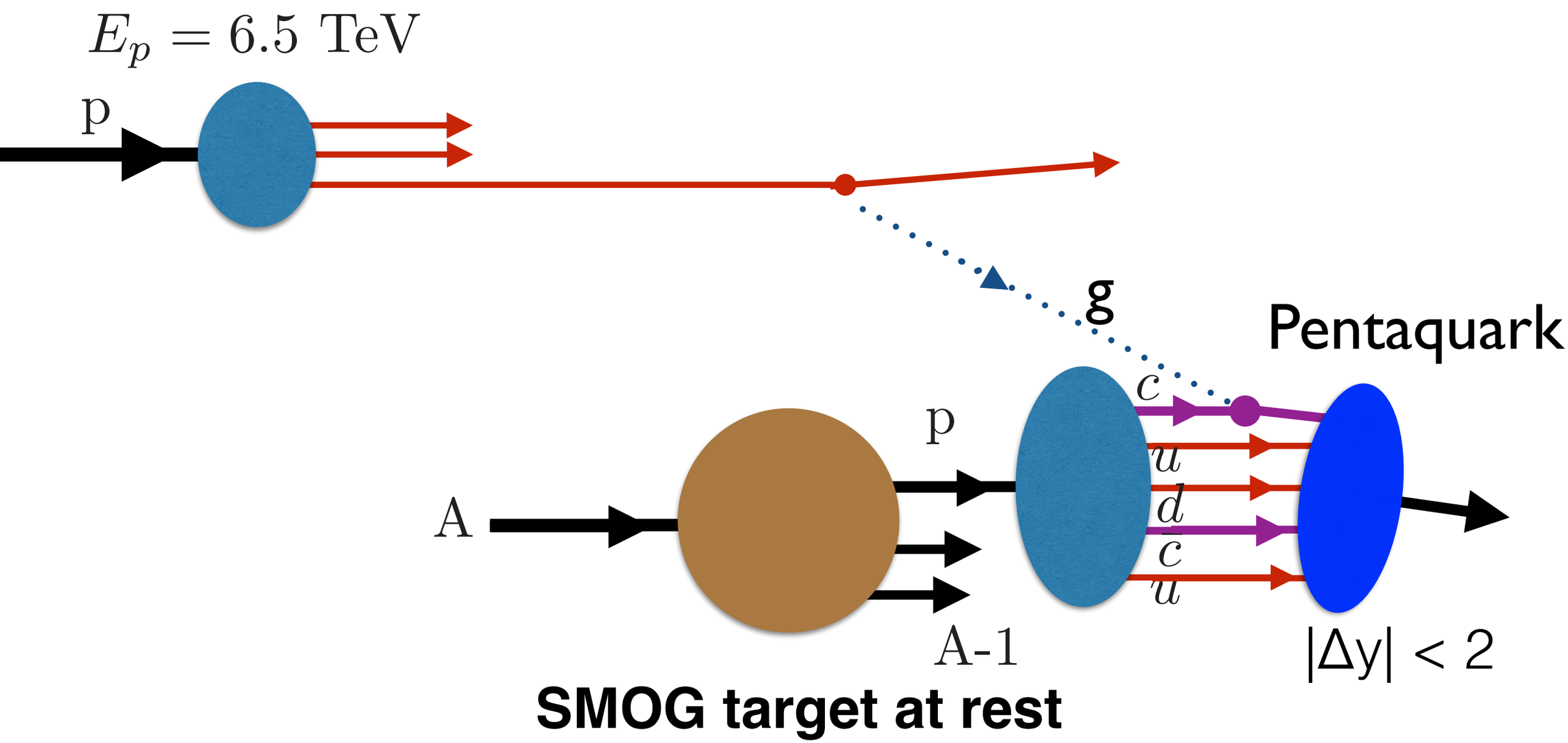
$$pA \to Tetraquark(|cu\bar{c}\bar{d}>)X$$



