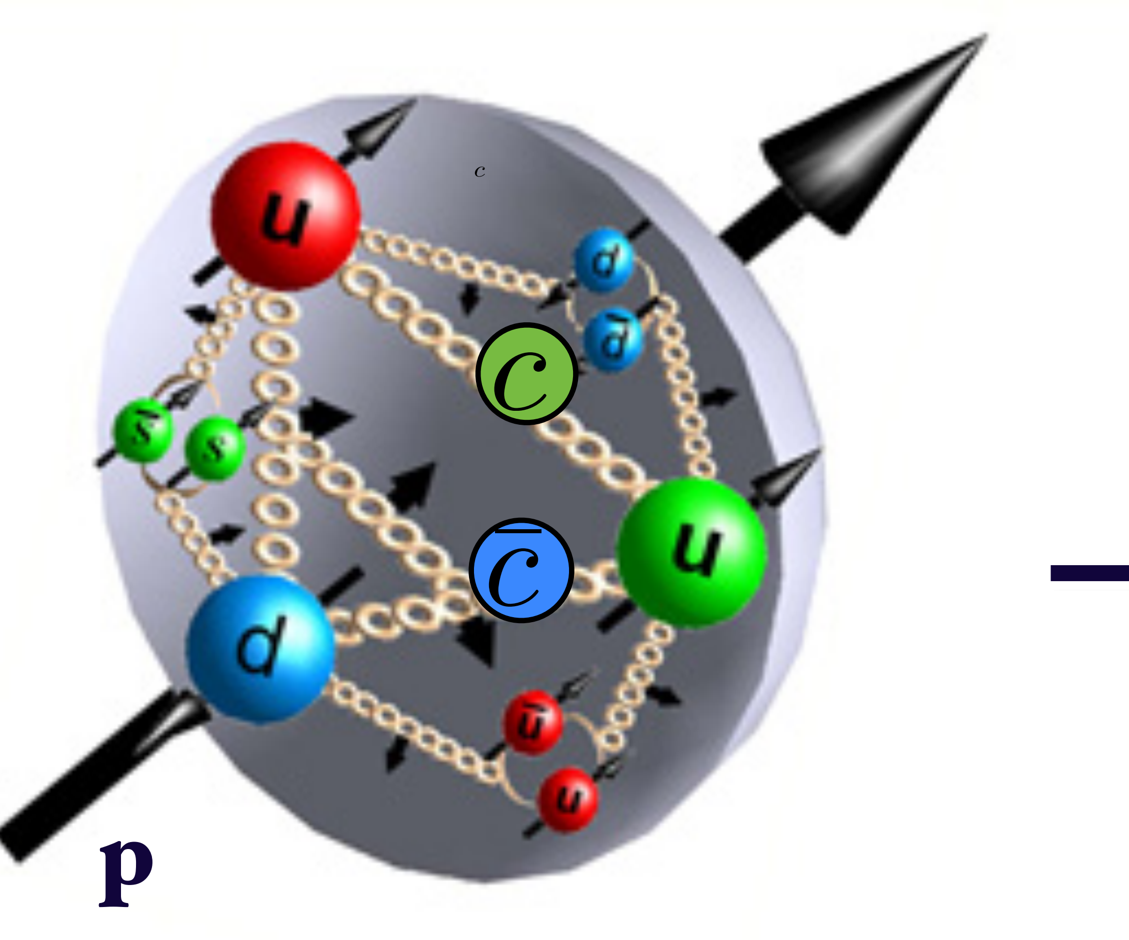
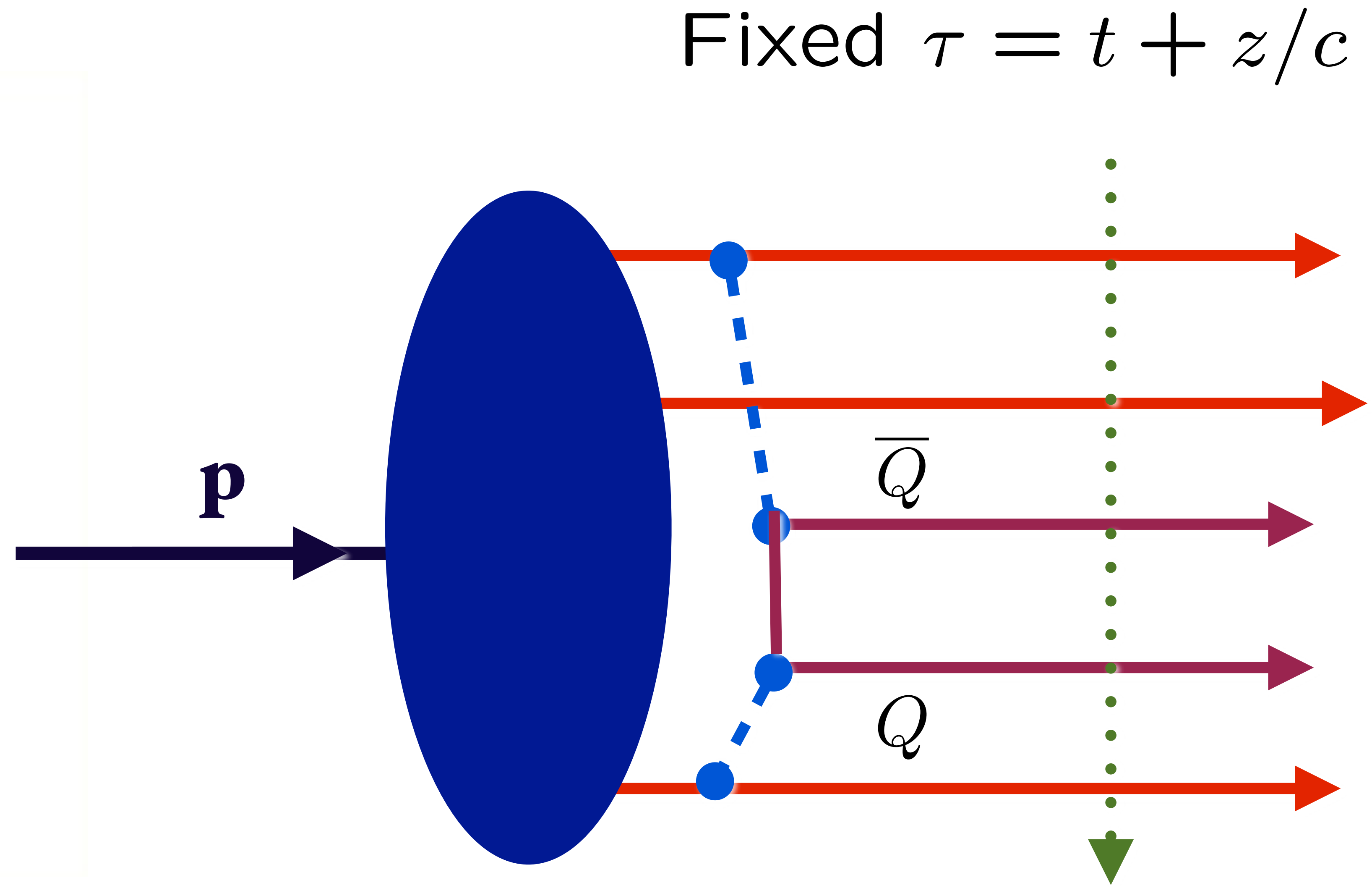
Novel Features of QCD Phenomenology at the LHC





LHC Working-Group Workshop on Forward Physics and Diffraction

Instituto de Física Teórica
UAM-CSIC

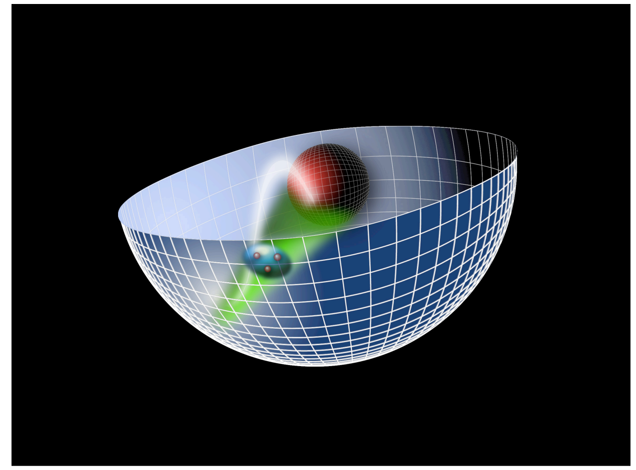
Madrid
March 22, 2018

Stan Brodsky
SLAC NATIONAL ACCELERATOR LABORATORY

de Tèramond, Dosch, sjb

AdS/QCD
Soft-Wall Model

Single scheme-independent fundamental mass scale
κ



Light-Front Holography

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

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

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:

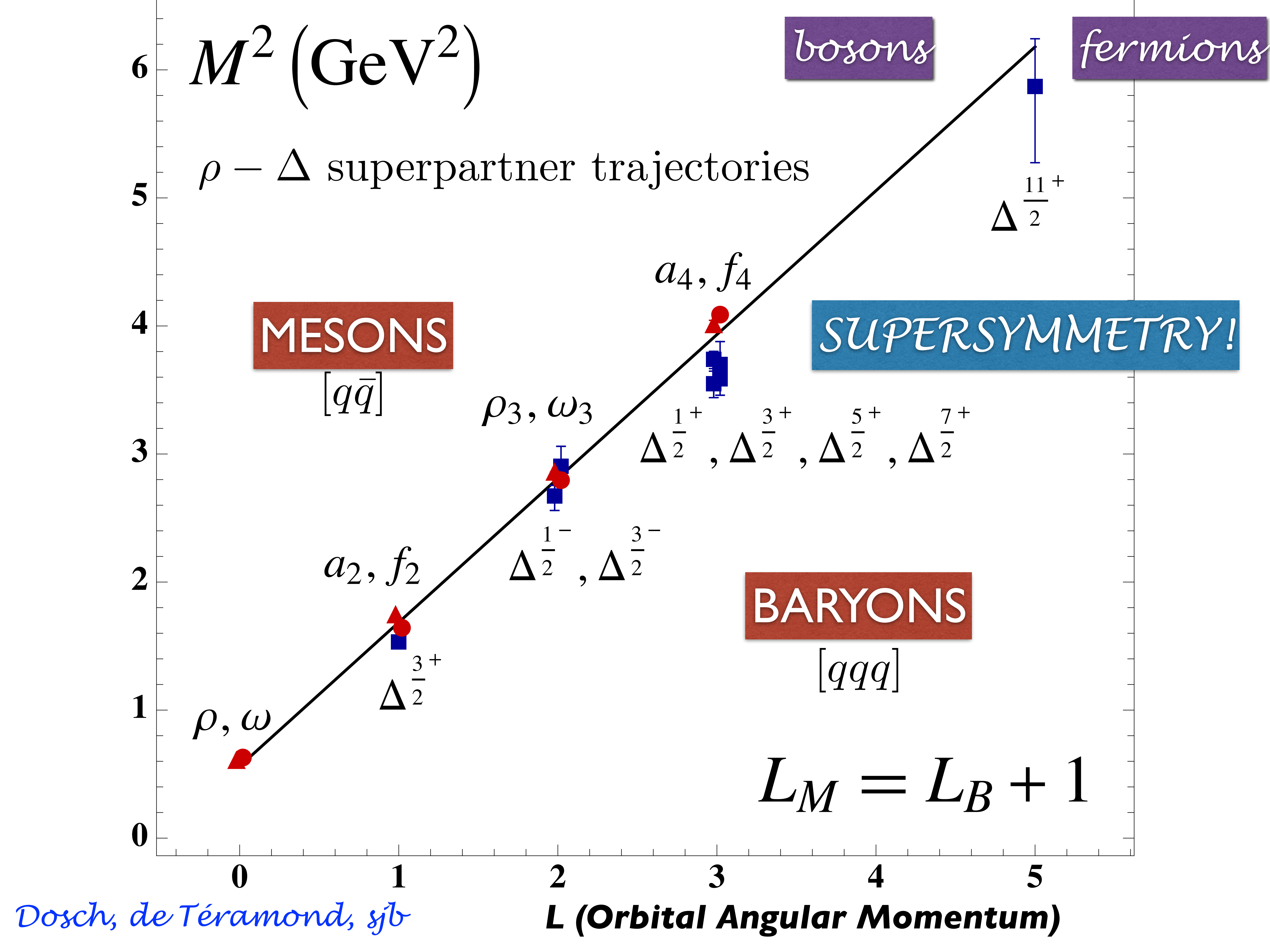
(m_q=0)

$$\kappa \simeq 0.6\ GeV$$

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

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

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

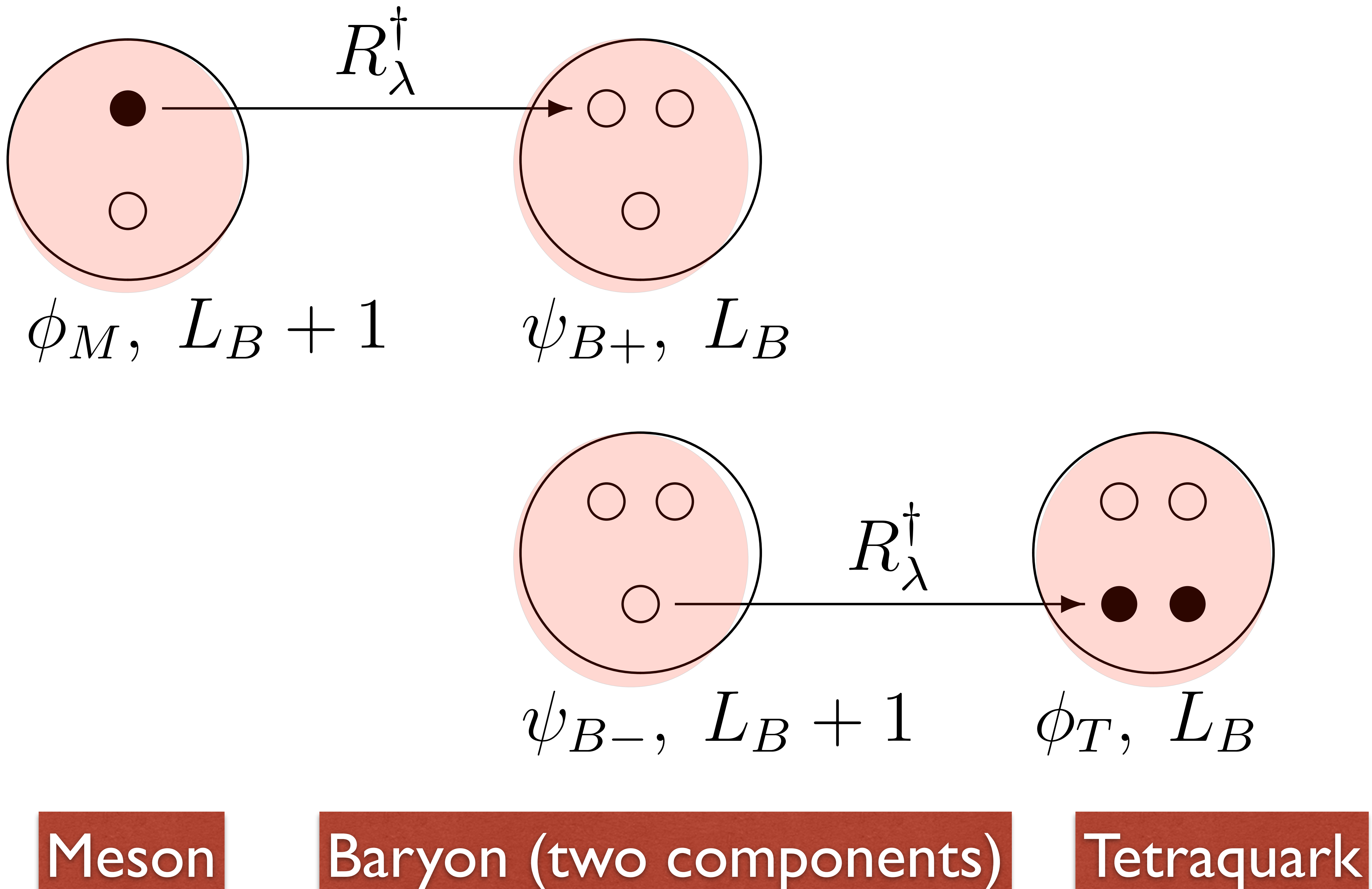


$M^2\,(\mathrm{GeV}^2)$
$\rho - \Delta$ superpartner trajectories
bosons
fermions
MESONS
$[q\bar{q}]$
SUPERSYMMETRY!
BARYONS
$[qqq]$
ρ, ω
a_2, f_2
ρ_3, ω_3
a_4, f_4
$\Delta^{\frac{3}{2}^+}$
$\Delta^{\frac{1}{2}^-}, \Delta^{\frac{3}{2}^-}$
$\Delta^{\frac{1}{2}^+}, \Delta^{\frac{3}{2}^+}, \Delta^{\frac{5}{2}^+}, \Delta^{\frac{7}{2}^+}$
$\Delta^{\frac{11}{2}^+}$
$L_M = L_B + 1$
0
1
2
3
4
5
6
L (Orbital Angular Momentum)
Dosch, de Téramond, sjb

de Tèramond, Dosch, Lorce, sjb

Superconformal Algebra

2X2 Hadronic Multiplets



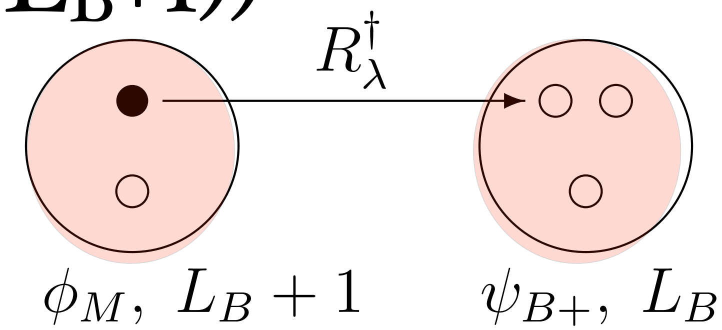
de Tèramond, Dosch, Lorce, sjb

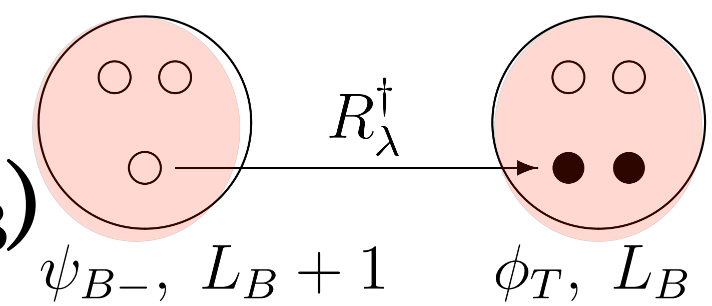
Superconformal Algebra

2X2 Hadronic Multiplets

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

- quark-antiquark meson ($L_M = L_B + 1$))
- quark-diquark baryon (L_B)
- quark-diquark baryon ($L_B + 1$)
- diquark-antidiquark tetraquark ($L_T = L_B$)
- Universal Regge slopes $\lambda = \kappa^2$





$$M_H^2/\lambda = \underbrace{\overbrace{(2n + L_H + 1)}^{}}_{kinetic} + \underbrace{(2n + L_H + 1)}_{potential} \quad \text{(contribution from 2-dim light-front harmonic oscillator)} + \overbrace{2(L_H + s) + 2\chi}^{\text{contribution from AdS and superconformal algebra}} + < \sum_i \frac{m_i^2}{x_i} >$$

$\chi(mesons) = -1$ $\qquad$ $\chi(baryons, tetraquarks) = +1$

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^{++}	$a_3(\sim 2070)?$
$\bar{q}s$	$0^{-(+)}$	$K(495)$	—	—	—	—	—	—
$\bar{q}s$	$1^{+(-)}$	$\bar{K}_1(1270)$	$[ud]s$	$(1/2)^+$	$\Lambda(1115)$	$[ud][\bar{s}\bar{q}]$	$0^{+(+)}$	$K_0^*(1430)$
$\bar{q}s$	$2^{-(+)}$	$K_2(1770)$	$[ud]s$	$(1/2)^-$	$\Lambda(1405)$	$[ud][\bar{s}\bar{q}]$	$1^{-(+)}$	$K_1^*(\sim 1700)?$
				$(3/2)^-$	$\Lambda(1520)$			
$\bar{s}q$	$0^{-(+)}$	$K(495)$	—	—	—	—	—	—
$\bar{s}q$	$1^{+(-)}$	$K_1(1270)$	$[sq]q$	$(1/2)^+$	$\Sigma(1190)$	$[sq][\bar{s}\bar{q}]$	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