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

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

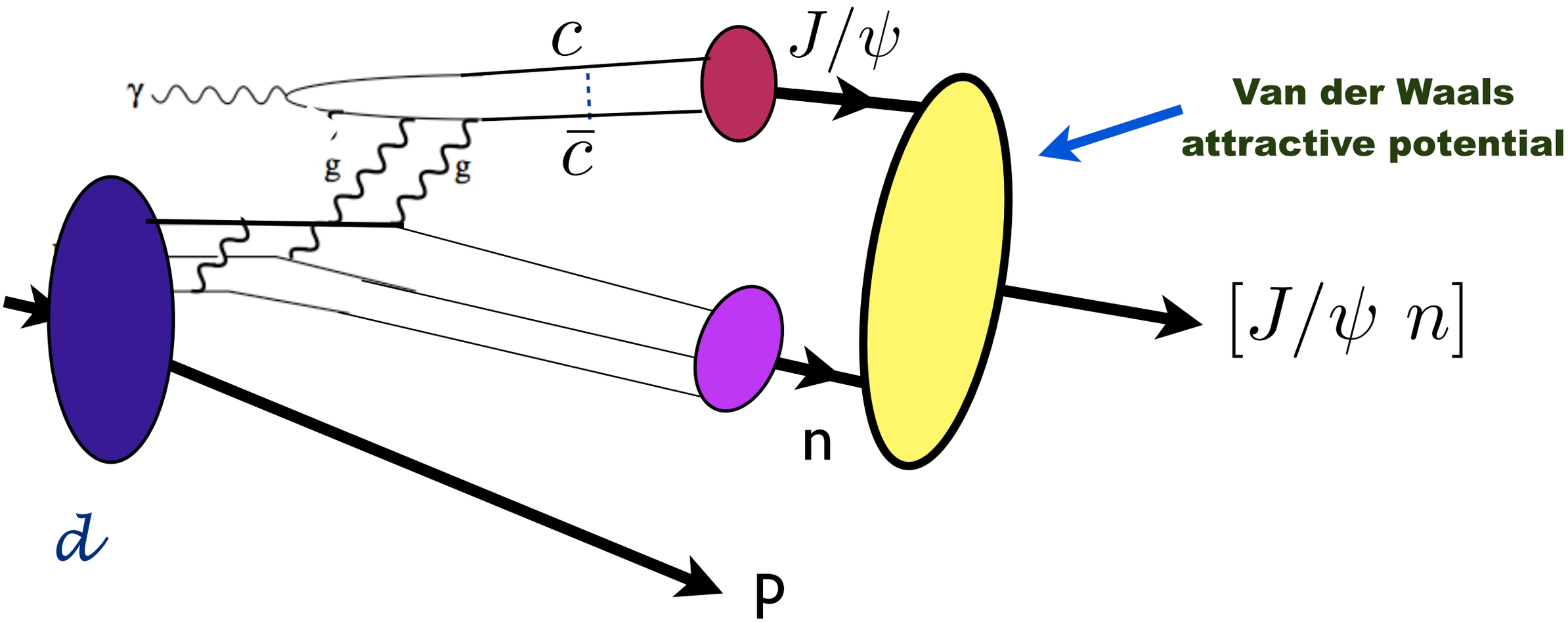
$$pA \to Pentaquark(|uudc\bar{c}>)X$$



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

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

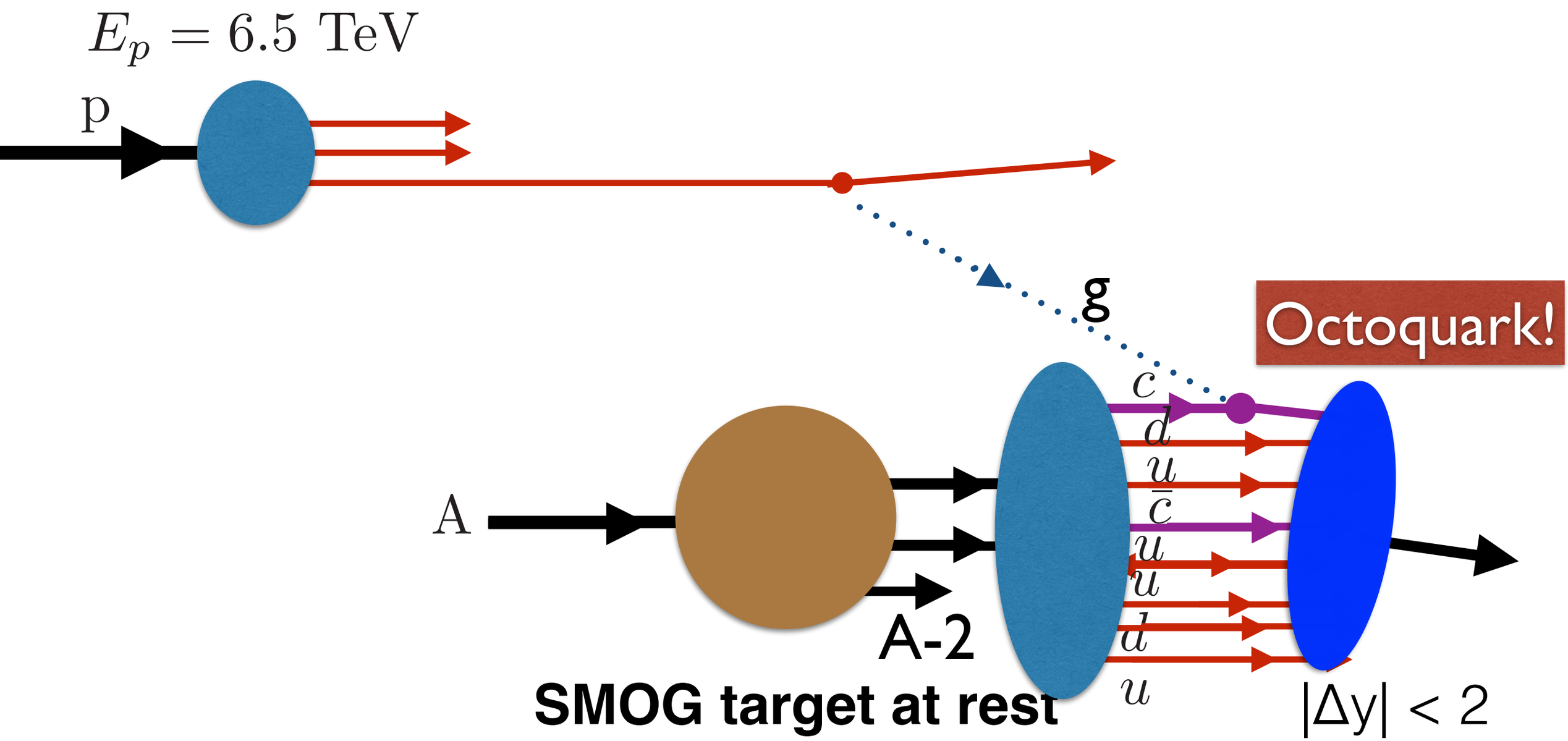
Charmonium Production at Threshold



$$\gamma\ d \to [J/\psi\ n]\ p \qquad\qquad \gamma\ d \to [J/\psi\ p]\ n$$

Form nucleon-charmonium bound state! $|uudc\bar{c}>$

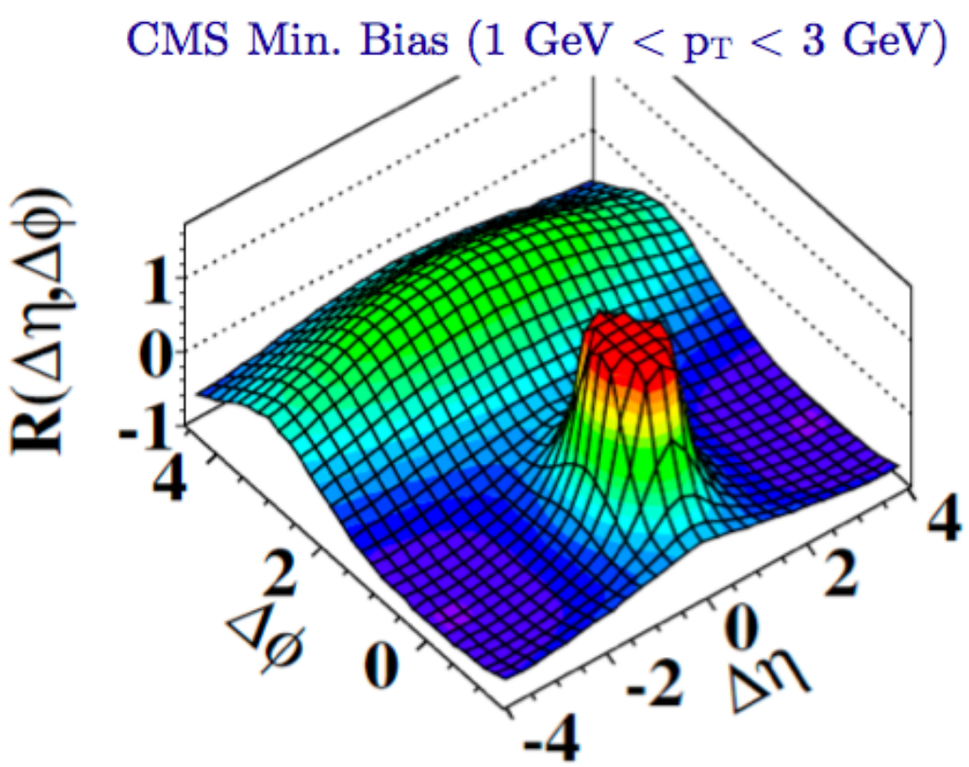
$$pA \to Octoquark(|uuduudc\bar{c}>)X$$



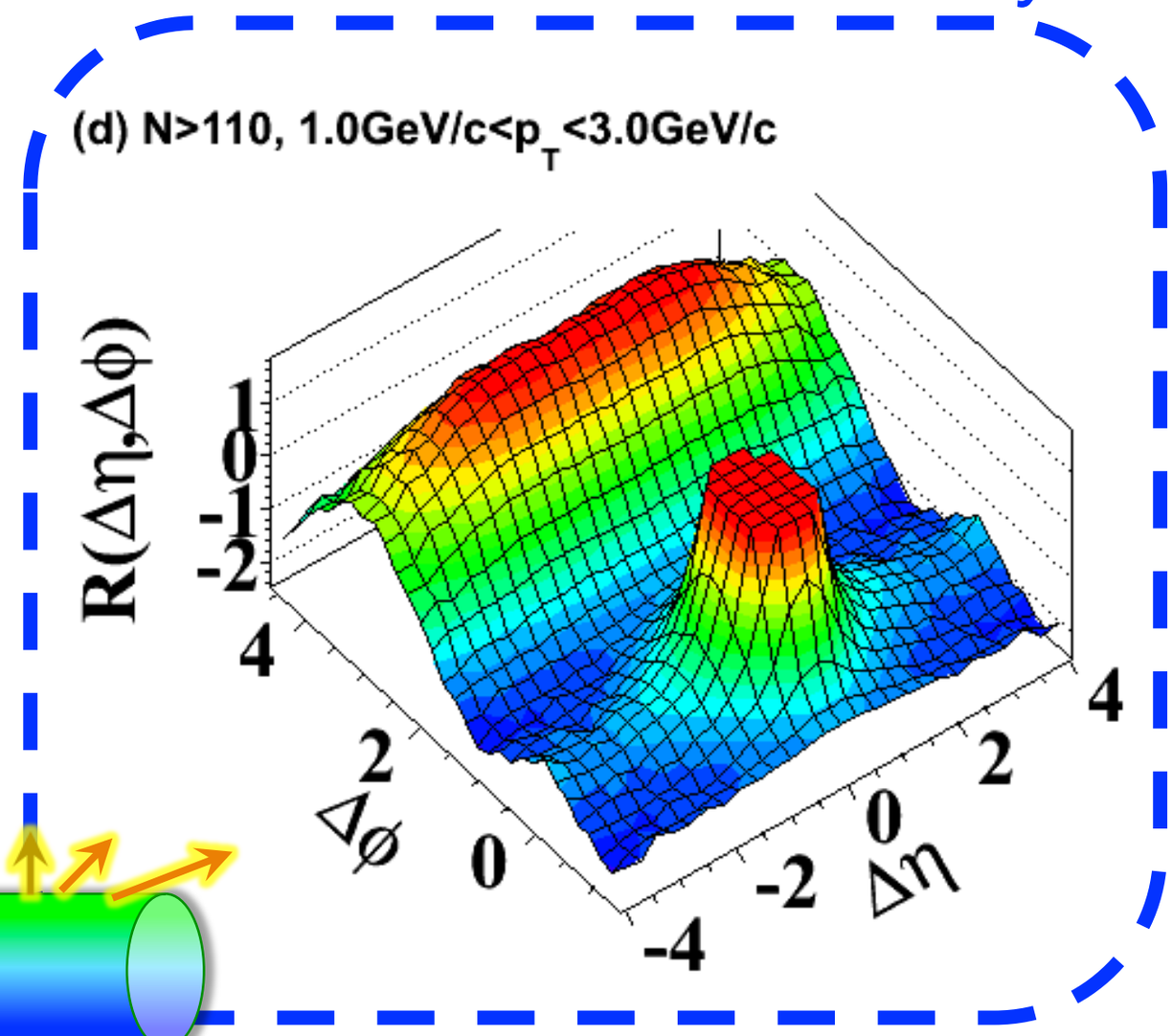
Intrinsic heavy quark probability in the nucleon maximal at minimum off-shellness