States with two heavy quarks

Trawinski, Stanislaw, Glazek, Brodsky, De Te'ramond, Dosch, PRD90(2104)

quadratic potential in FF for light quarks ⟷ linear potential in IF $V=Cr$

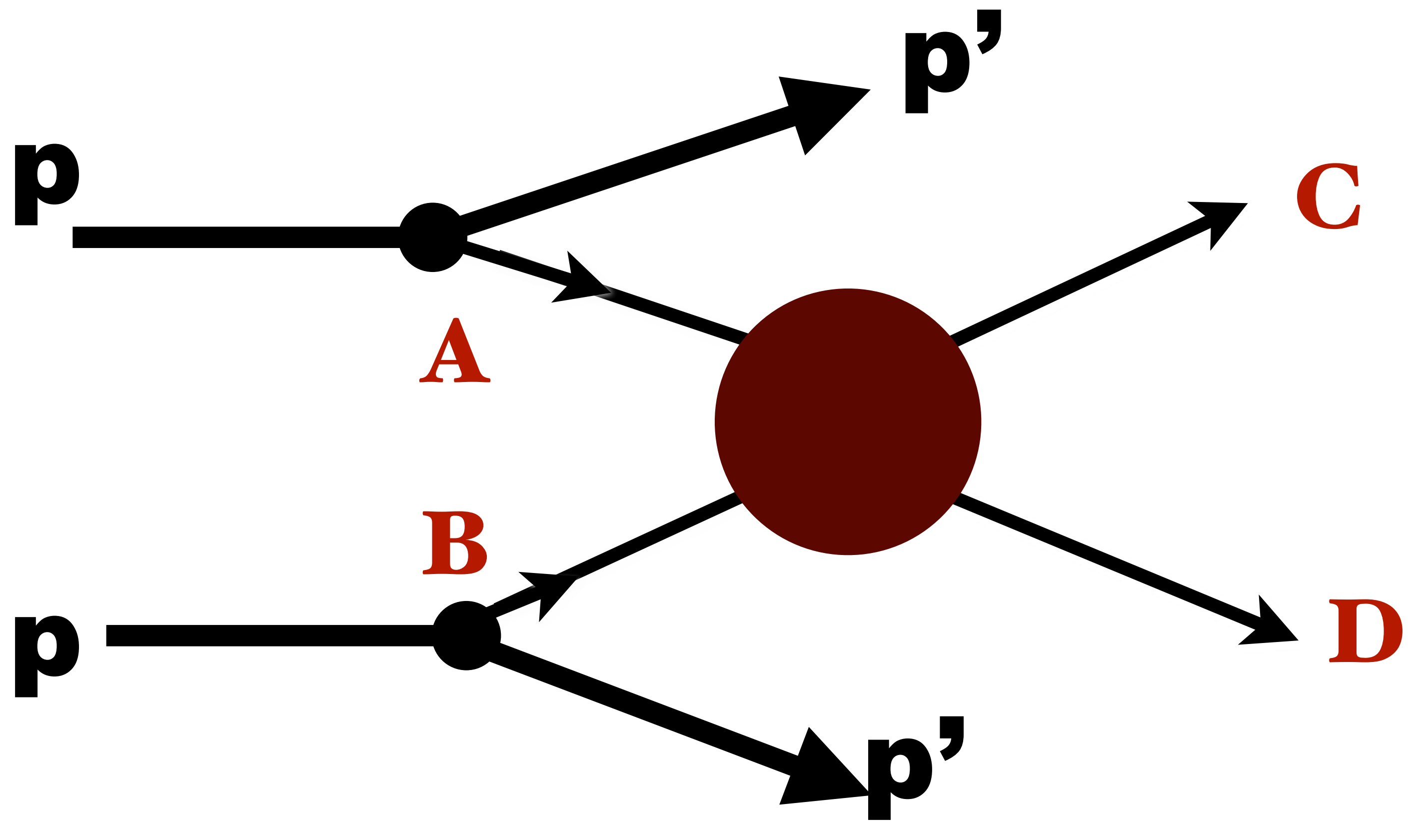
Cornell potential for heavy quarks

I=0, I=1?

The LF confinement potential for systems containing two heavy quarks will be modified. Therefore the extension of superconformal algebra to such states is somewhat speculative. However...

Meson			Baryon			Tetraquark		
q-cont	$J^{P(C)}$	Name	q-cont	J^P	Name	q-cont	$J^{P(C)}$	Name
$\bar{c}c$	0^{-+}	$\eta_c(2984)$	—	—	—	—	—	—
$c\bar{c}$	1^{+-}	$h_c(3525)$	$[cq]c$	$(1/2)^+$	$\Xi_{cc}^{SELEX}(3520)$ $\Xi_{cc}^{LHCb}(3620)$	$[cq][\bar{c}\bar{q}]$	0^{++}	$\chi_{c0}(3415)$
$\bar{c}c$	1^{--}	$J/\psi(3096)$	—	—	—	—	—	—
$\bar{c}c$	2^{++}	$\chi_{c2}(3556)$	$(cq)c$	$(3/2)^+$	$\Xi_{cc}^{LHCb}(3620)$	$(cq)[\bar{c}\bar{q}]$	1^{++}	$\chi_{c1}(3510)$

Identify exotics at the LHC: glueballs, tetraquarks, pentaquarks



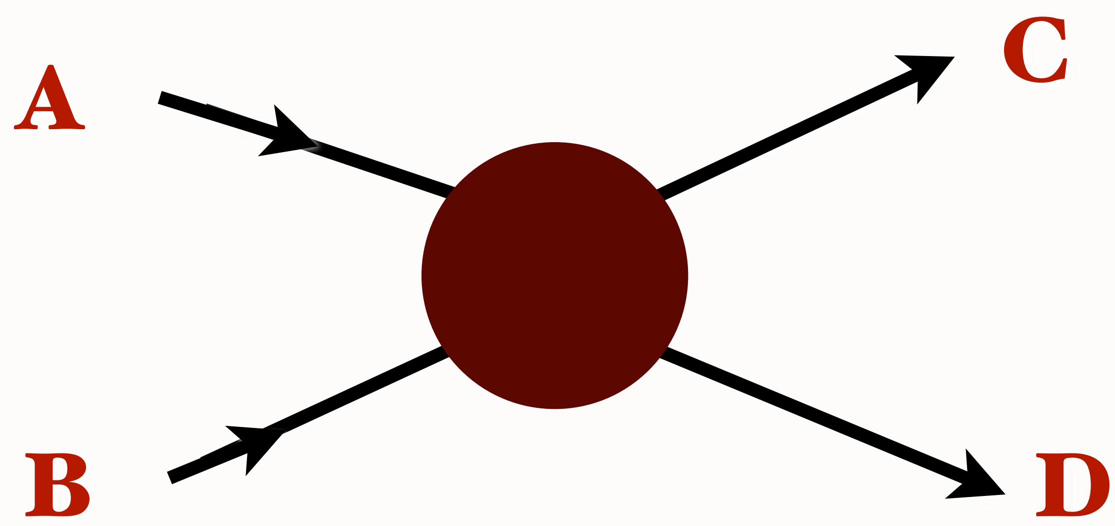
CEP: Central Exclusive Processes

R. McNulty

"Counting Rule" *Farrar and sjb; Muradyan, Matveev, Tavkelidze*

$$\frac{d\sigma}{dt}(A + B \to C + D) = \frac{F(t/s)}{s^{n_{tot}-2}}$$

$$n_{tot} = n_A + n_B + n_C + n_D$$

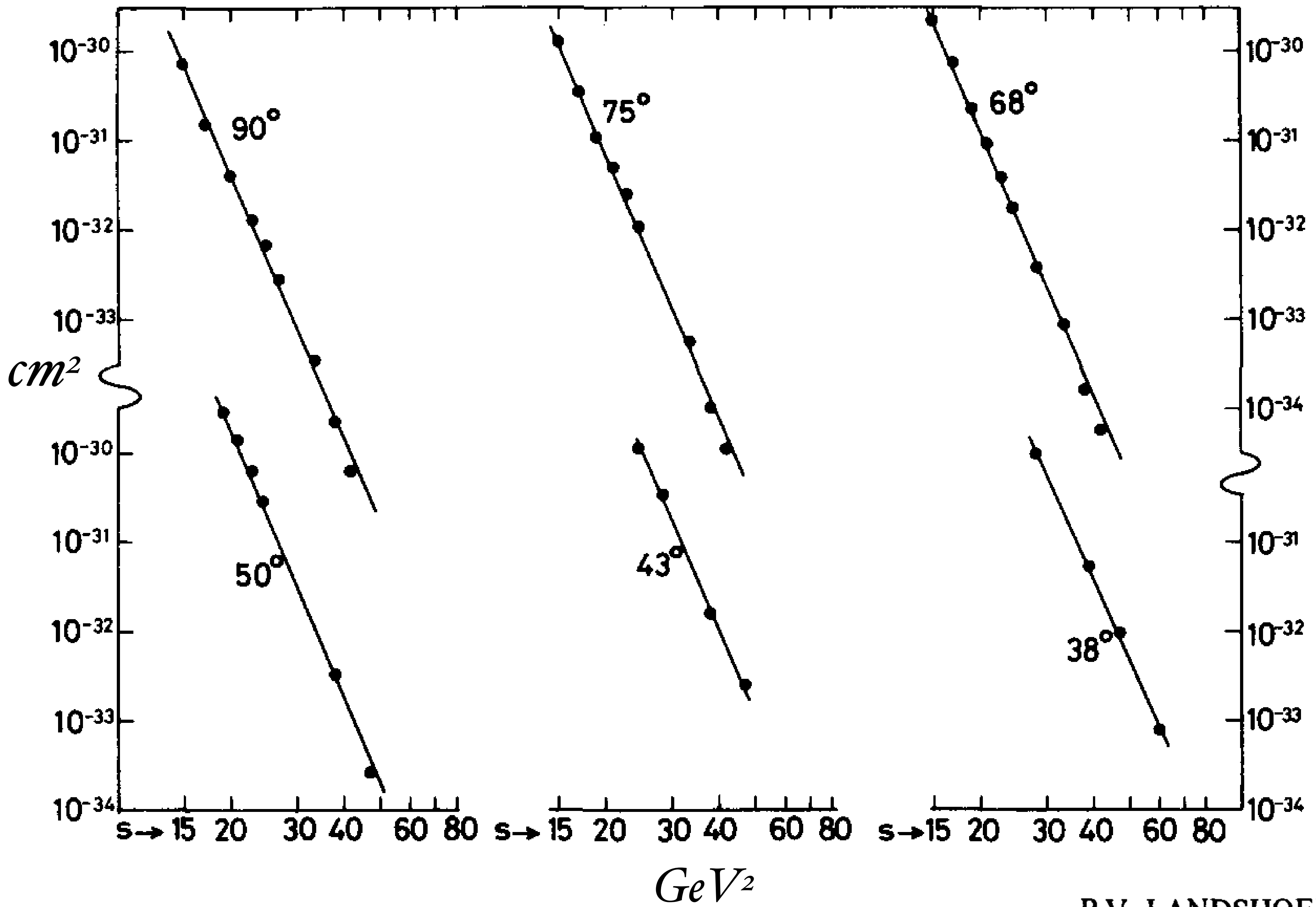


Counting rules
n = twist =
dimension-spin

e.g. $n_{tot} - 2 = n_A + n_B + n_C + n_D - 2 = 10$ for $pp \to pp$

Predict: $$\frac{d\sigma}{dt}(p + p \to p + p) = \frac{F(\theta_{CM})}{s^{10}}$$

Quark-Counting : $\frac{d\sigma}{dt}(pp \to pp) = \frac{F(\theta_{CM})}{s^{10}}$ $n = 4 \times 3 - 2 = 10$

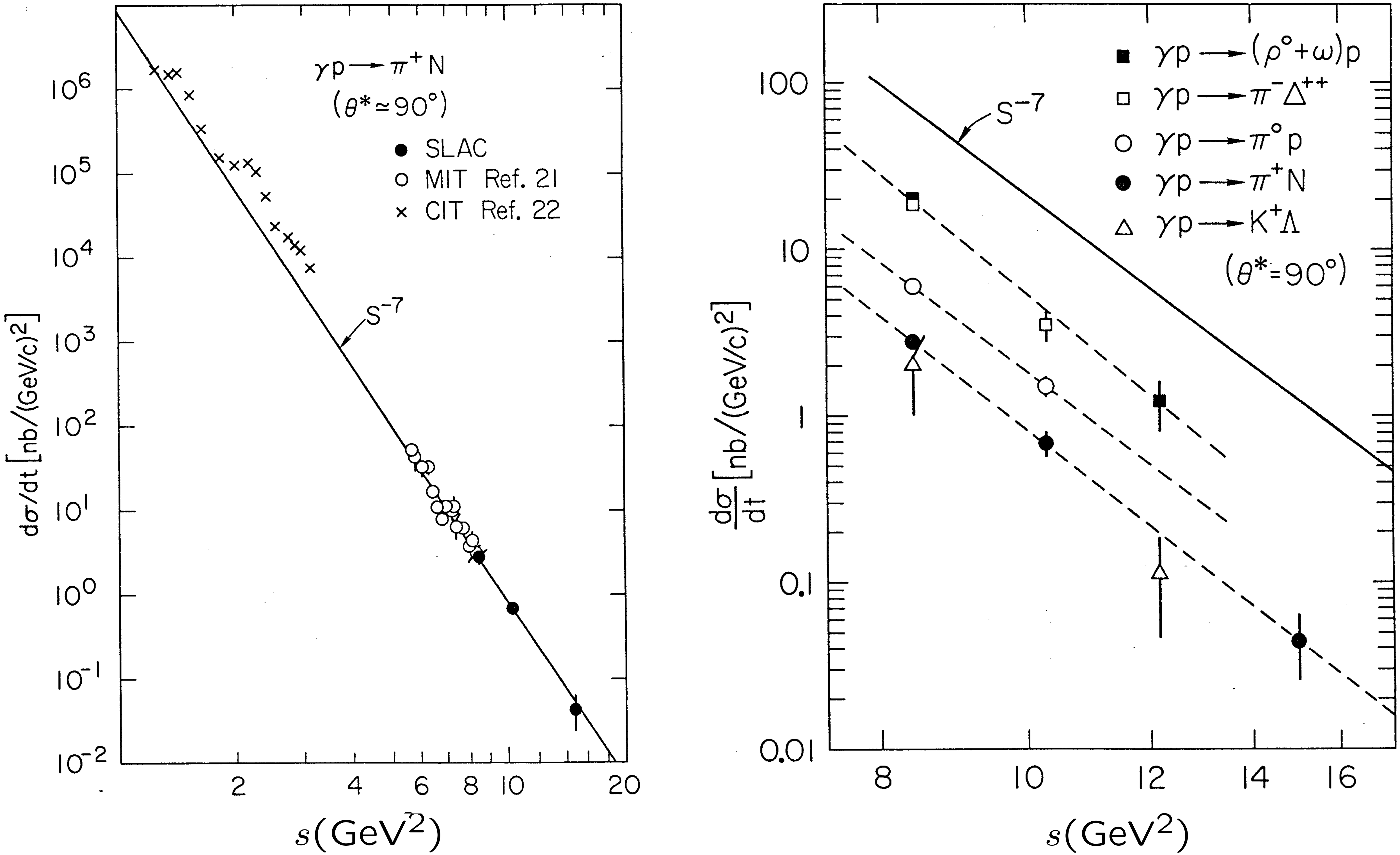


P.V. LANDSHOFF and J.C. POLKINGHORNE

Best Fit

$n = 9.7 \pm 0.5$

Reflects underlying conformal, scale-free interactions



Counting Rules: N=9

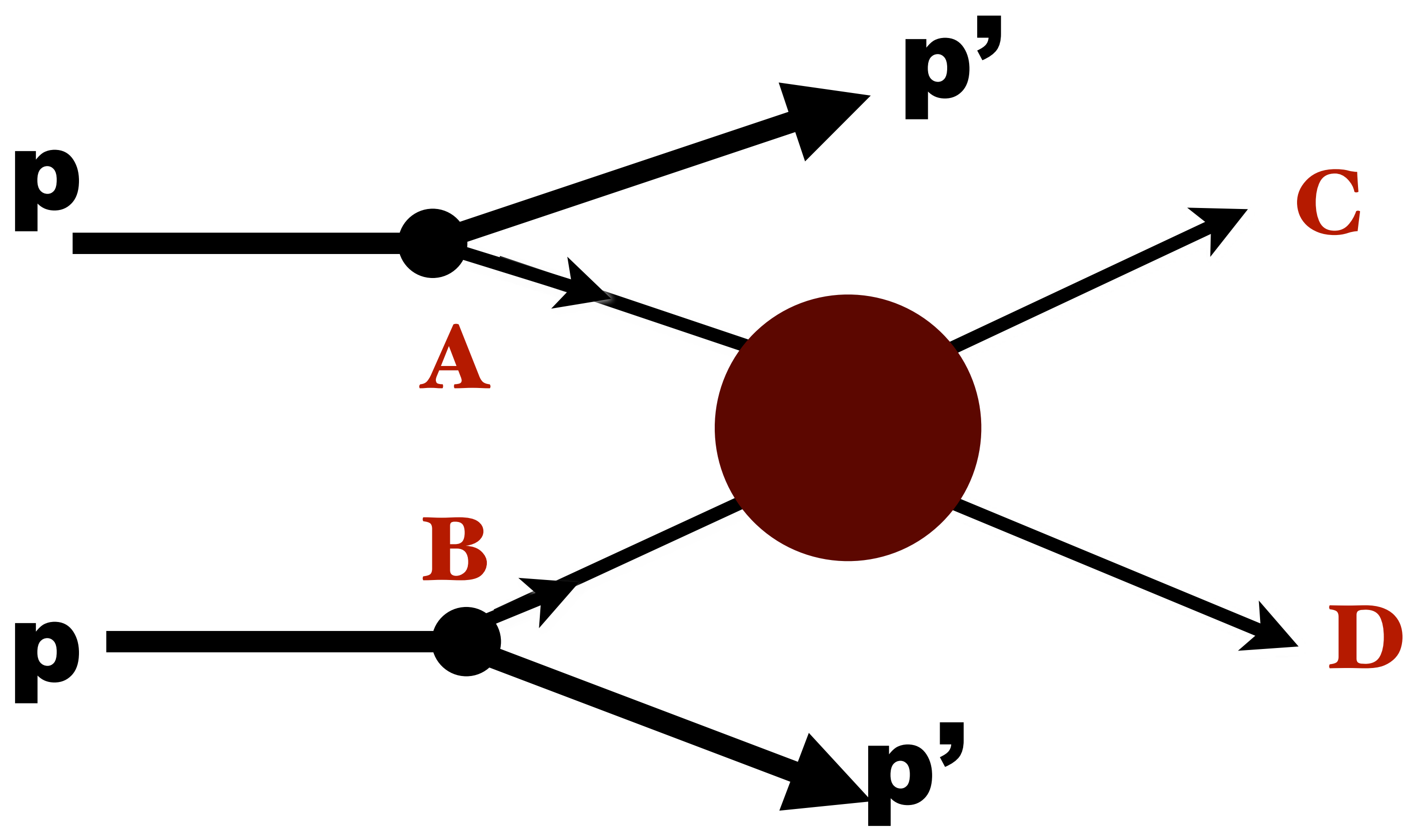
$$\frac{d\sigma}{dt}(\gamma p \to MB) = \frac{F(\theta_{cm})}{s^7}$$