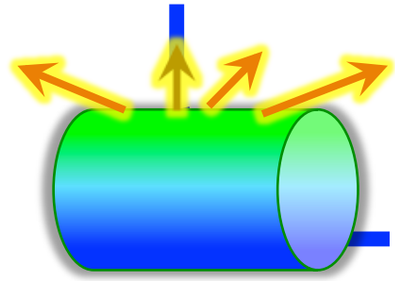
Produced nearly at rest — has small rapidity in target rest frame

Two particle correlations: CMS results



"Discovery"

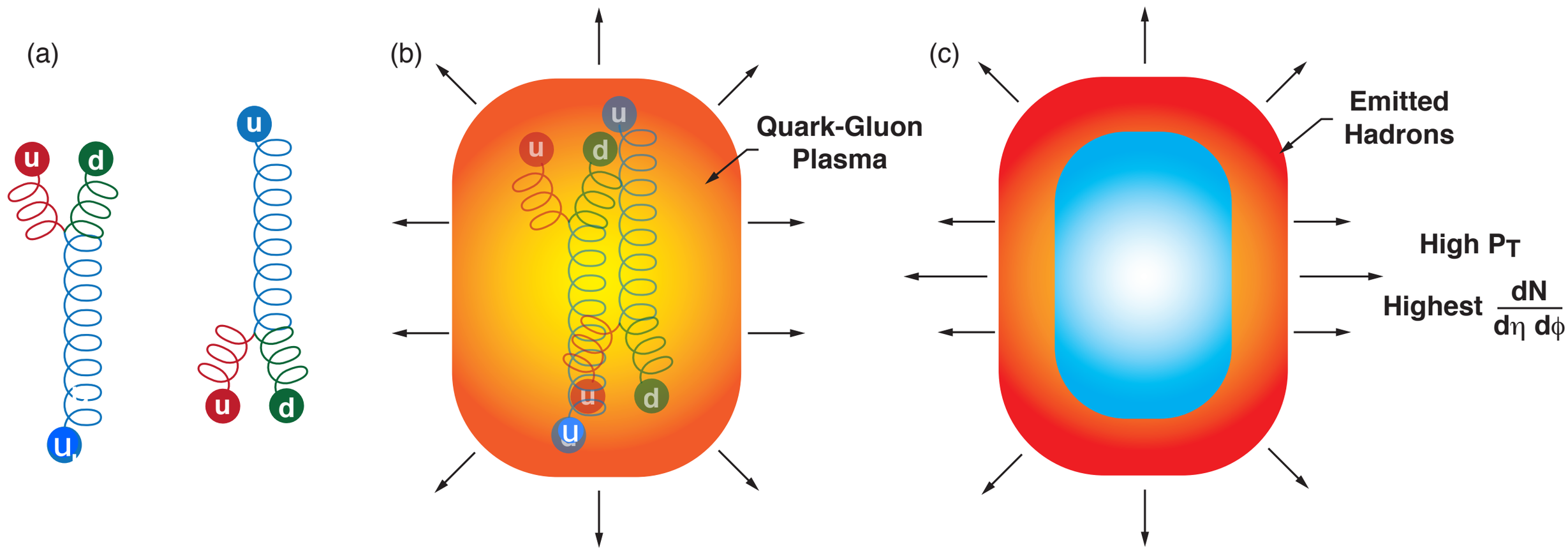




- **Ridge: Distinct long range correlation in η collimated around ΔΦ≈ 0 for two hadrons in the intermediate 1 < p_T, q_T < 3 GeV**

Possible origin of same-side CMS ridge in p p Collisions

Bjorken, Goldhaber, sjb



$$\vec{V} = \sum_{i=1}^{N} [\cos 2\phi_i \hat{x} + \sin 2\phi_i \hat{y}]$$

Possible multiparticle ridge-like correlations in very high multiplicity proton-proton collisions

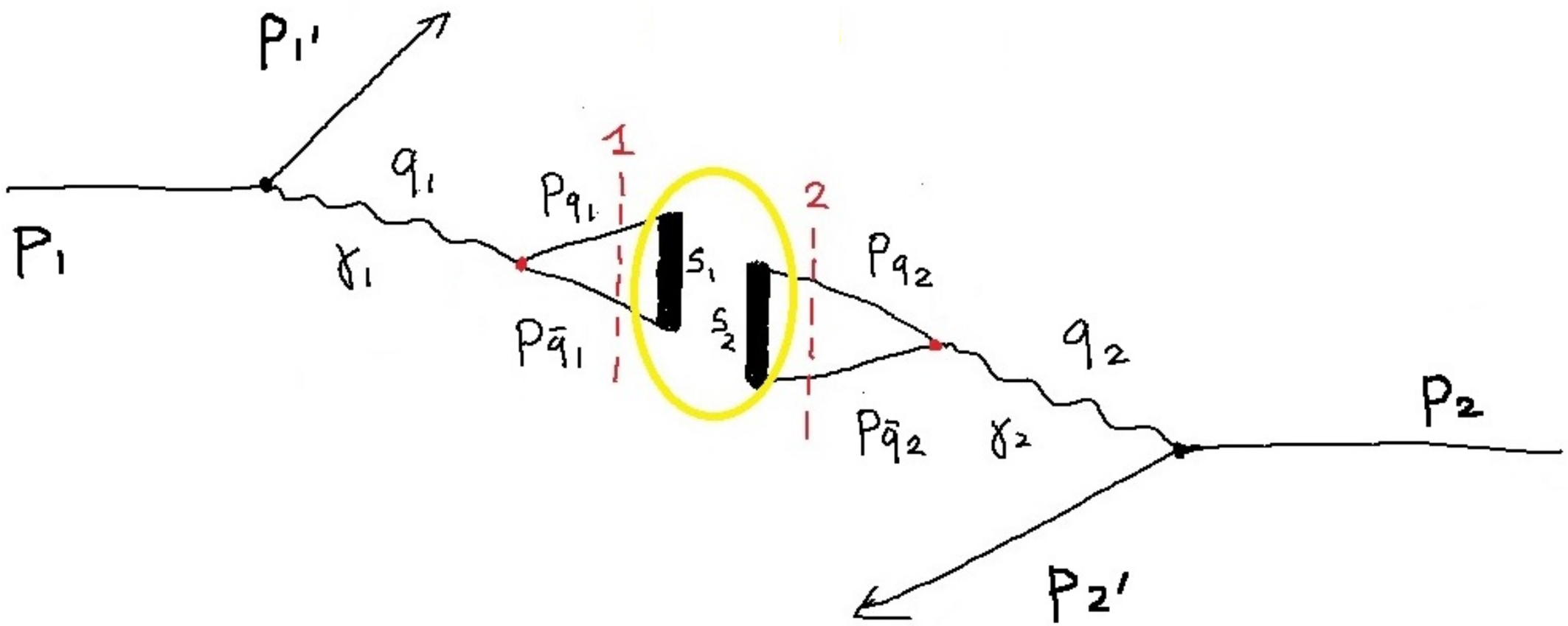
Bjorken, Goldhaber, sjb

We suggest that this "ridge"-like correlation may be a reflection of the rare events generated by the collision of aligned flux tubes connecting the valence quarks in the wave functions of the colliding protons.

The "spray" of particles resulting from the approximate line source produced in such inelastic collisions then gives rise to events with a strong correlation between particles produced over a large range of both positive and negative rapidity.

Collisions of Aligned Flux Tubes produce high multiplicity events

Brown, Glazek, Goldhaber, sjb



Ridges correlate with scattering plane of proton!

Novel QCD

- Flavor-Dependent Anti-Shadowing;
- No nuclear structure function sum rules
- LF Vacuum and Cosmological Constant: No QCD vacuum condensates
- Principle of Maximum Conformality (PMC): Eliminate renormalization ambiguity; scheme independent
- Match Perturbative and Non-Perturbative Domains
- Hadronization at Amplitude Level
- Intrinsic Heavy Quarks from AdS/QCD: Higgs at high x_F
- Ridge from Flux-Tube Collisions
- Baryon-to-Meson Anomaly at high P_T

PRL 110, 192001 (2013) PHYSICAL REVIEW LETTERS week ending 10 MAY 2013

Systematic All-Orders Method to Eliminate Renormalization-Scale and Scheme Ambiguities in Perturbative QCD