$$\frac{d\sigma}{dt}(A+B \to C+D) = \frac{F(t/s)}{s^{n_{tot}-2}}$$

$$n_{tot} = n_A + n_B + n_C + n_D$$

$$s = (p_A + p_B)^2 = (p_C + p_D)^2$$

Counting rules
n = twist = dimension-spin



R. McNulty, sjb

CEP: Central Exclusive Processes

$$A, B : \gamma(n=1), pomeron(n=2), odderon(n=3)$$

$$C, D : \gamma(n=1), meson, glueball(n=2), baryon(n=3), tetraquark(n=4)$$

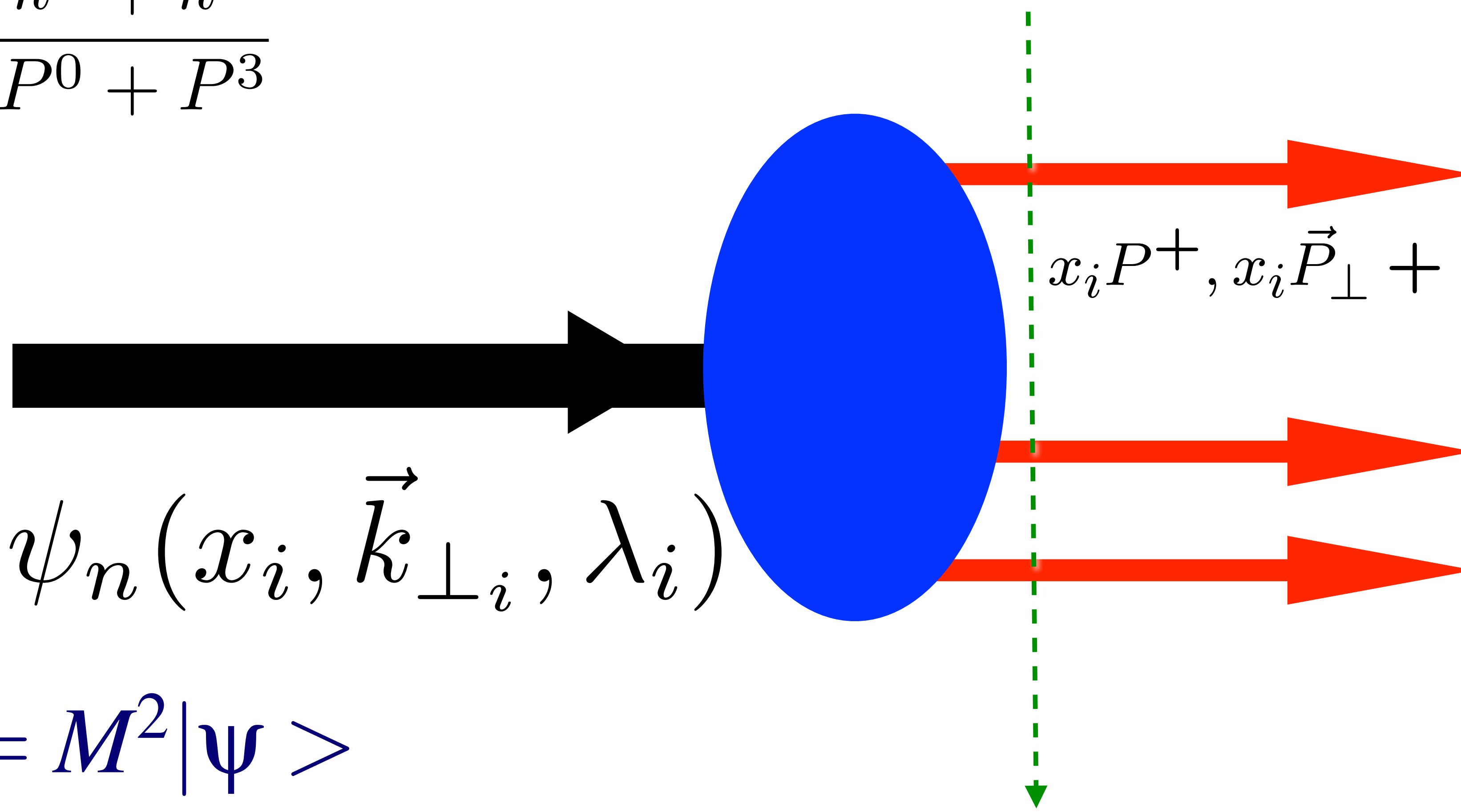
Light-Front Wavefunctions: rigorous representation of composite systems in quantum field theory

Eigenstate of LF Hamiltonian

Fixed $\tau = t + z/c$

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

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



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

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

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

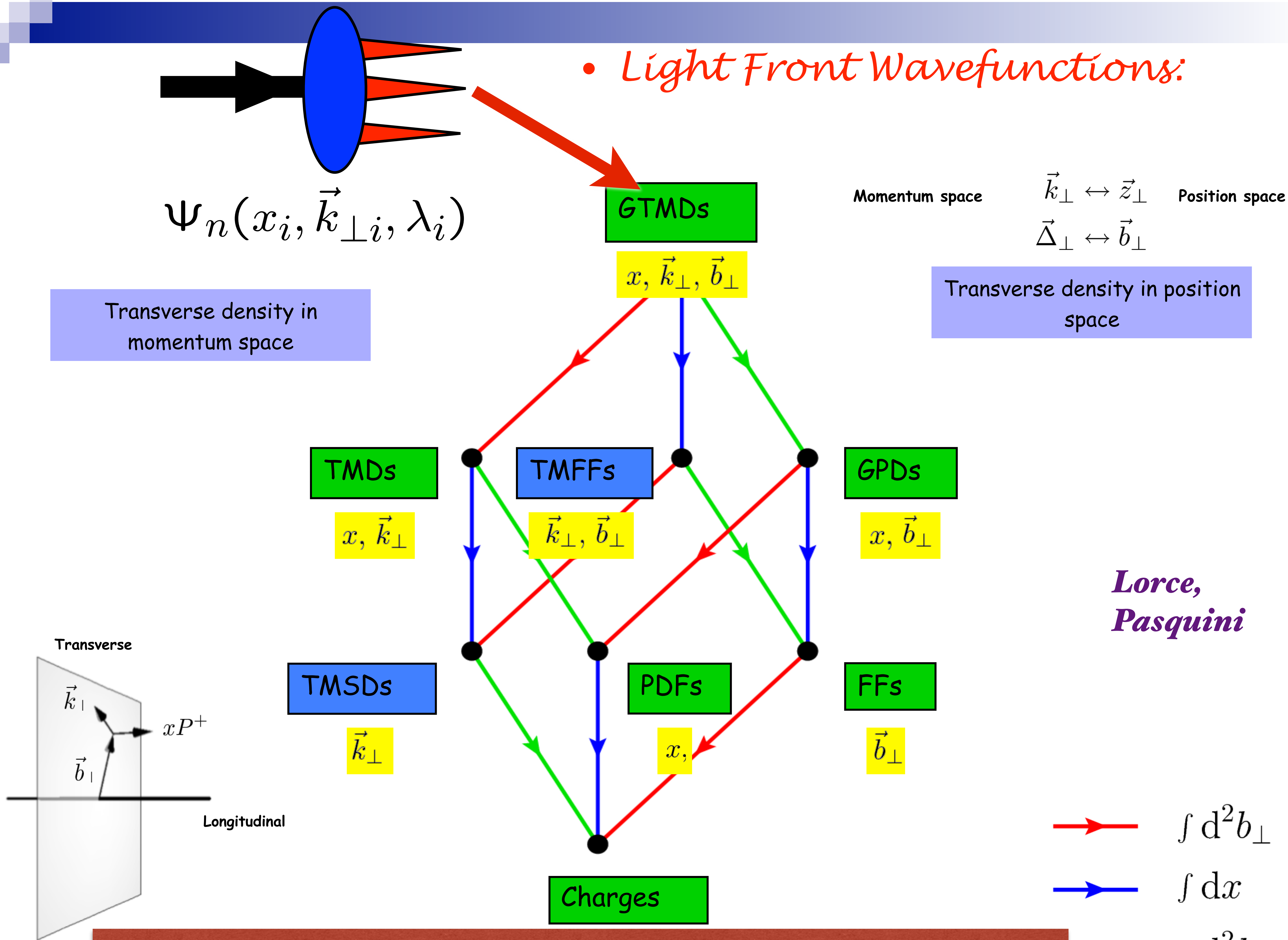
$\sum_i^n x_i = 1$

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

Invariant under boosts! Independent of P^μ

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

- *Light Front Wavefunctions:*

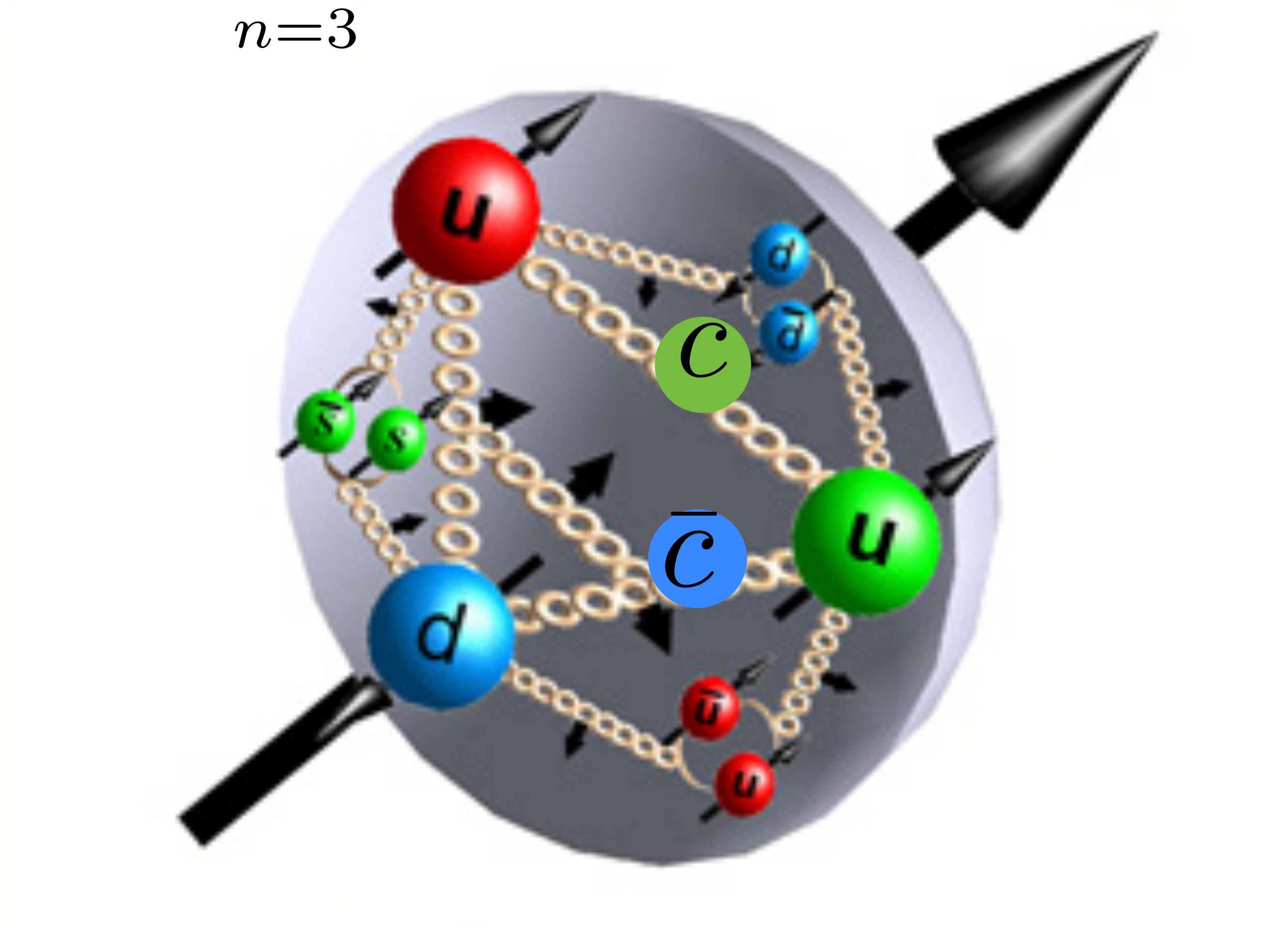


+ Factorization-Breaking Lensing Corrections: Sivers, T-odd

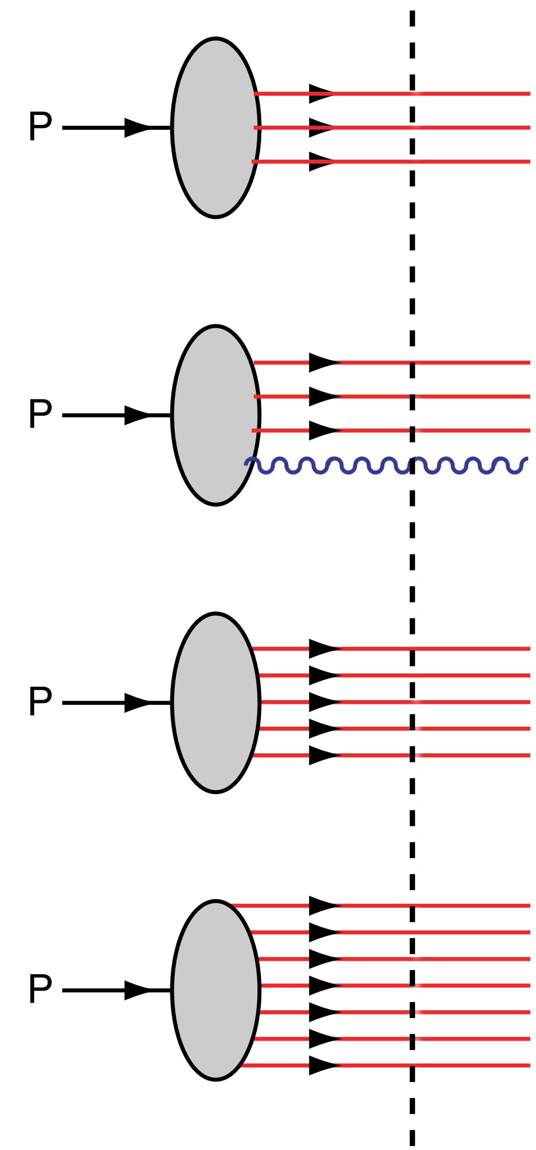
Wavefunction at fixed LF time: Off-Shell in Invariant Mass

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

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

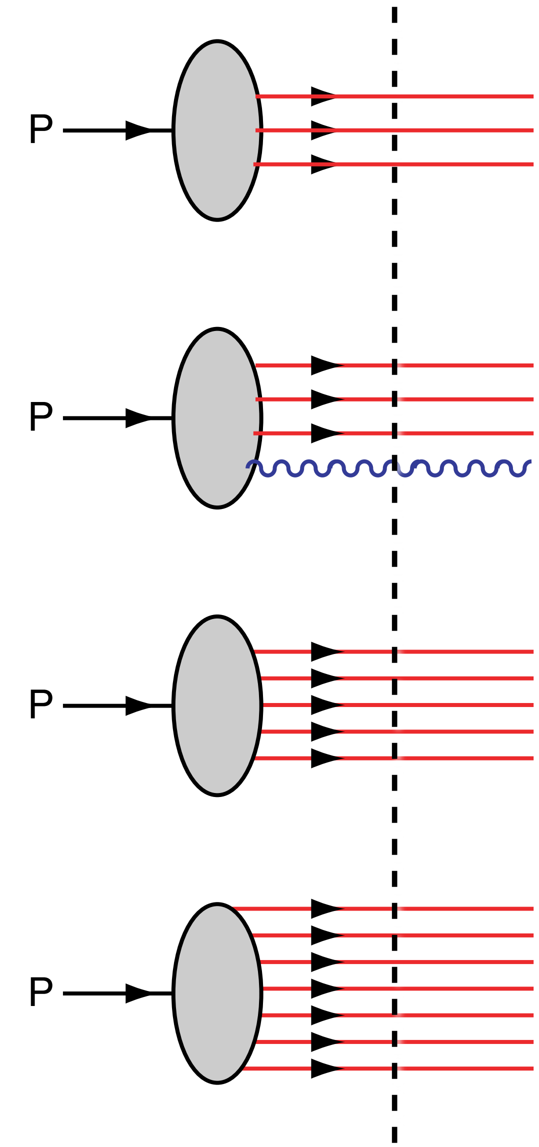
are boost invariant; they are independent of the hadron's energy and momentum P^μ.

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 !

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

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

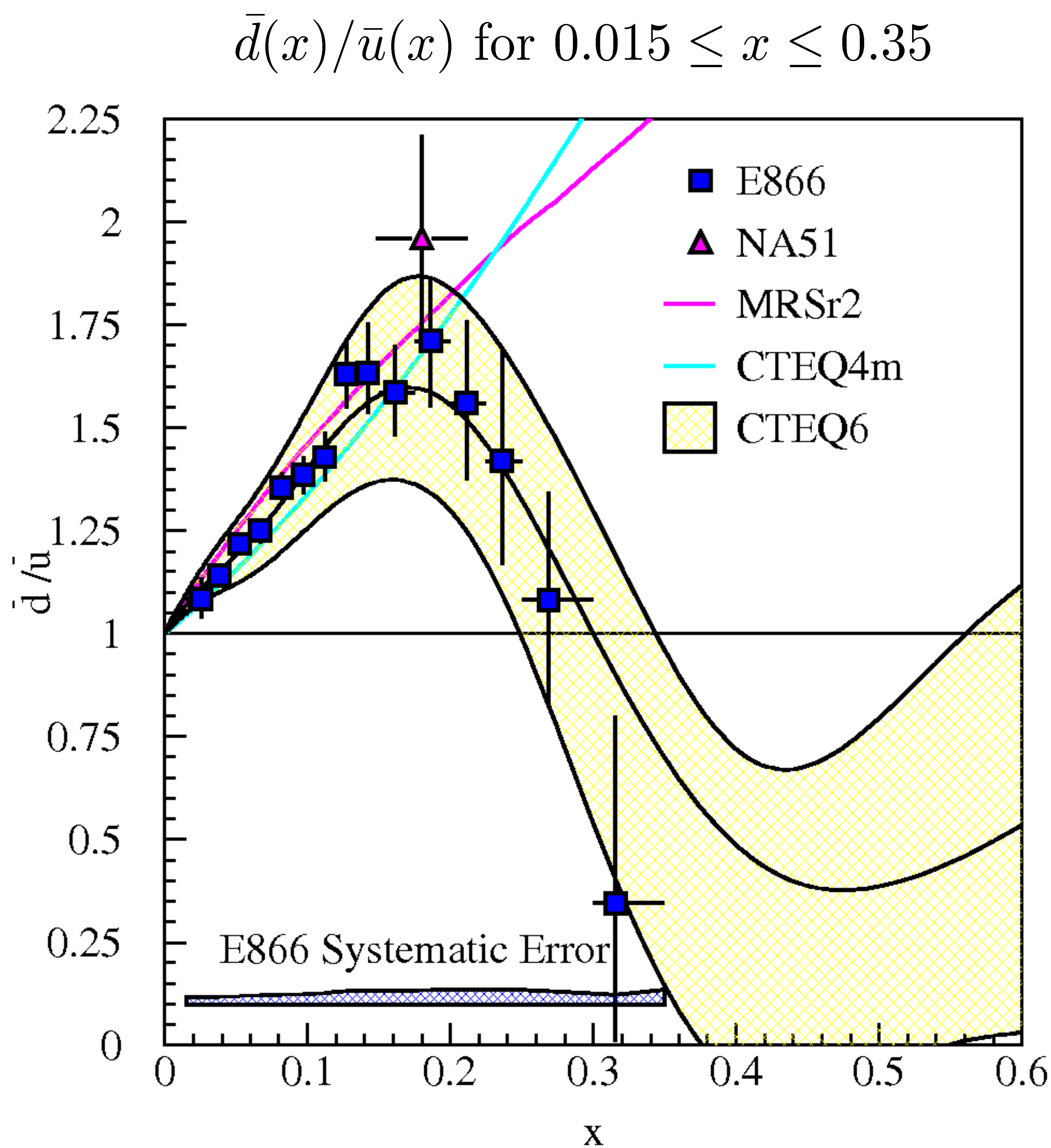
Deuteron: Hidden Color

- 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



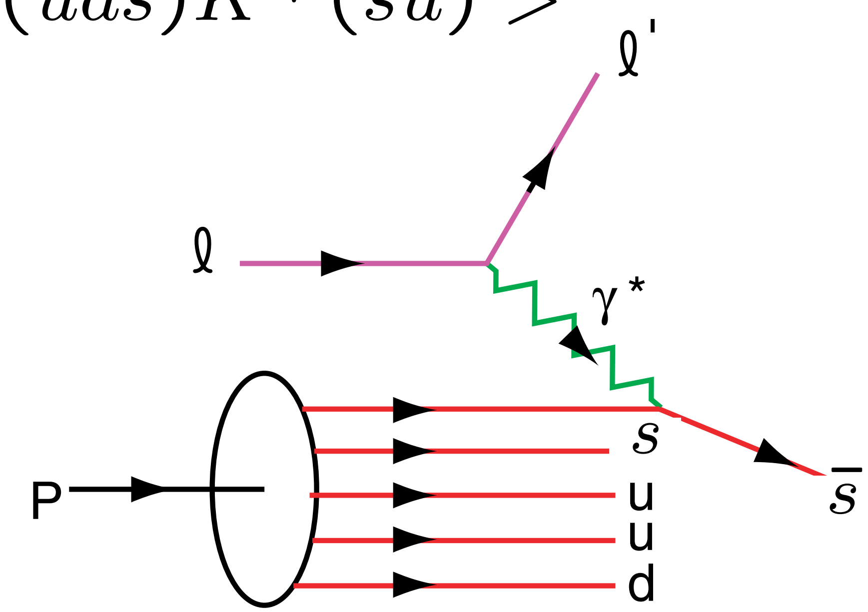
Measure strangeness distribution in Semi-Inclusive DIS at JLab