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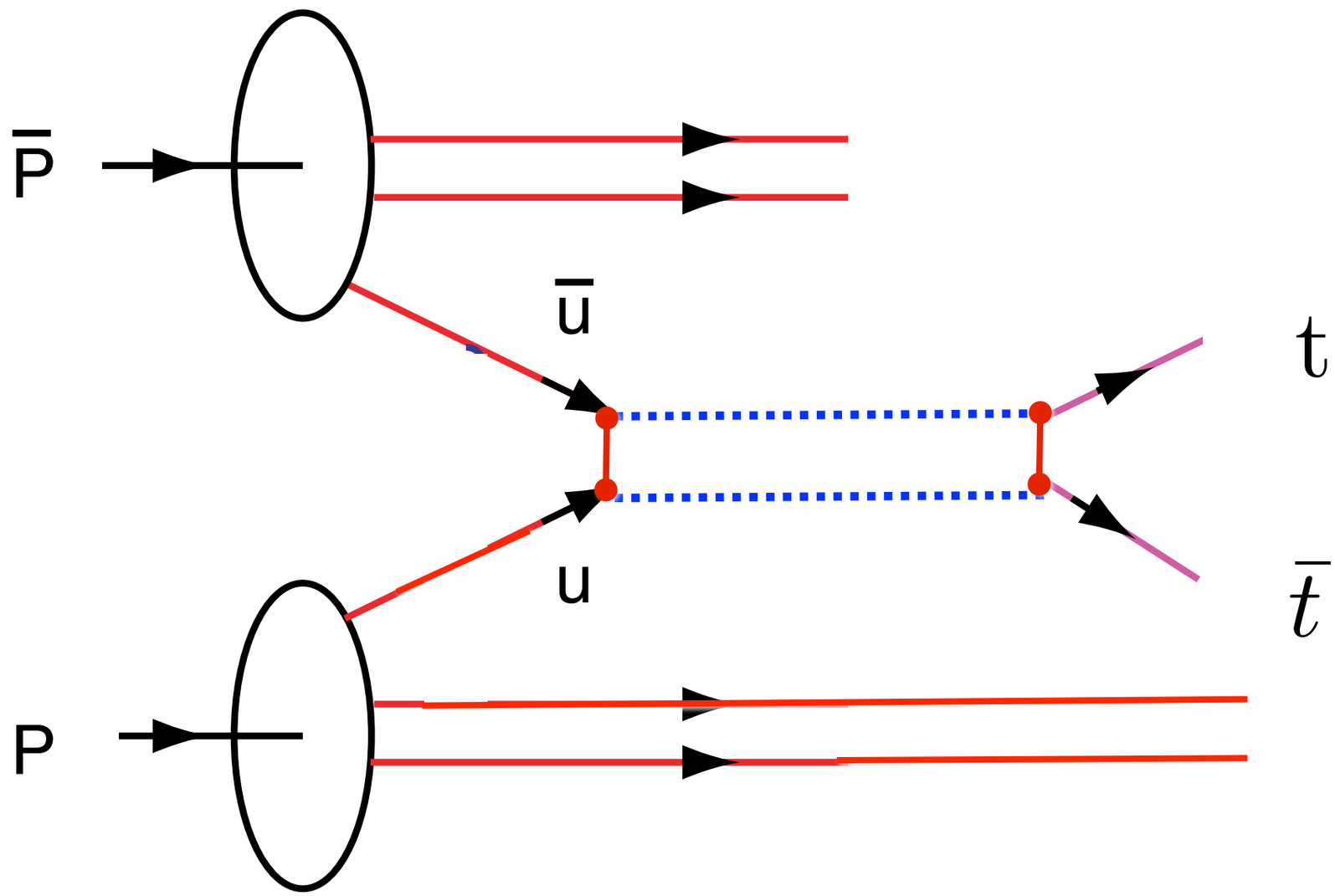
We introduce a generalization of the conventional renormalization schemes used in dimensional regularization, which illuminates the renormalization scheme and scale ambiguities of perturbative QCD predictions, exposes the general pattern of nonconformal $\{\beta_i\}$ terms, and reveals a special degeneracy of the terms in the perturbative coefficients. It allows us to systematically determine the argument of the running coupling order by order in perturbative QCD in a form which can be readily automatized. The new method satisfies all of the principles of the renormalization group and eliminates an unnecessary source of systematic error.

PMC: Principle of Maximum Conformality

Implications for the $\bar{p}p \to t\bar{t}X$ asymmetry at the Tevatron

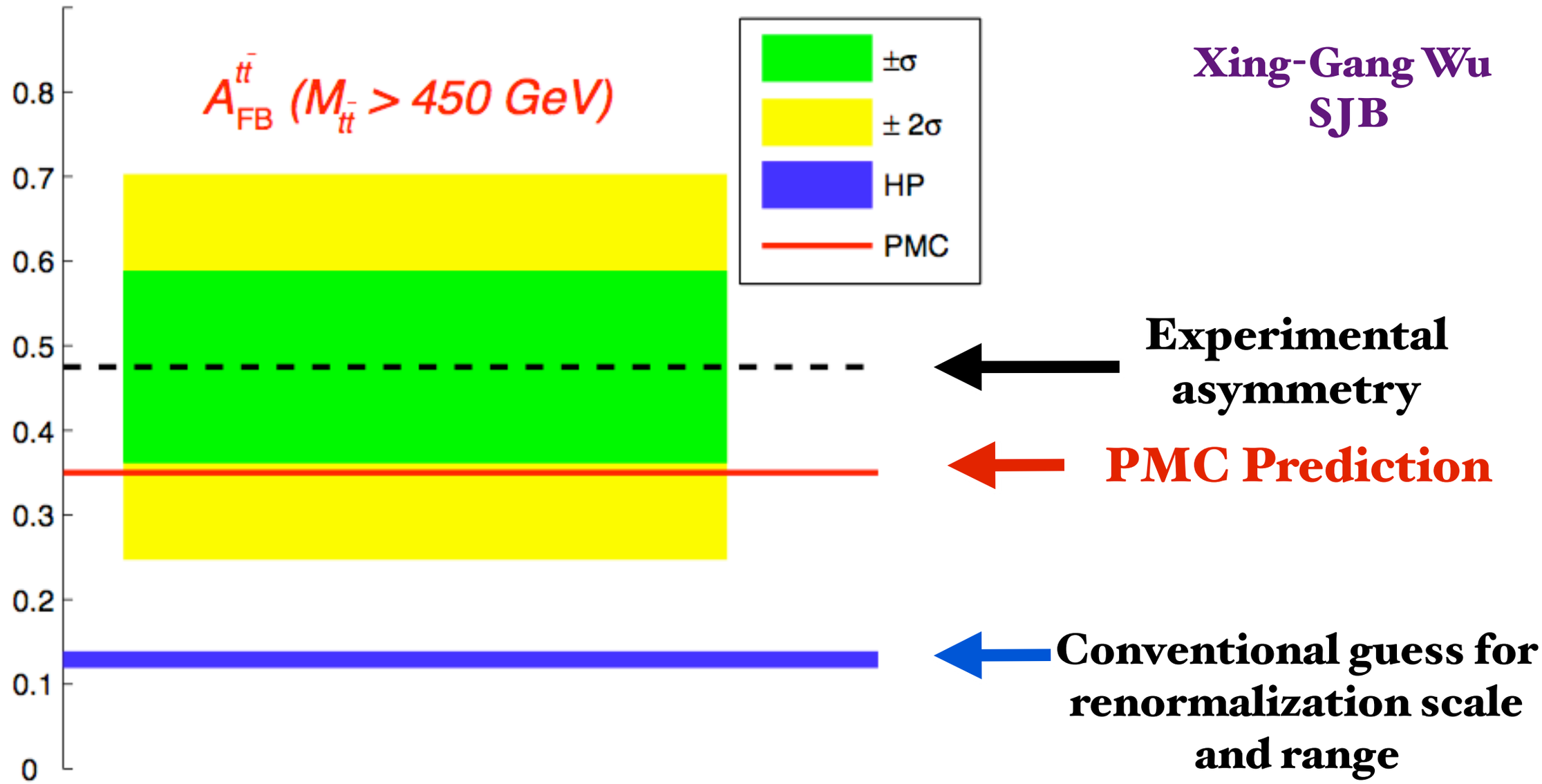


Interferes with Born term.

Small value of renormalization scale increases asymmetry, just as in QED

Xing-Gang Wu, sjb

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



Top quark forward-backward asymmetry predicted by pQCD NNLO within 1 σ of CDF/D0 measurements using PMC/BLM scale setting

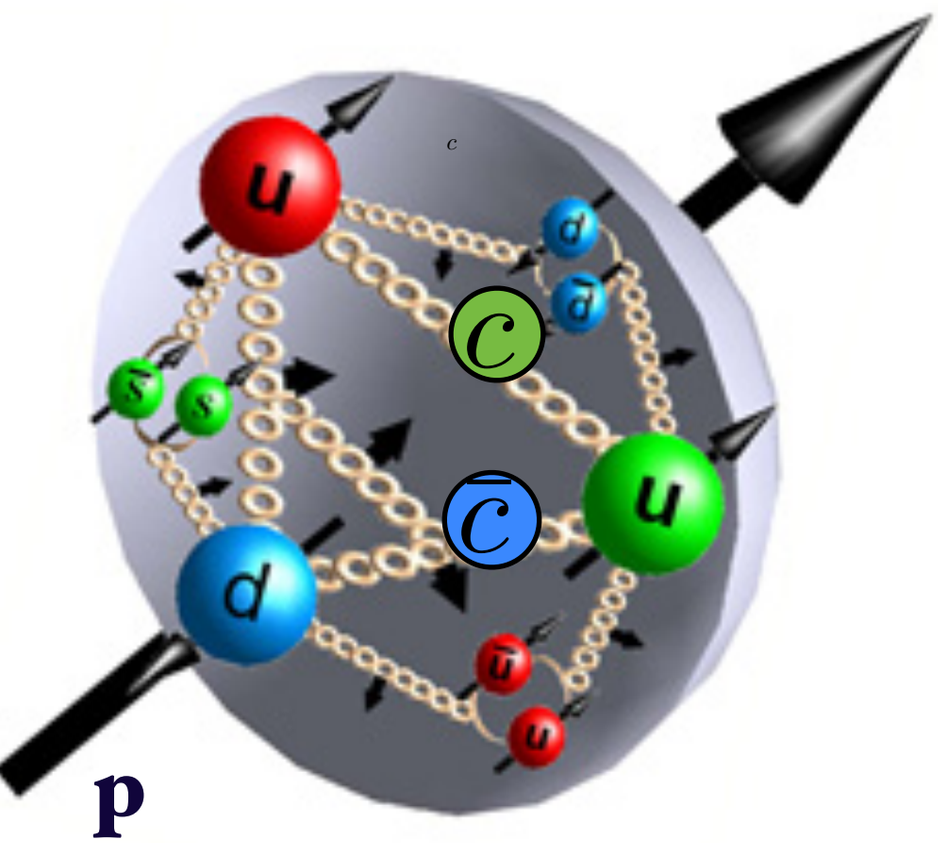
Why is IQ Important for Flavor Physics?