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

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

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

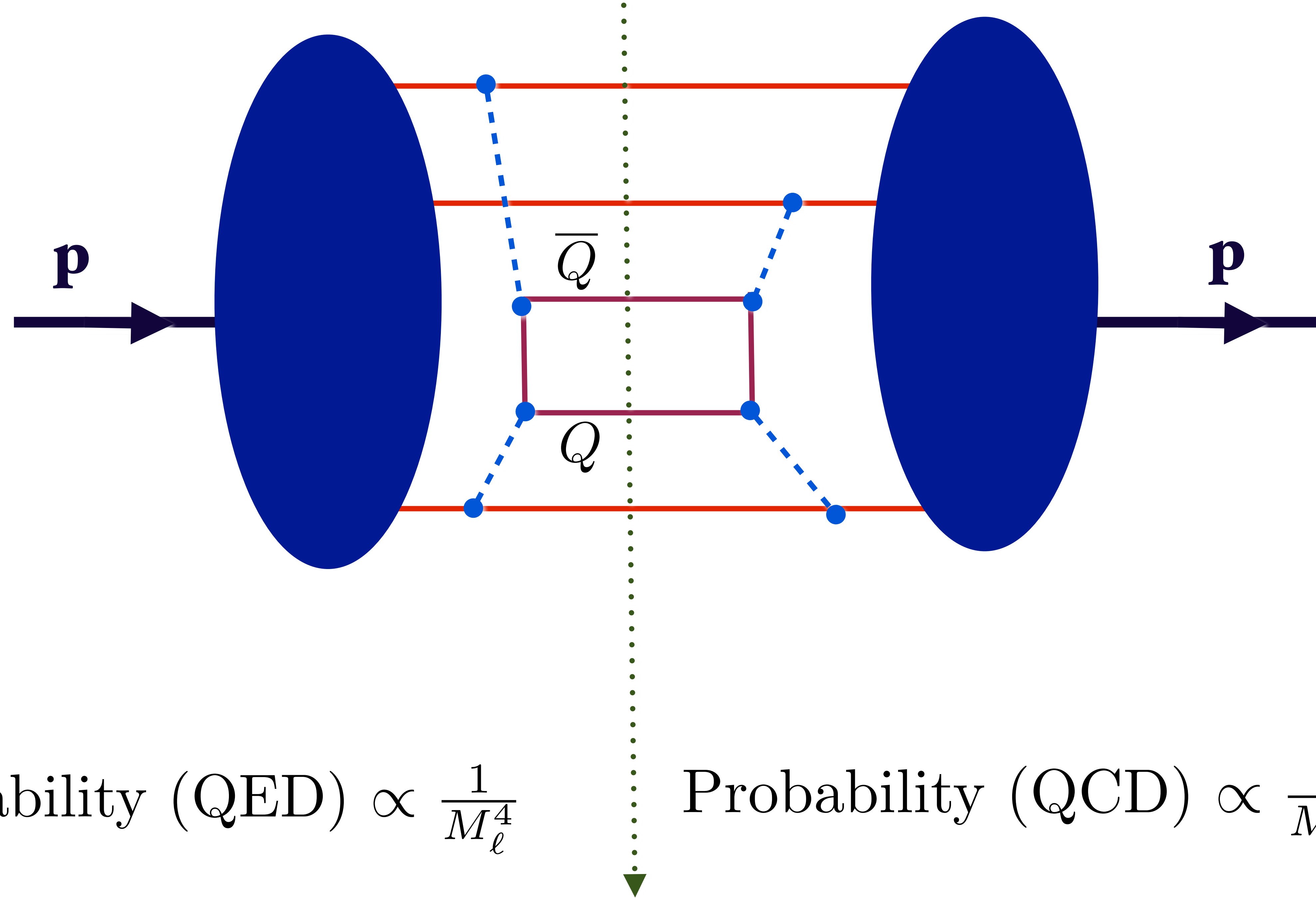
B. Q. Ma, sjb



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

Fixed LF time

Proton Self Energy
Intrinsic Heavy Quarks



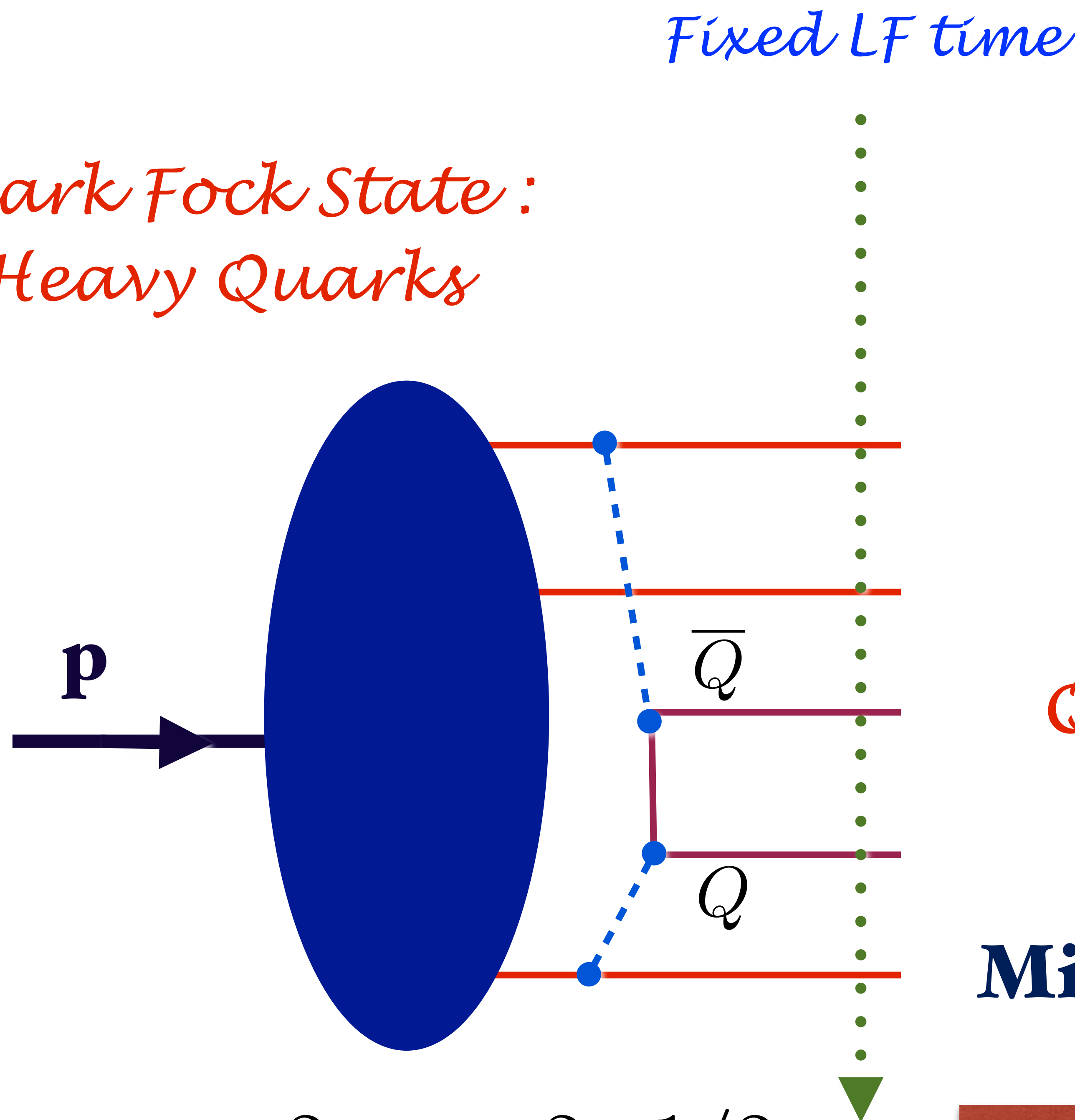
$$\text{Probability (QED)} \propto \frac{1}{M_\ell^4}$$

$$\text{Probability (QCD)} \propto \frac{1}{M_Q^2}$$

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!

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

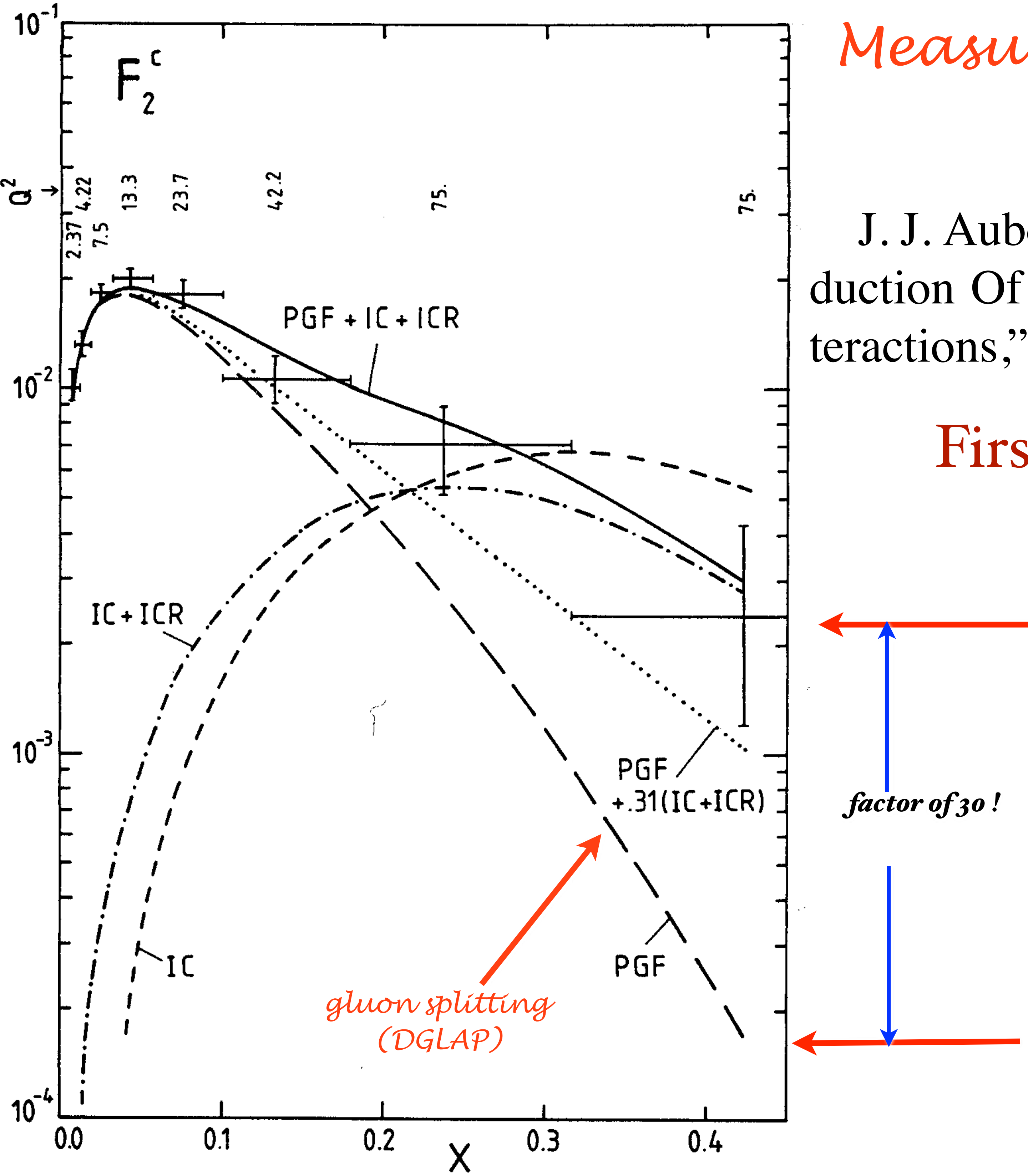
$$\text{Probability (QED)} \propto \frac{1}{M_\ell^4} \qquad \text{Probability (QCD)} \propto \frac{1}{M_Q^2}$$

Rigorous OPE Analysis

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

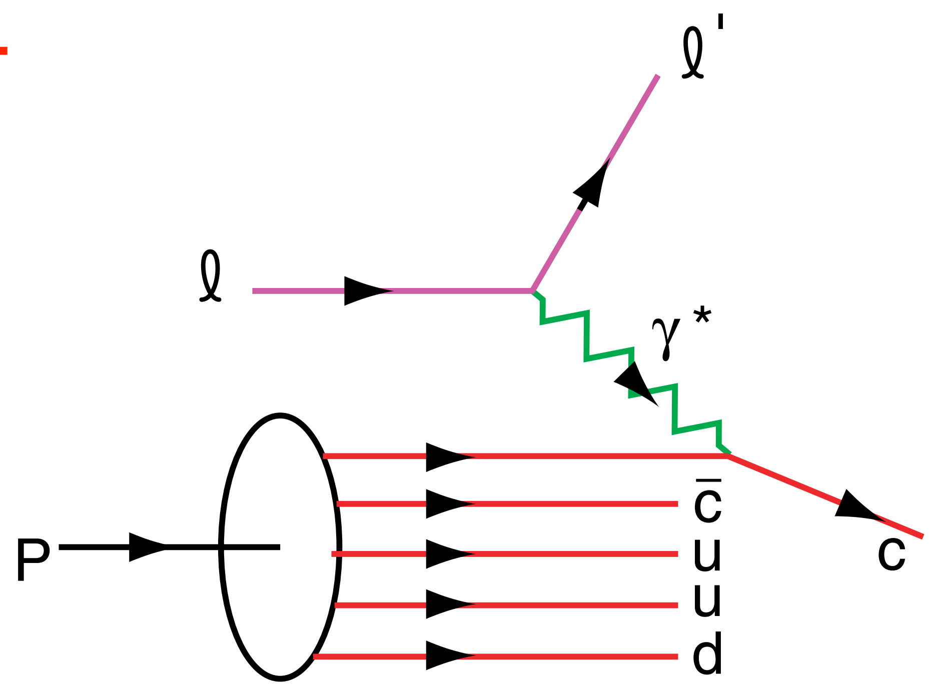
Measurement of Charm Structure Function!

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

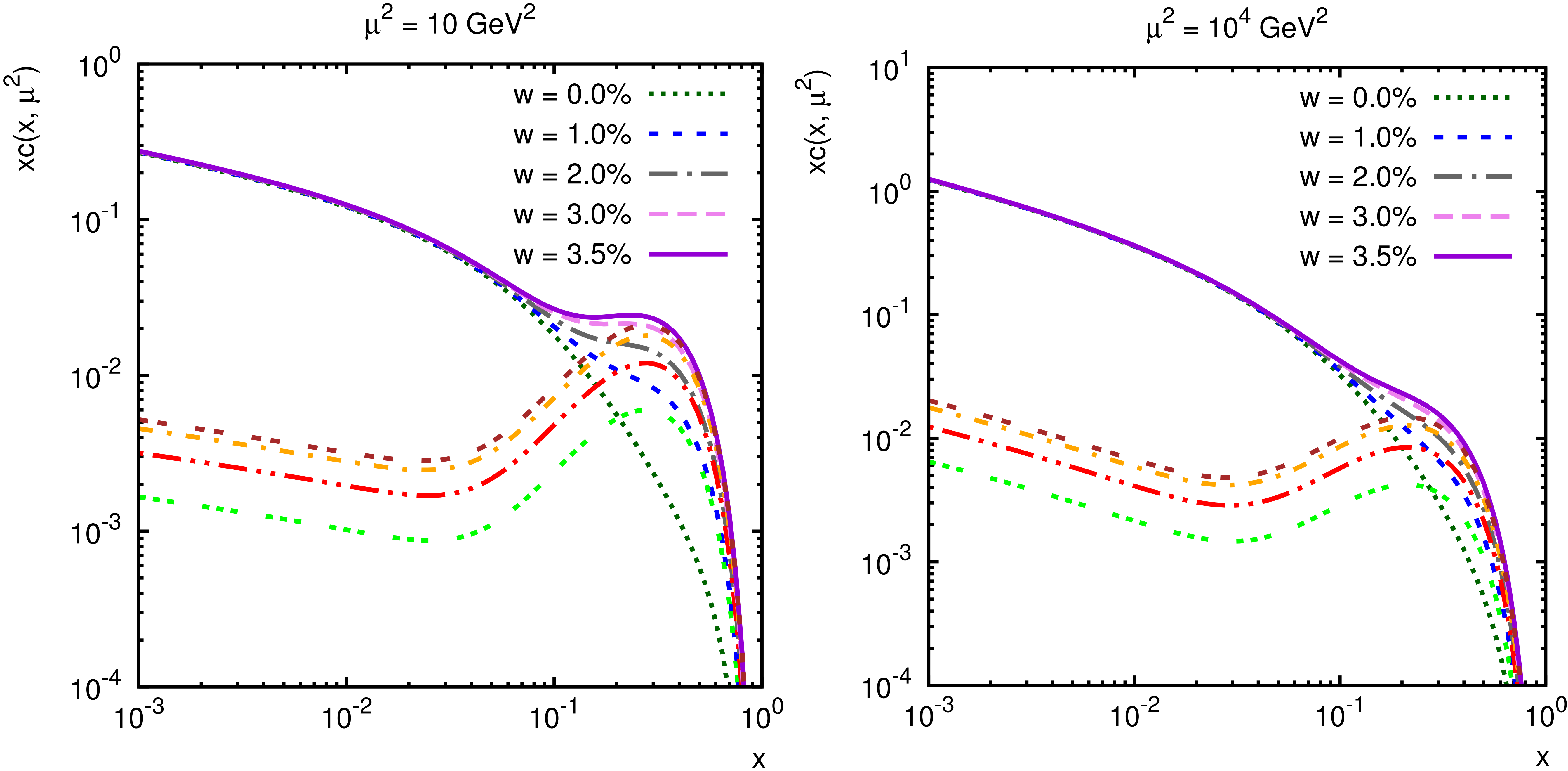
Two Components (separate evolution):