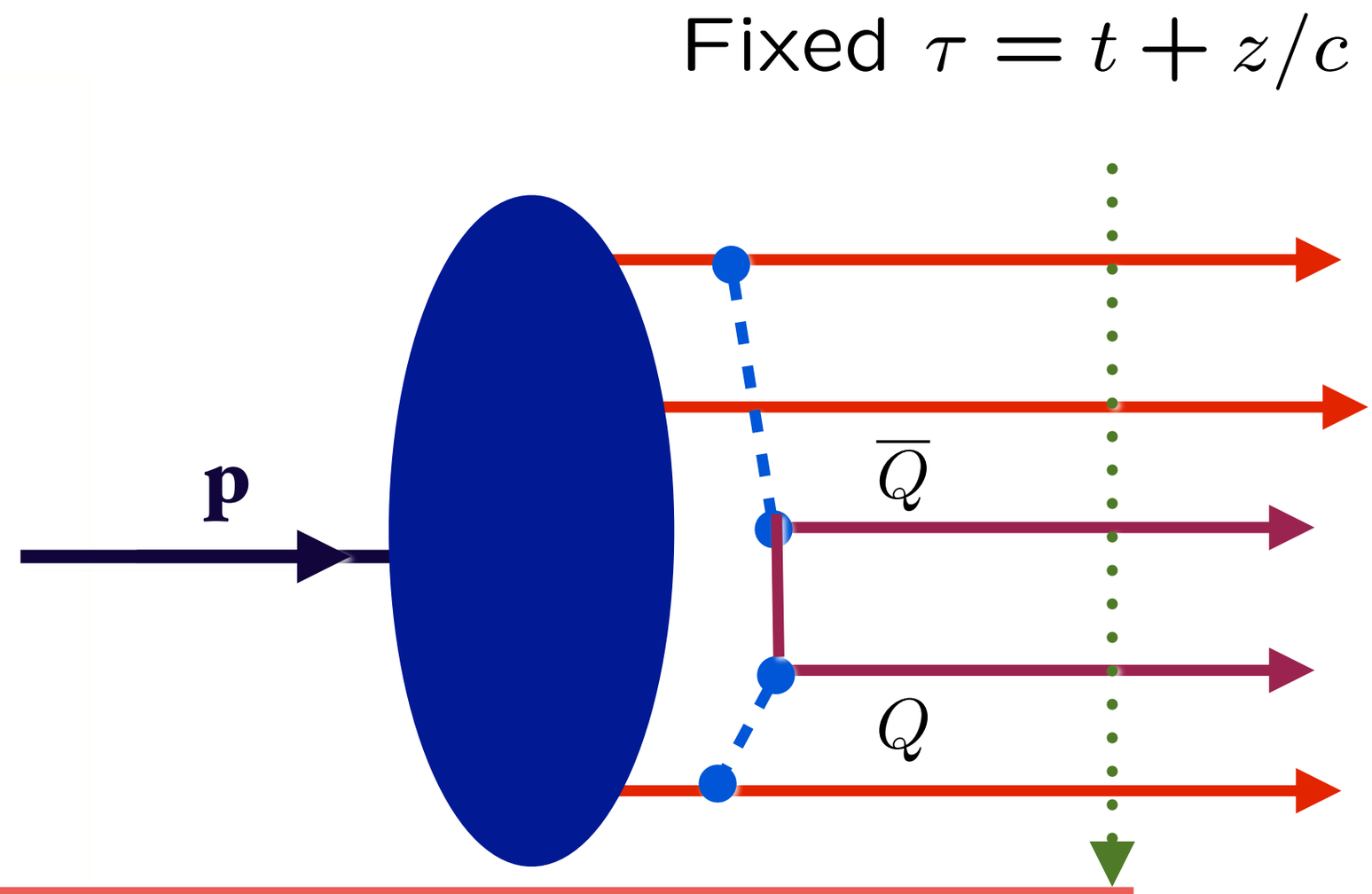
- **New perspective on fundamental nonperturbative hadron structure**
- **Charm structure function at high x**
- **Dominates high x_F charm and charmonium production**
- **Hadroproduction of new heavy quark states such as ccu, ccd, bcc, bbb, at high x_F**
- **Intrinsic charm -- long distance contribution to penguin mechanisms for weak decay** *Gardner, sjb*
- $J/\psi \to \rho\pi$ ***BES* puzzle explained** *Karliner , sjb*
- **Novel Nuclear Effects from color structure of IC, Heavy Ion Collisions**
- **New mechanisms for high x_F Higgs hadroproduction**
- **Dynamics of b production: LHCb**

New Multi-lepton Signals

- **AFTER LHCb: Fixed target program at LHC: produce exotic heavy quark states**

Novel Features of QCD Phenomenology at High X





CFNS workshop on Forward Physics And Instrumentation From Colliders To Cosmic Rays

Center for Frontiers in Nuclear Science

Stony Brook
October 17, 2018

Stan Brodsky

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