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

Bednyakov, Lykasov, Smiesko, Tokar, sjb

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

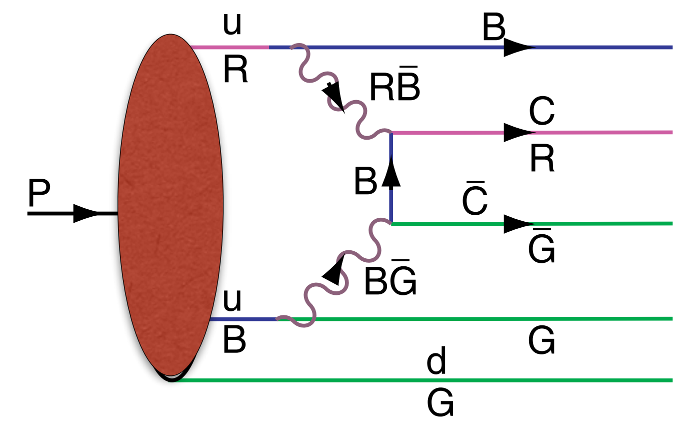
x



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

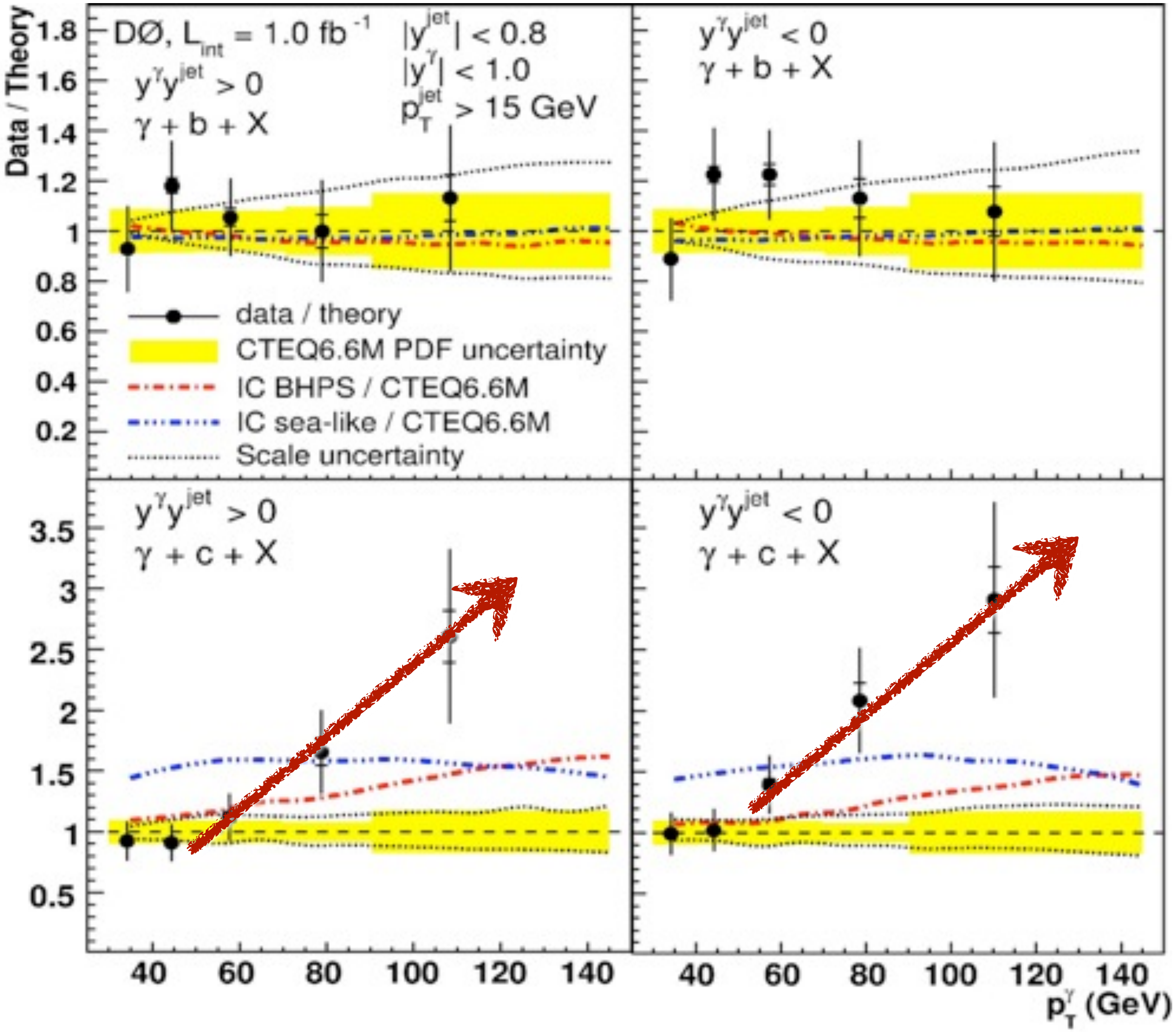
Hoyer, Peterson, Sakai, sjb

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)**

DØ 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

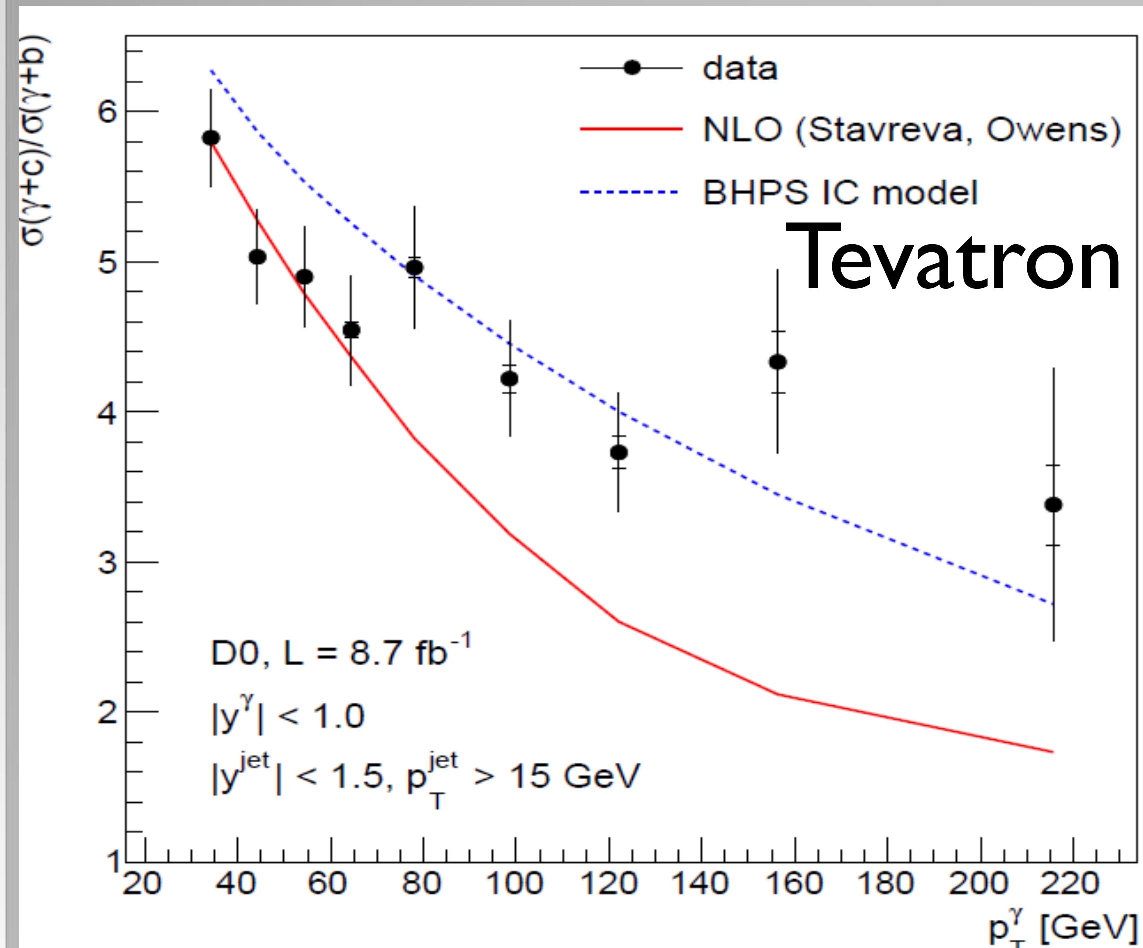
LHC: $pp \to Z^0 c X$

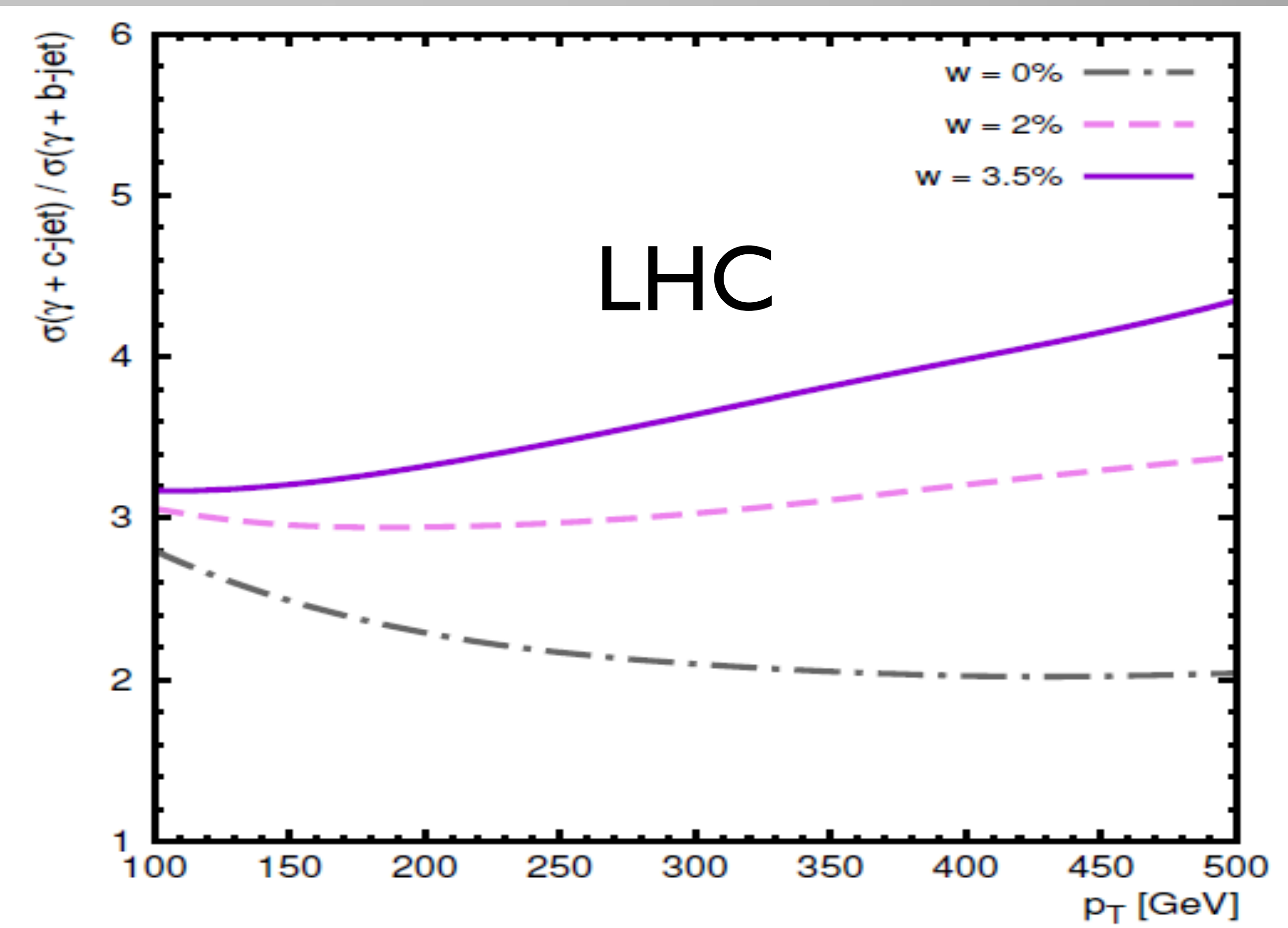
Boettcher, Ilten, Williams

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

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)



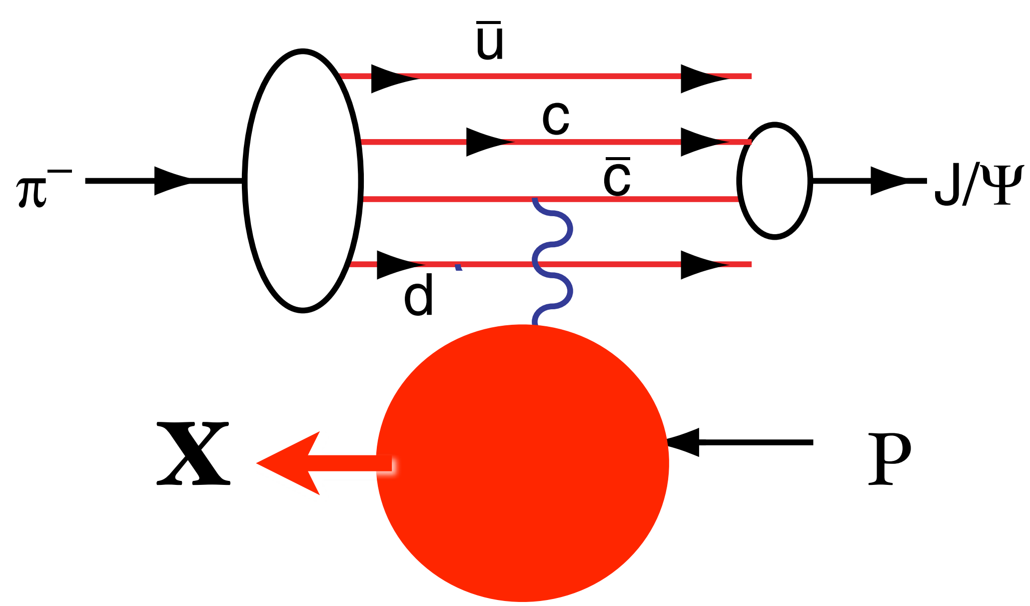


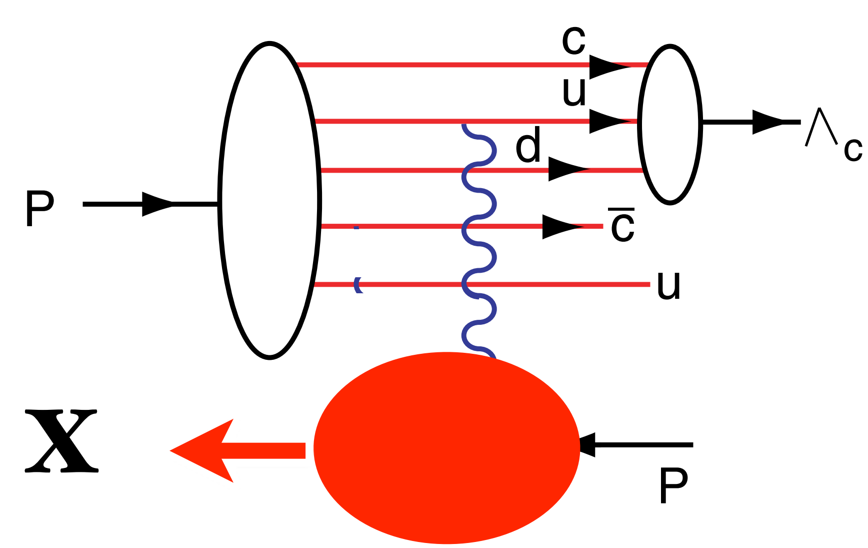
V,M,Abazov, et al. (D0) Phys.Lett. B719 (2013) 354 .

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

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

Coalesece of comovers produces high x_F heavy hadrons



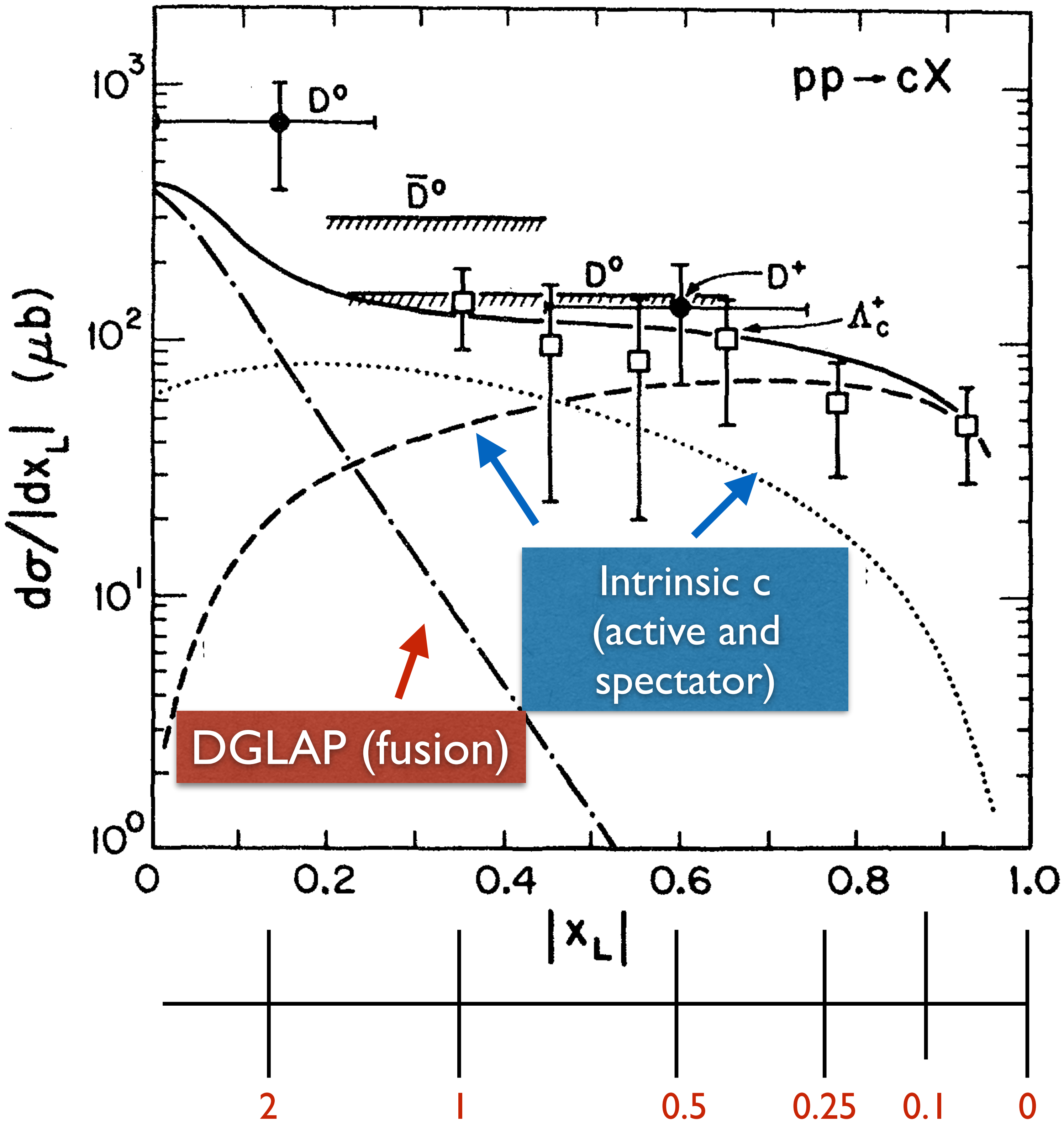


Spectator counting rules

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

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

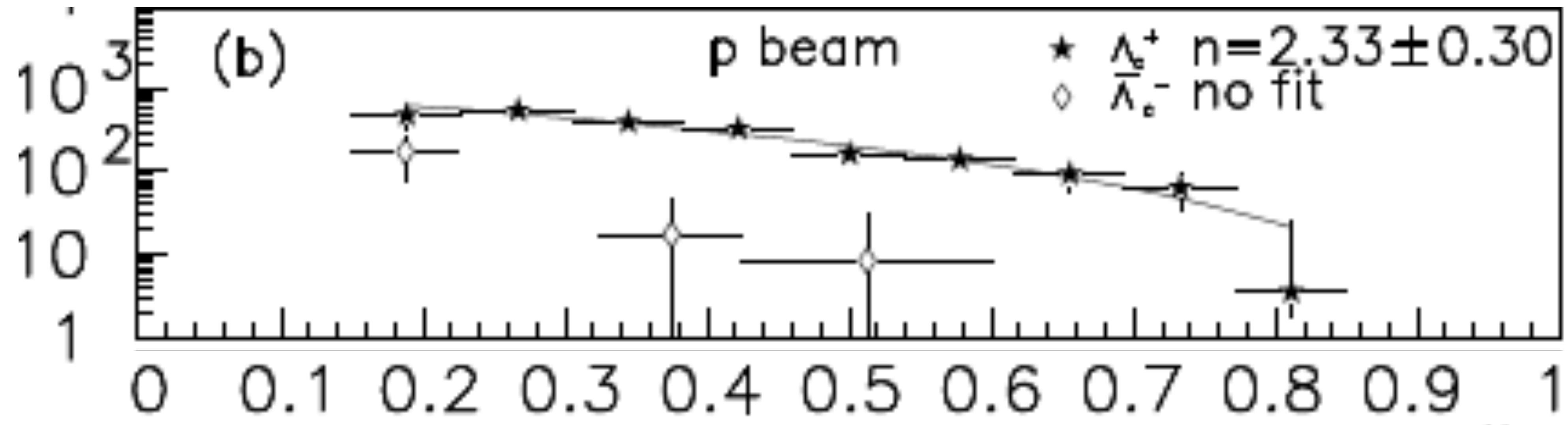
Barger, Halzen, Keung
PRD 25 (1981)



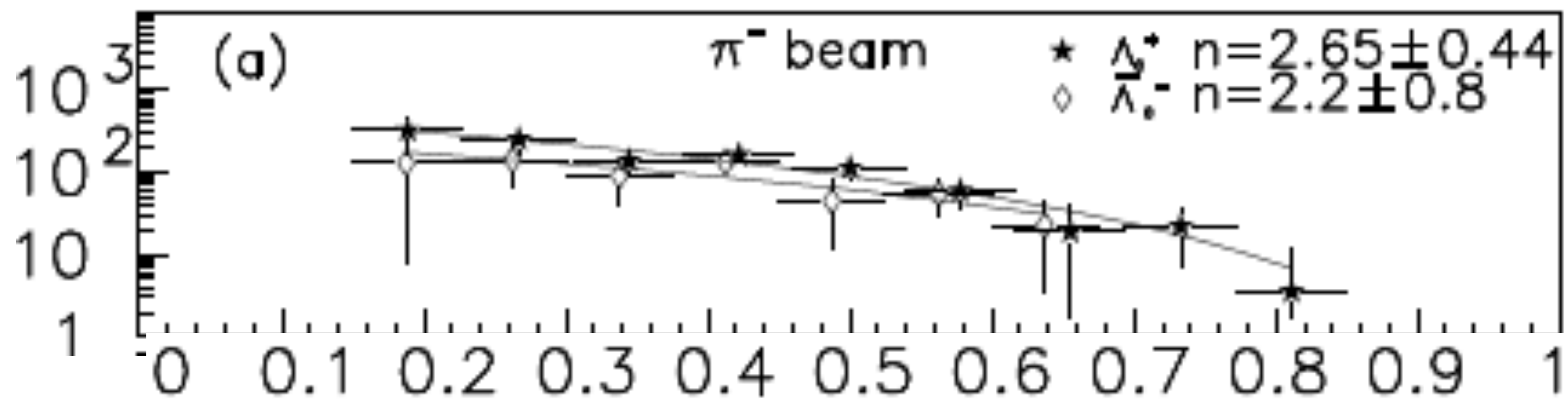
$\Delta y = \log x$

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

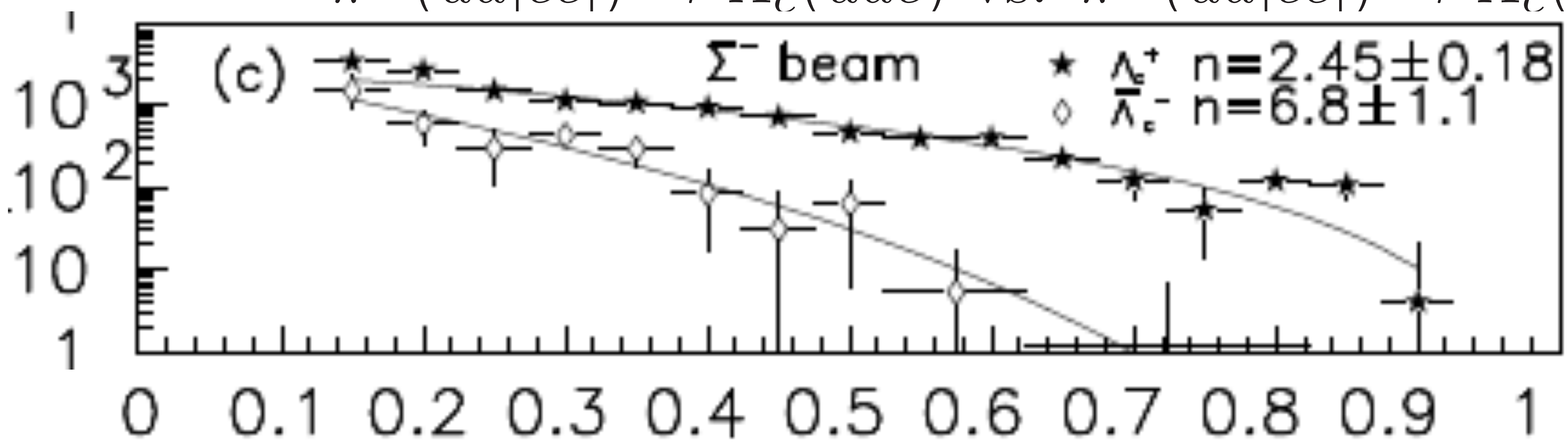
SELEX



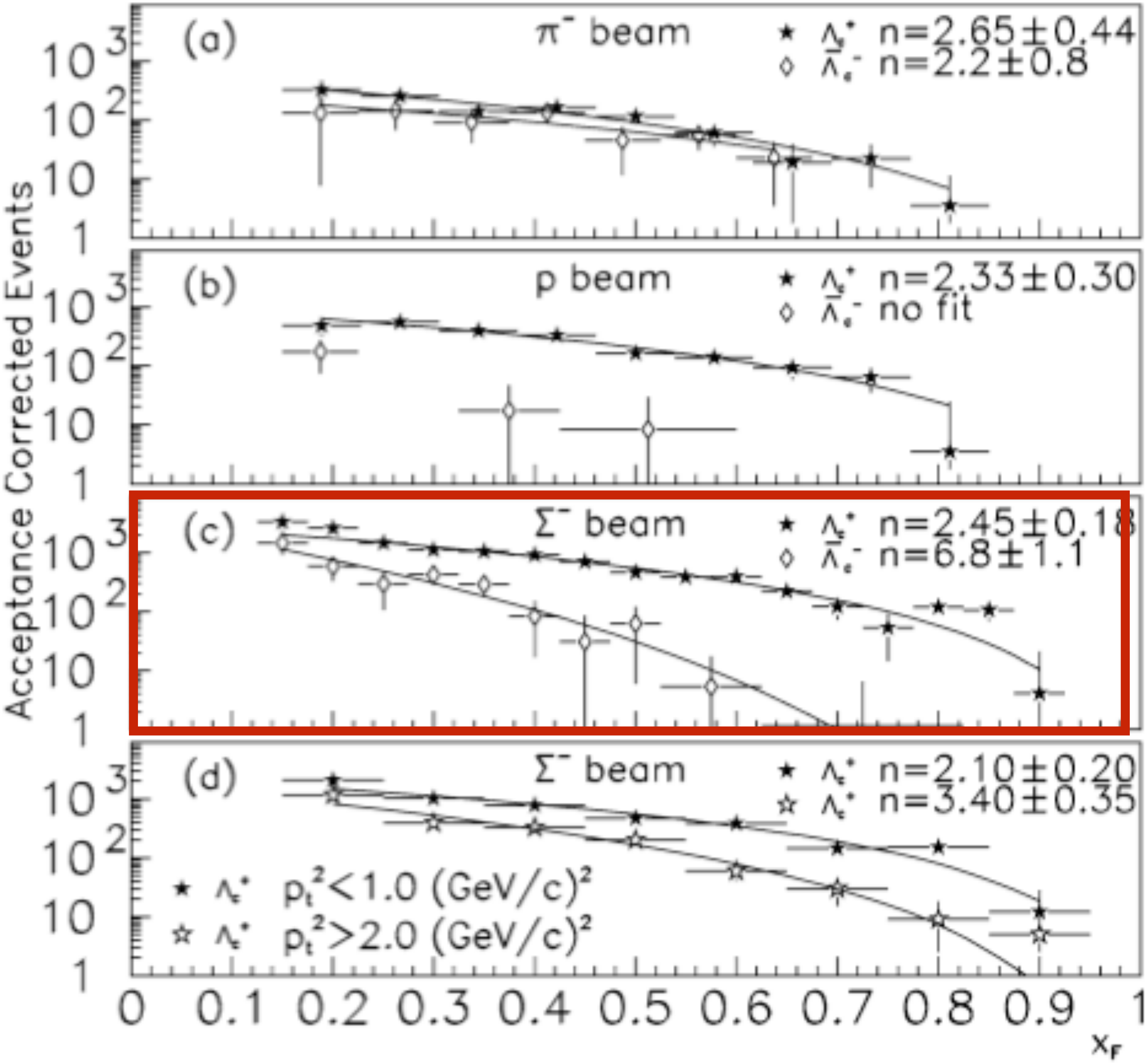
$p(uud[c\bar{c}]) \to \Lambda_c(udc)$ vs. $p(uud[c\bar{c}]) \to \bar{\Lambda}_c(\bar{u}\bar{d}\bar{c})$



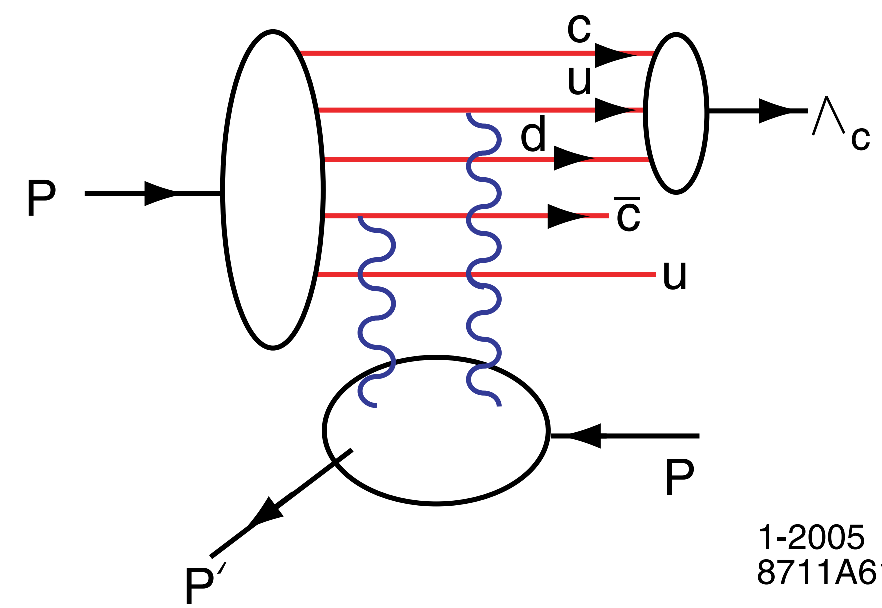
$\pi^-(\bar{u}d[c\bar{c}]) \to \Lambda_c(udc)$ vs. $\pi^-(\bar{u}d[c\bar{c}]) \to \bar{\Lambda}_c(\bar{u}\bar{d}\bar{c})$



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



SELEX



$$p(uudc\bar{c})$$

$$\rightarrow \Lambda_c(cud)$$

$$n_s = 2$$

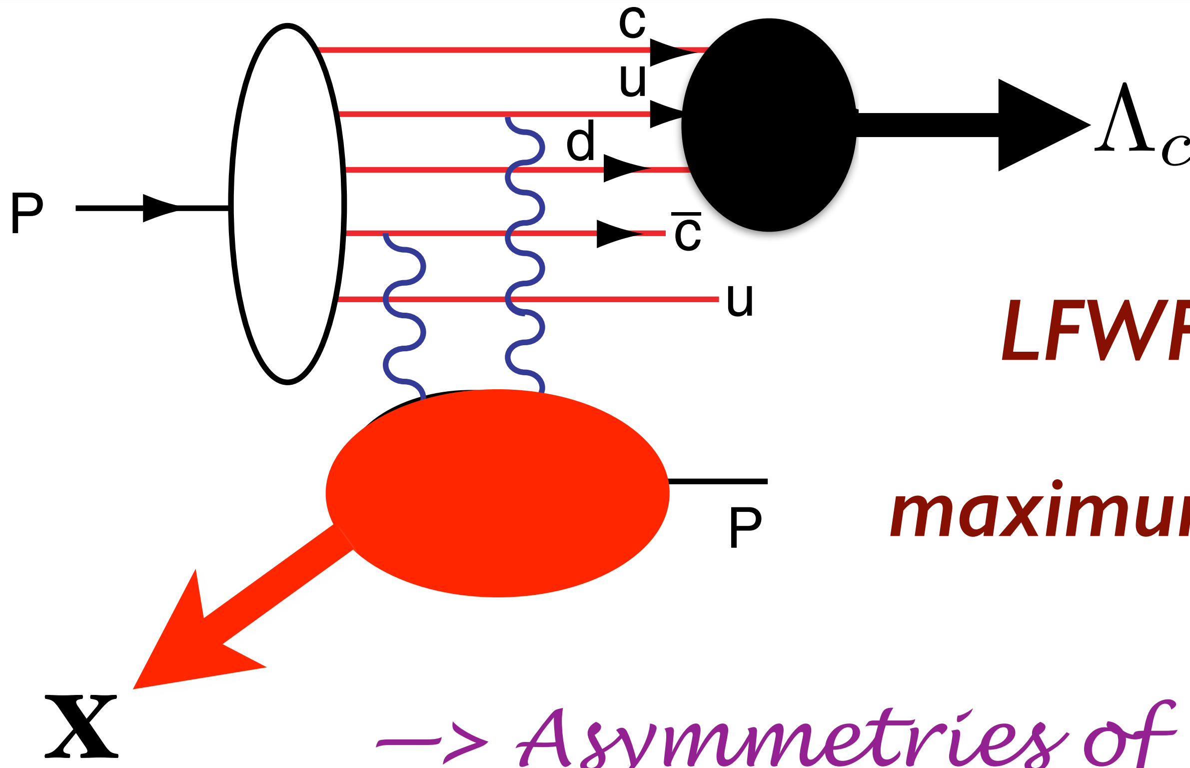
Phase space gives minimum power fall-off

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

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

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

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

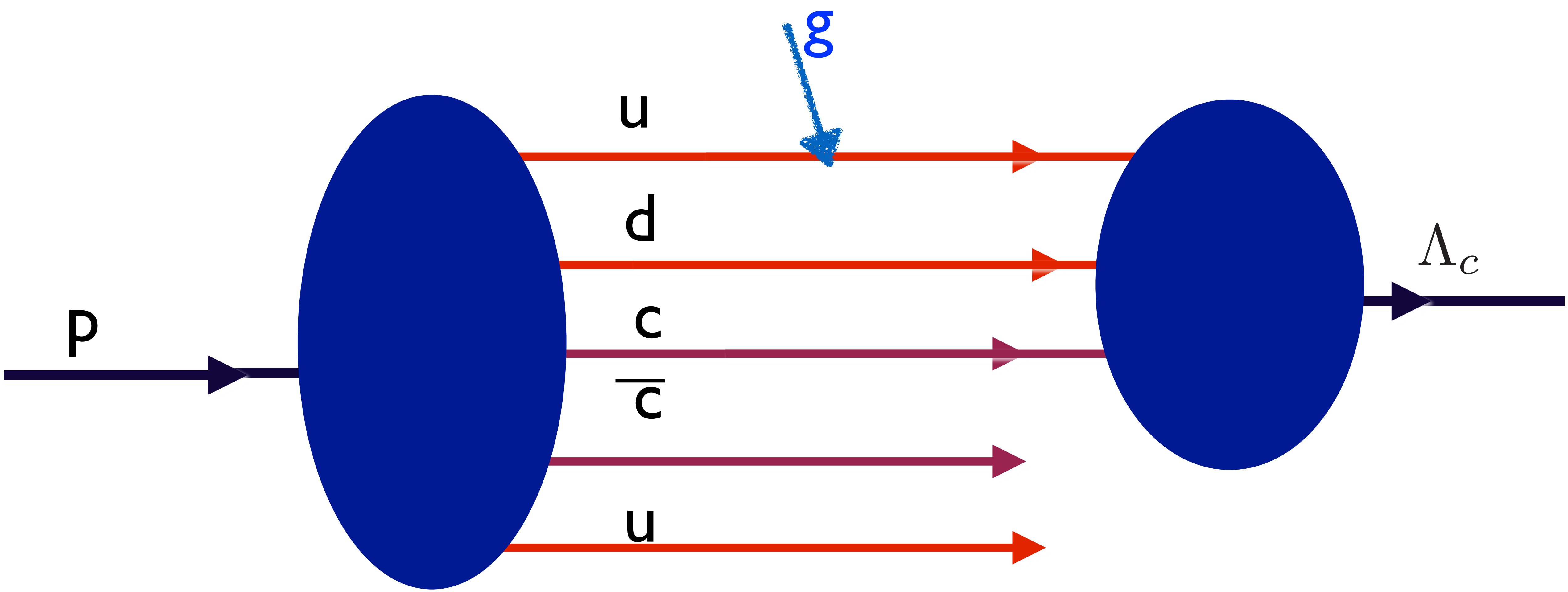
Coalescence of Comoving Charm and Valence Quarks
Produce J/ψ, Λ_c and other Charm Hadrons at High x_F

Vogt, sjb

$pp \to \Lambda_c X$

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

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



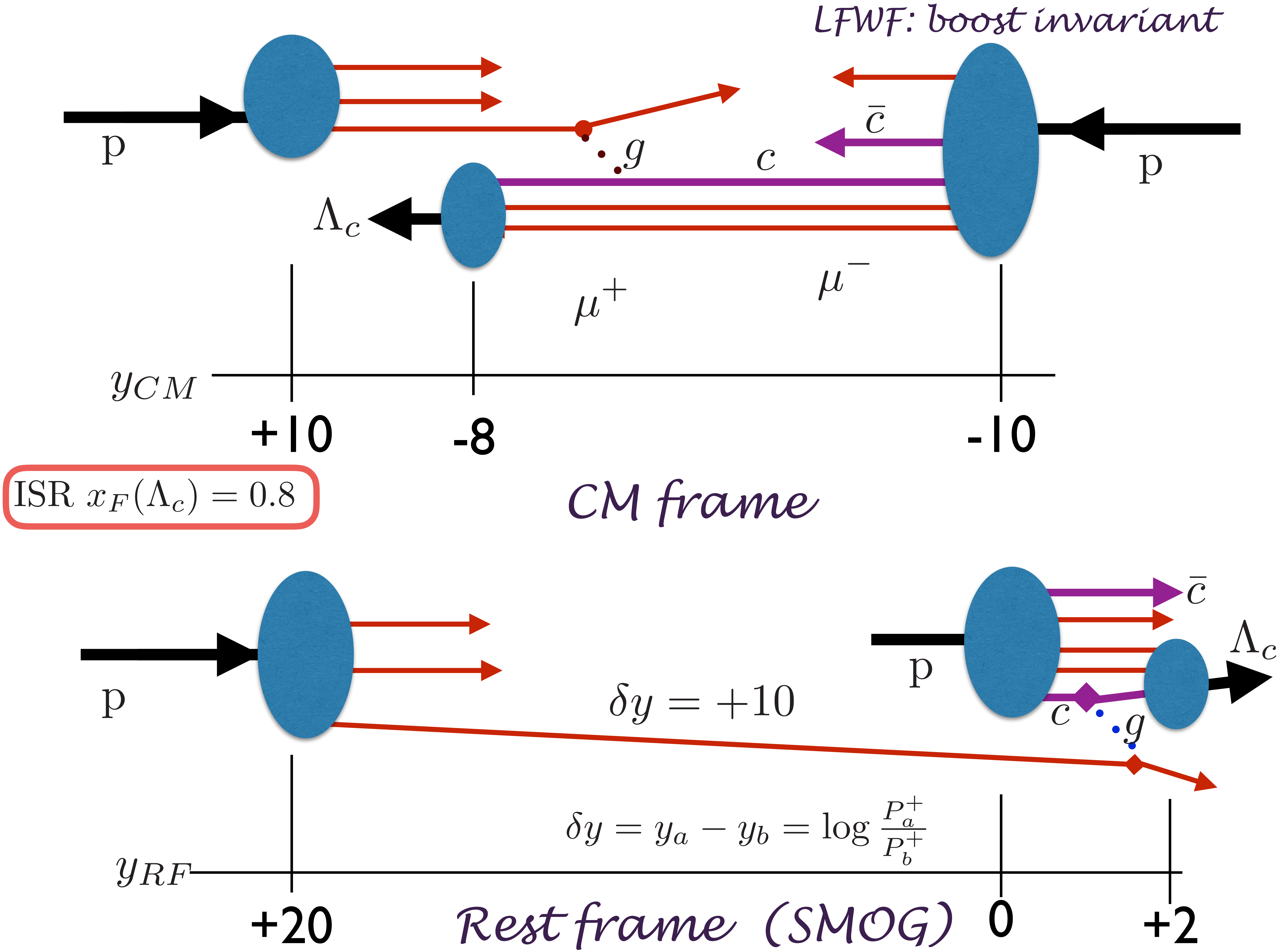
Coalescence maximal at matching rapidities

Fast proton:

High $x^F_{\Lambda_c}$

Rest frame proton:

low momentum Λ_c



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

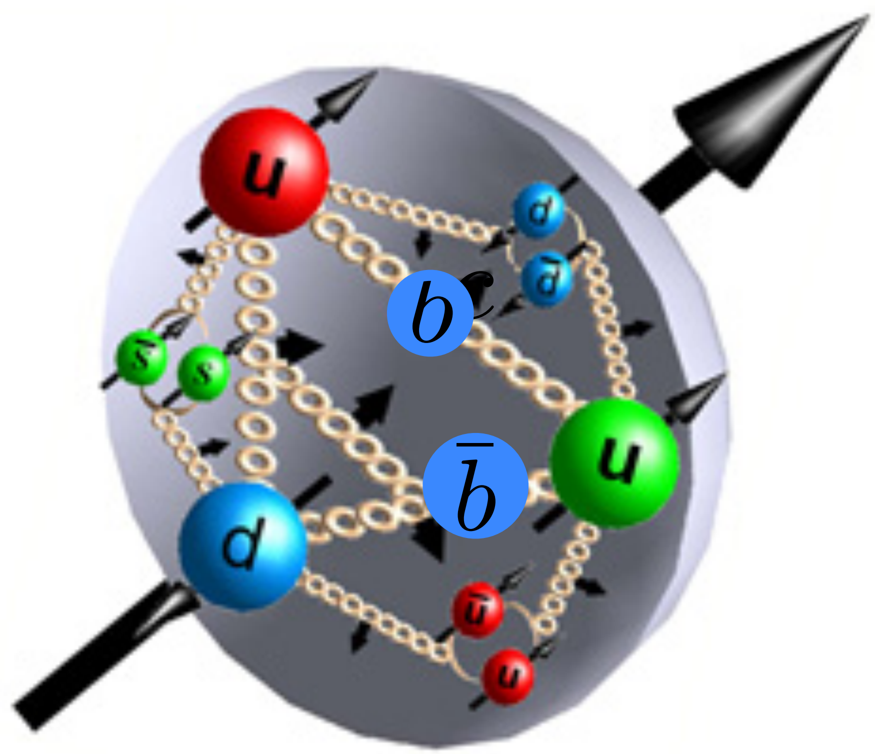
CM-P00063074

27 May 1991

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



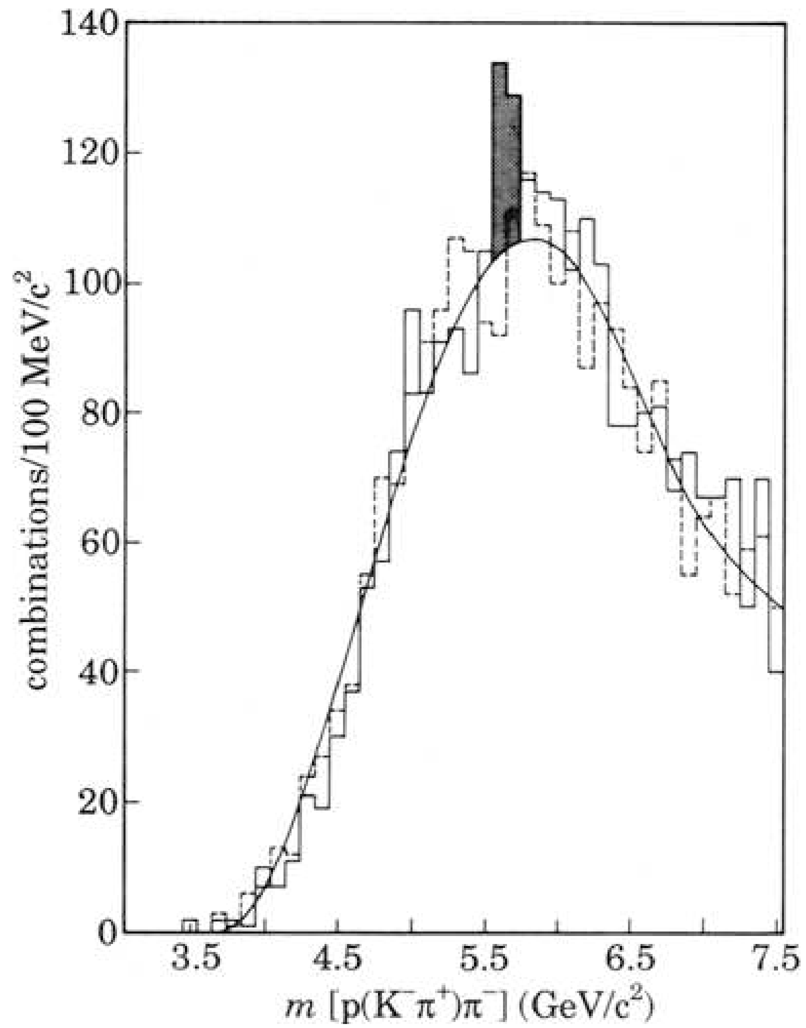
Abstract

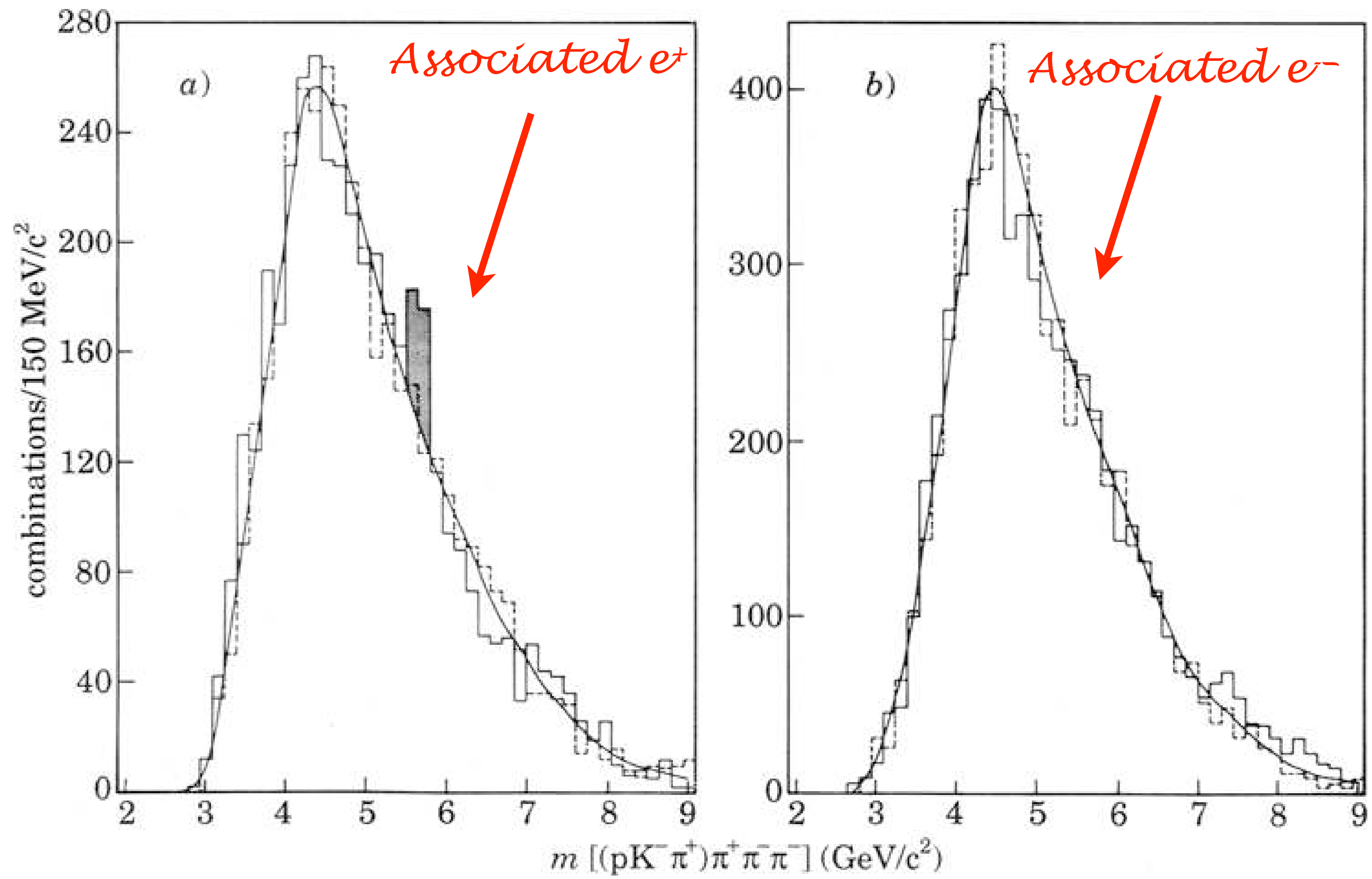
Another decay mode of the Λ_b^o (open-beauty baryon) state has been observed: $\Lambda_b^o \rightarrow \Lambda_c^+\pi^+\pi^-\pi^-$. In addition, new results on the previously observed decay channel, $\Lambda_b^o \rightarrow pD^o\pi^-$, are reported. These results confirm our previous findings on Λ_b^o 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!

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

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





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

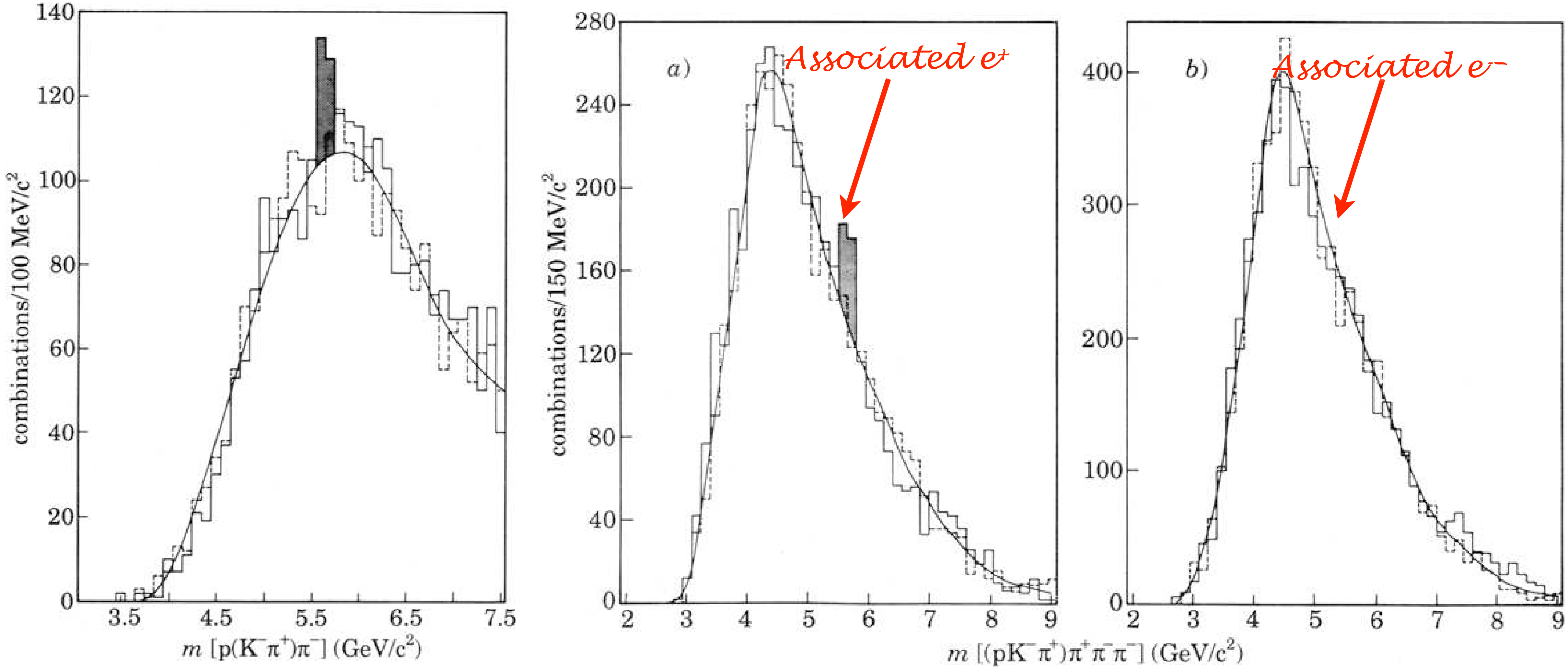
$m_{\Lambda_b} = 5.6$ GeV

Il Nuovo Cimento 104, 1787

First Evidence for Intrinsic Bottom!

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

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



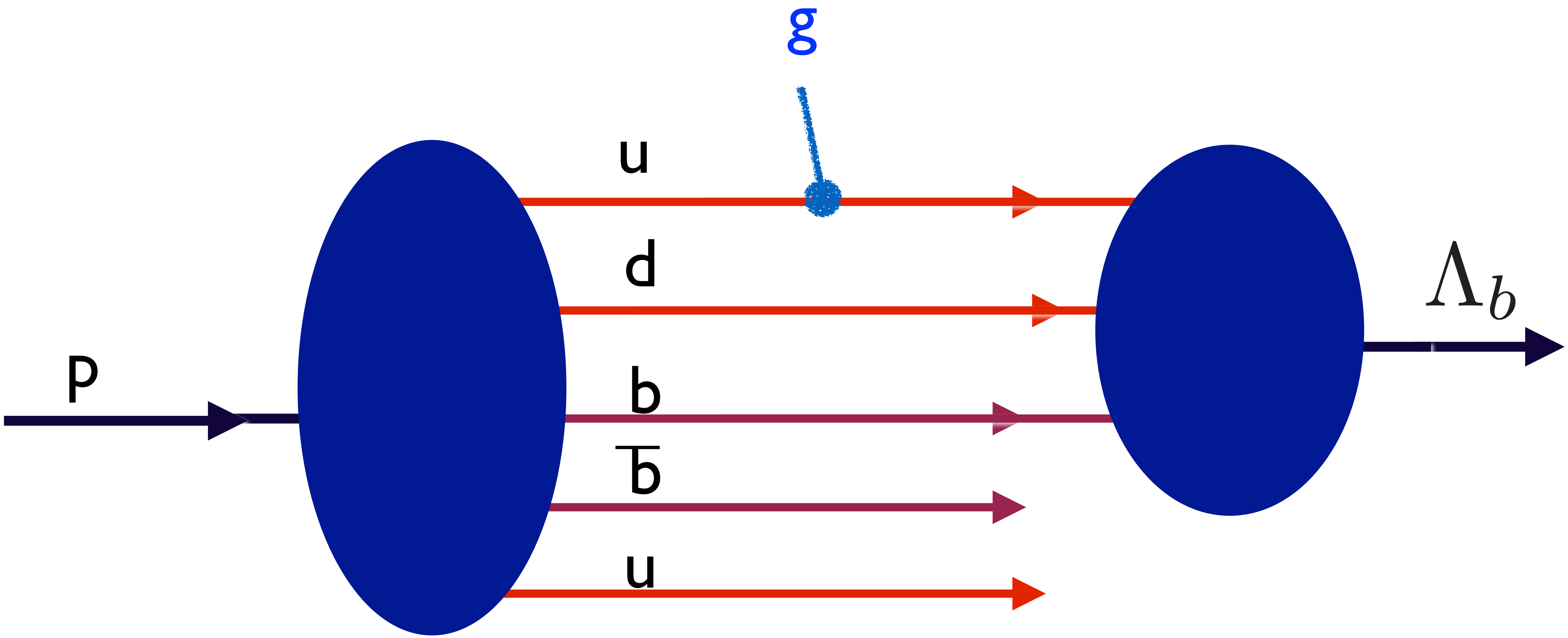
$\Lambda_b^0 \to pD^0\pi^-$ $\Lambda_b^0 \to \Lambda_c^+\pi^+\pi^-\pi^-$

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

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

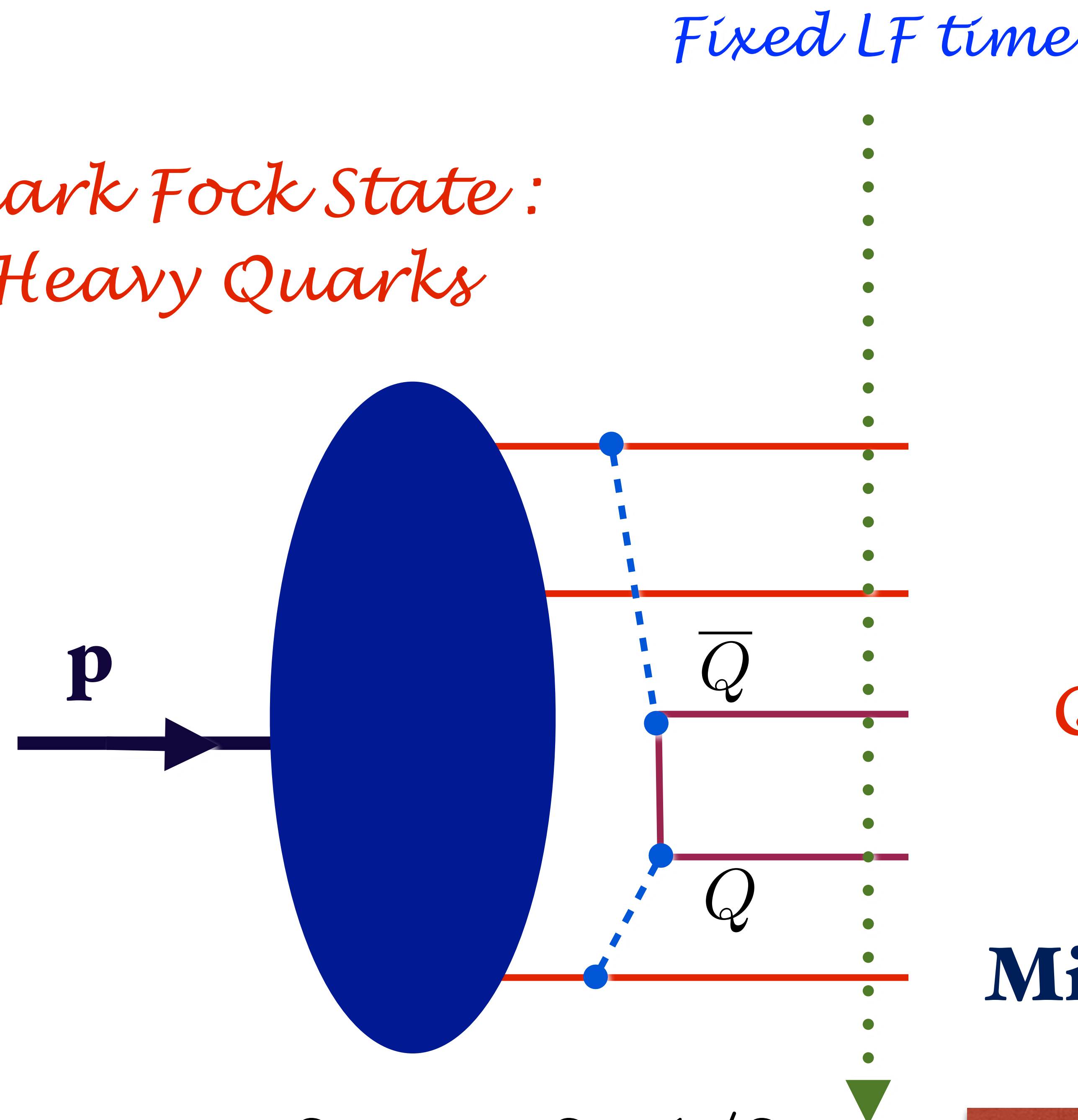
Λ_b^0 MASS

$m_{\Lambda_b^0}$

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	$e^+\,e^- \rightarrow Z$
5614 ±21 ±4	4	[4] BUSKULIC	1996L	ALEP	$e^+\,e^- \rightarrow Z$
*** 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	$\Lambda_b^0 \rightarrow pD^0\pi^-$
$5650\,^{+150}_{-200}$	90	BARI	1991	SFM	$\Lambda_b^0 \rightarrow \Lambda_c^+\pi^+\pi^-\pi^-$

Proton 5-quark Fock State : Intrinsic Heavy Quarks



QCD predicts Intrinsic Heavy Quarks at high x!

Minimal off-shellness

Maximum at Equal rapidity!

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

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

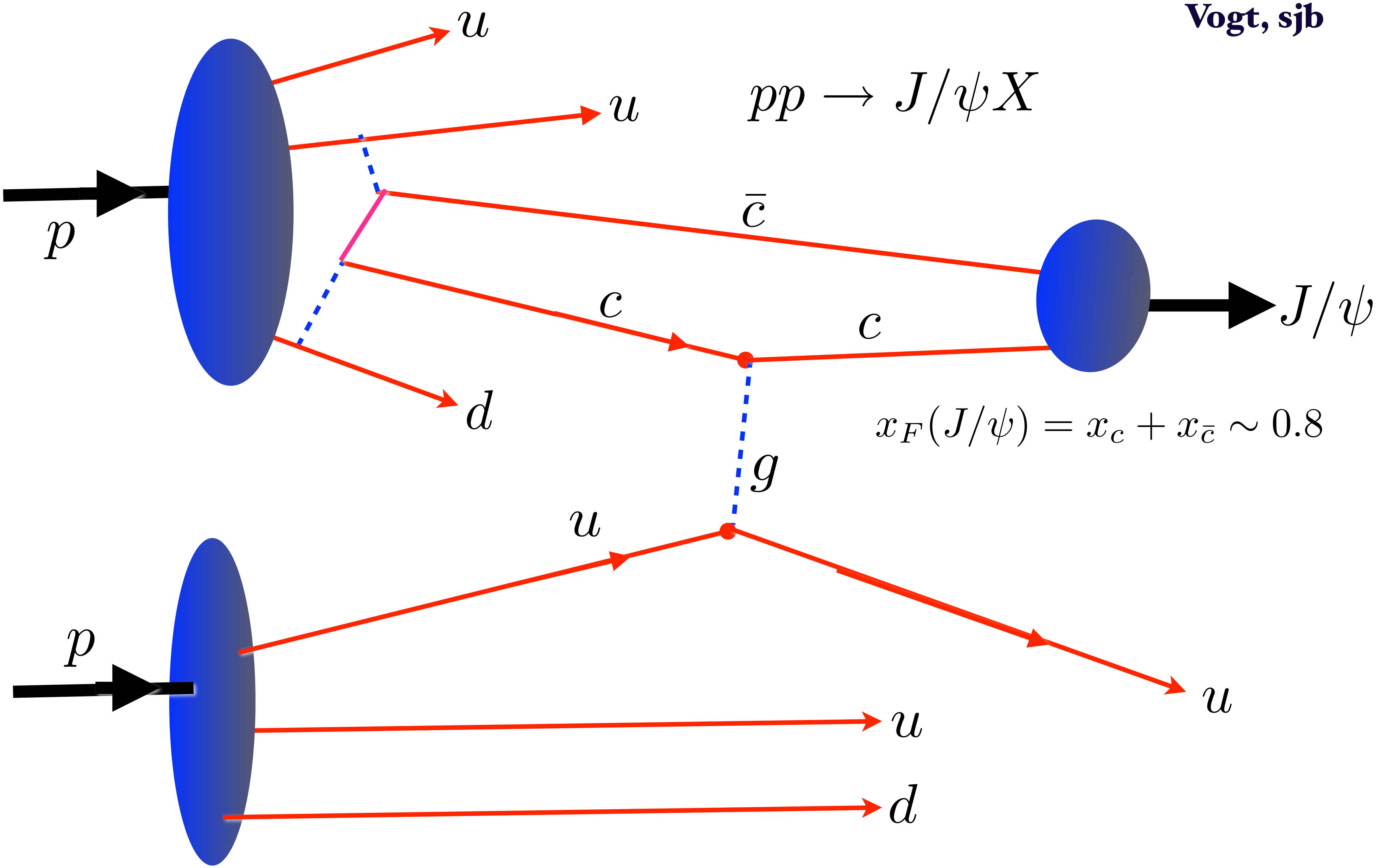
Rigorous OPE Analysis

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

Intrinsic Heavy Quark Contribution to Quarkonium Hadroproduction at High x_F

Lansberg, sjb

Vogt, sjb



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

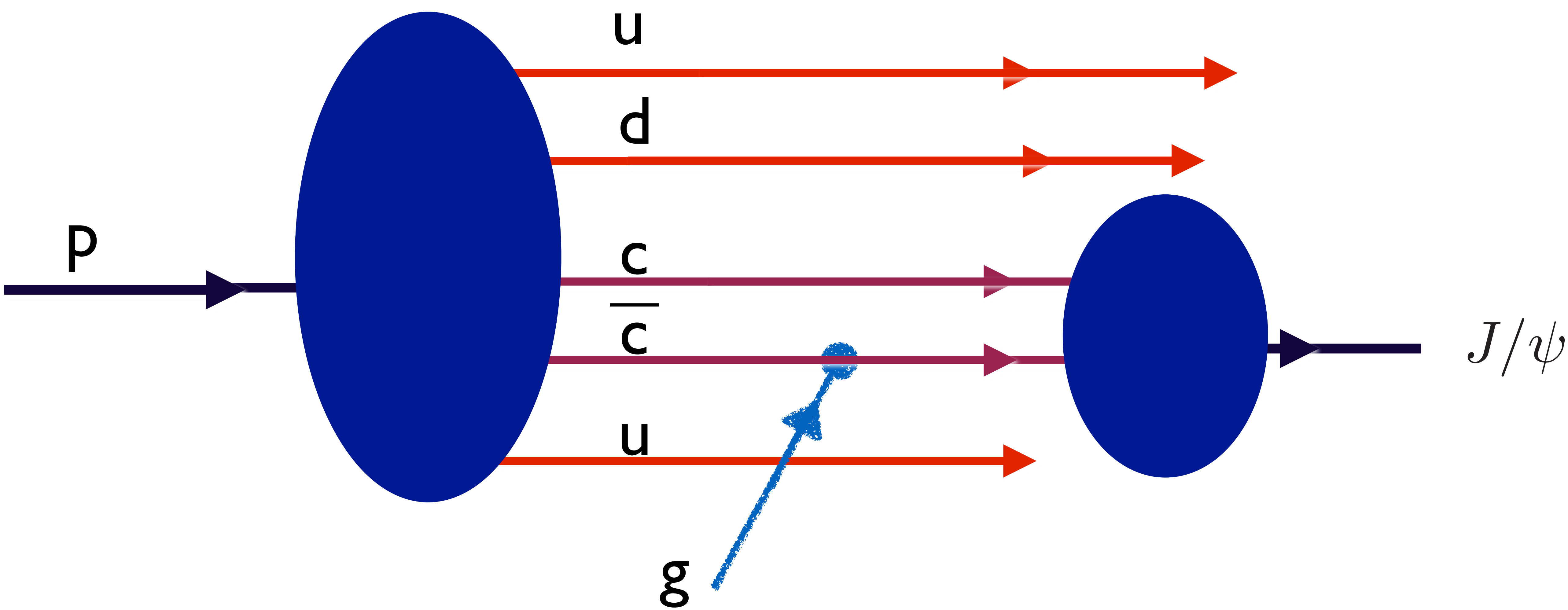
Maximal Wavefunction Strength at Minimal Invariant Mass : Equal Rapidity

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

$$\Delta y = y_p - y_{J/\psi} < 2$$

$$c\bar{c} \to J/\psi$$

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



Coalescence maximal at equal quark rapidity

Fast proton:

High $x^F_{J/\psi}$

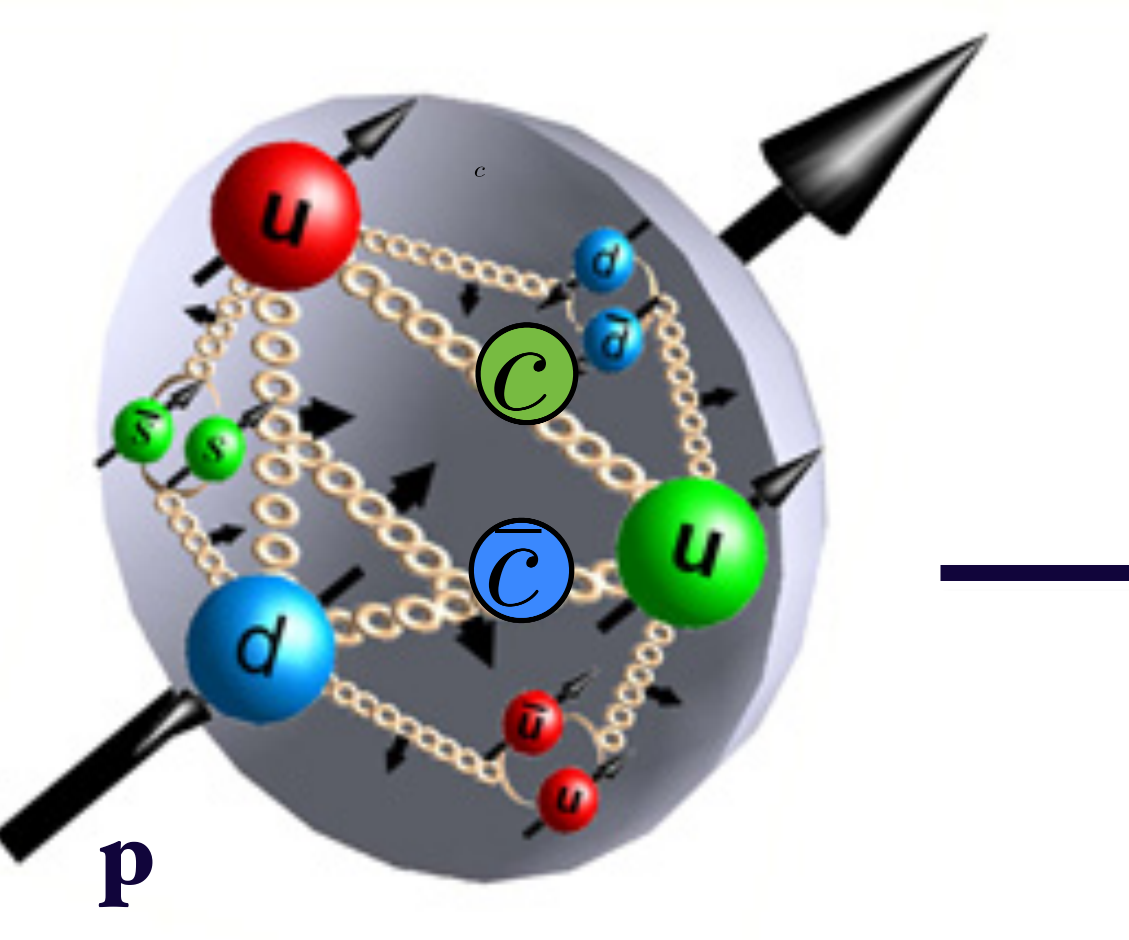
Rest frame proton

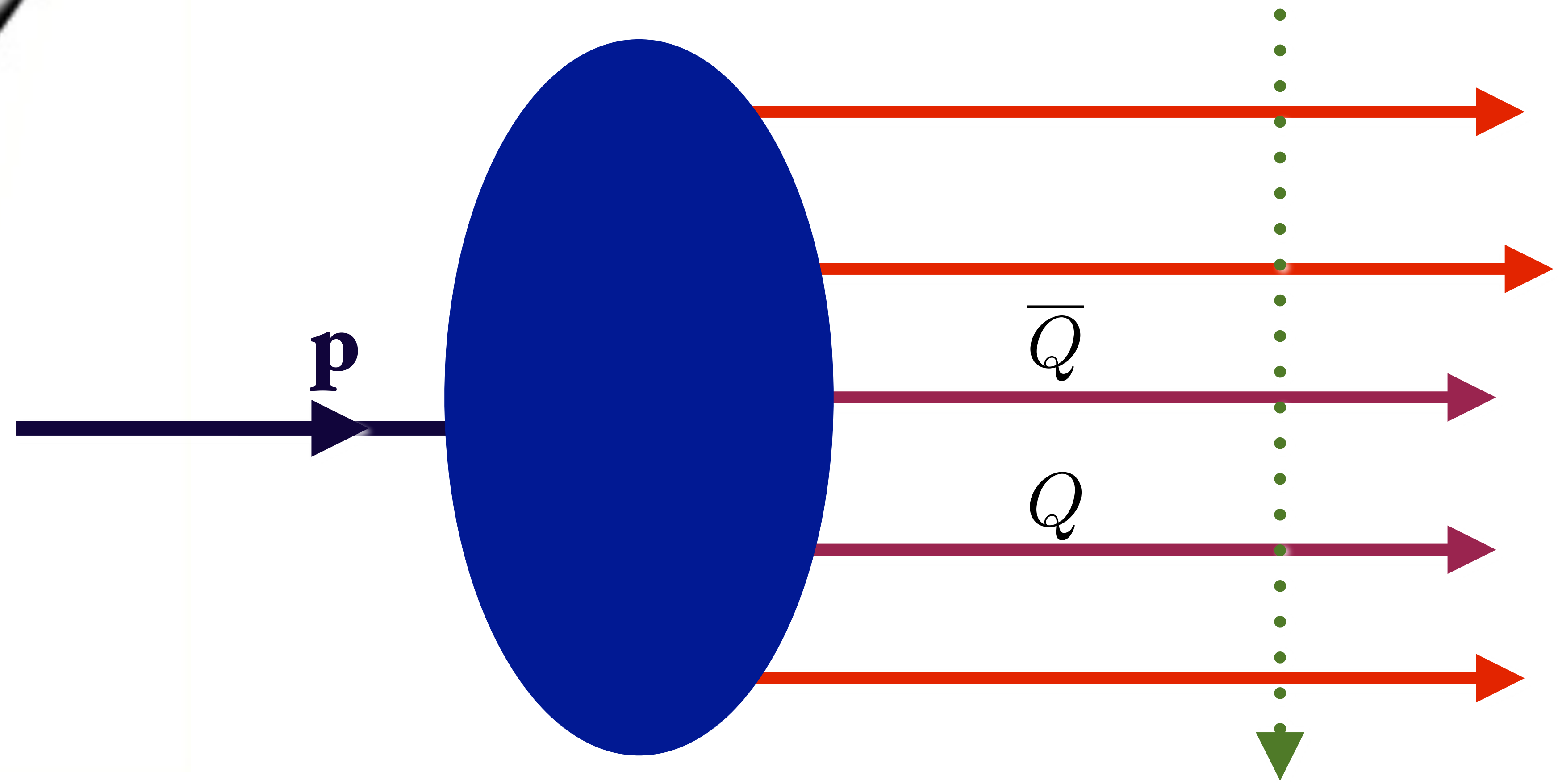
low momentum J/ψ

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

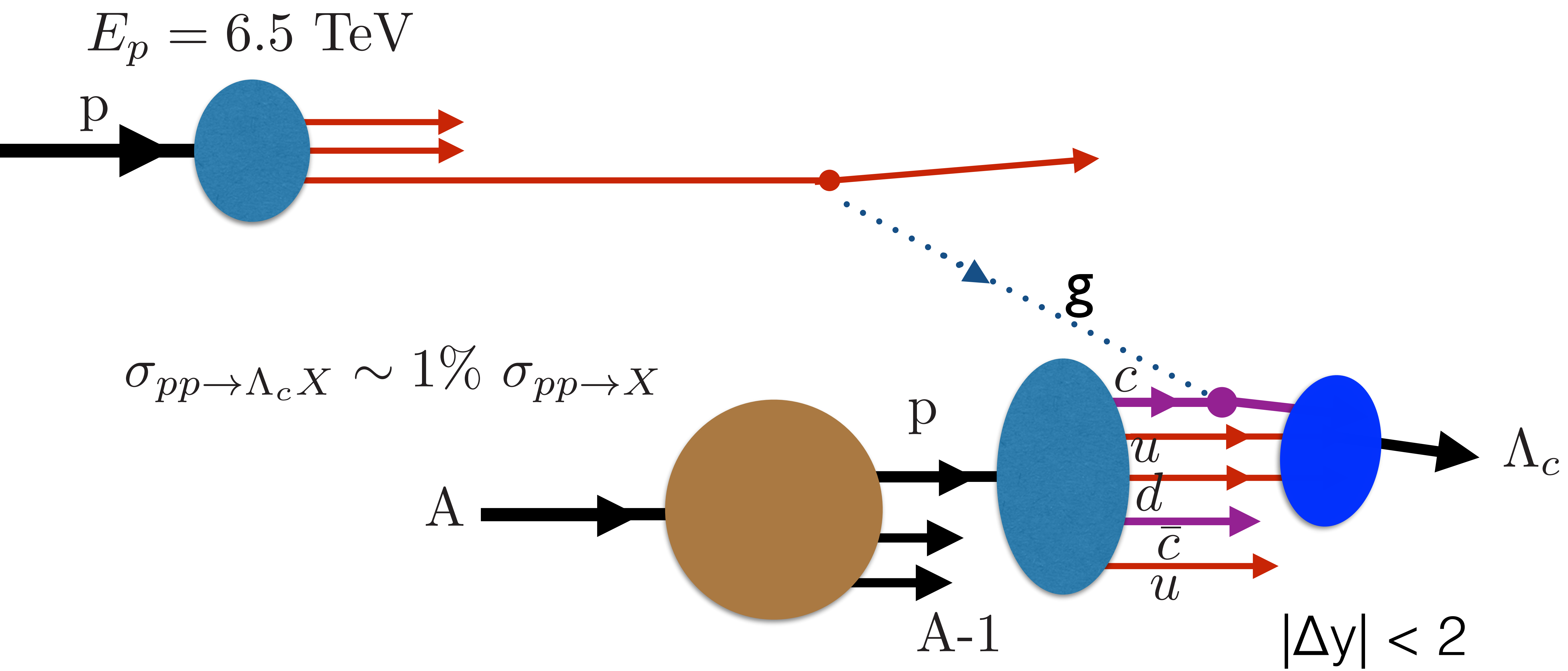
$$y = \frac{1}{2} \log \frac{k^+}{k^-} = \log \frac{x P^+}{m_\perp}$$

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 proton Δy < 2

$$pA \to \Lambda_c X$$

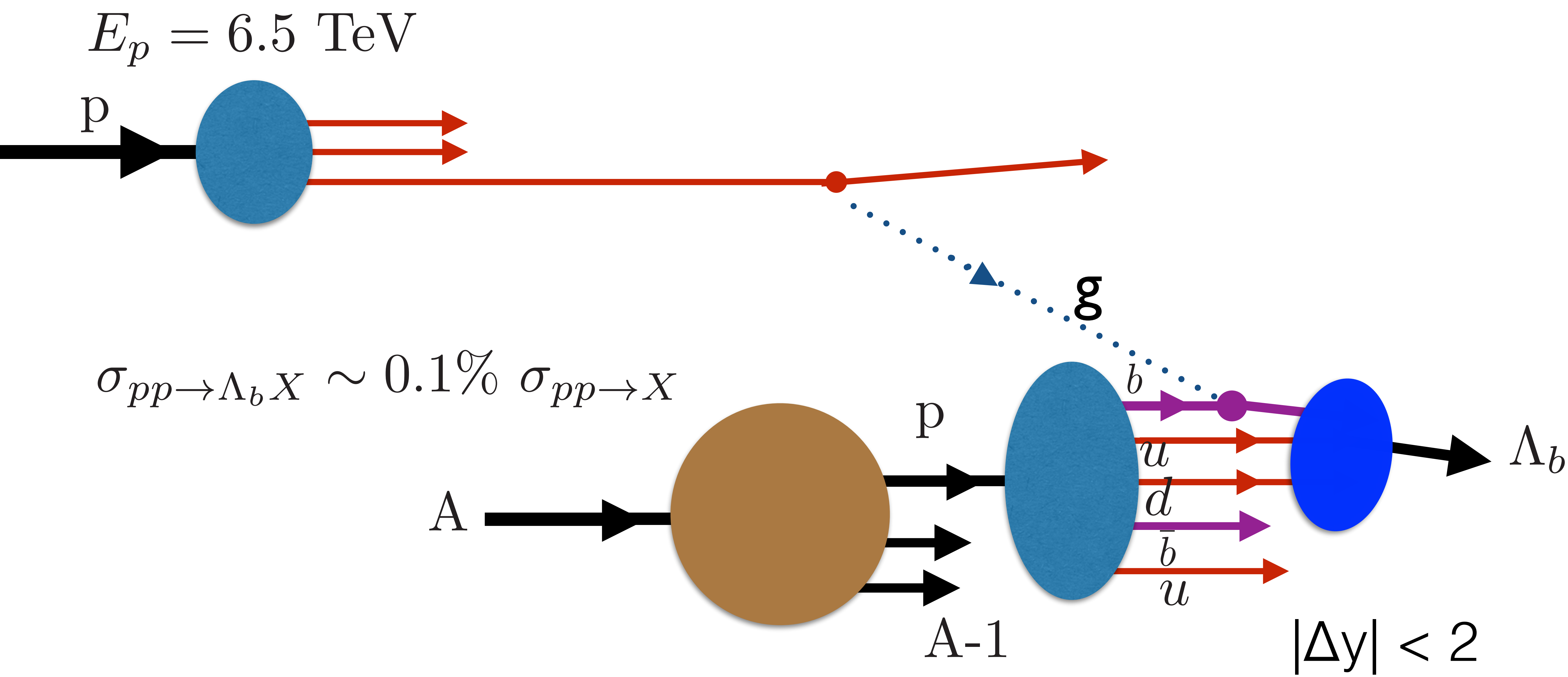


SMOG target at rest

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

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

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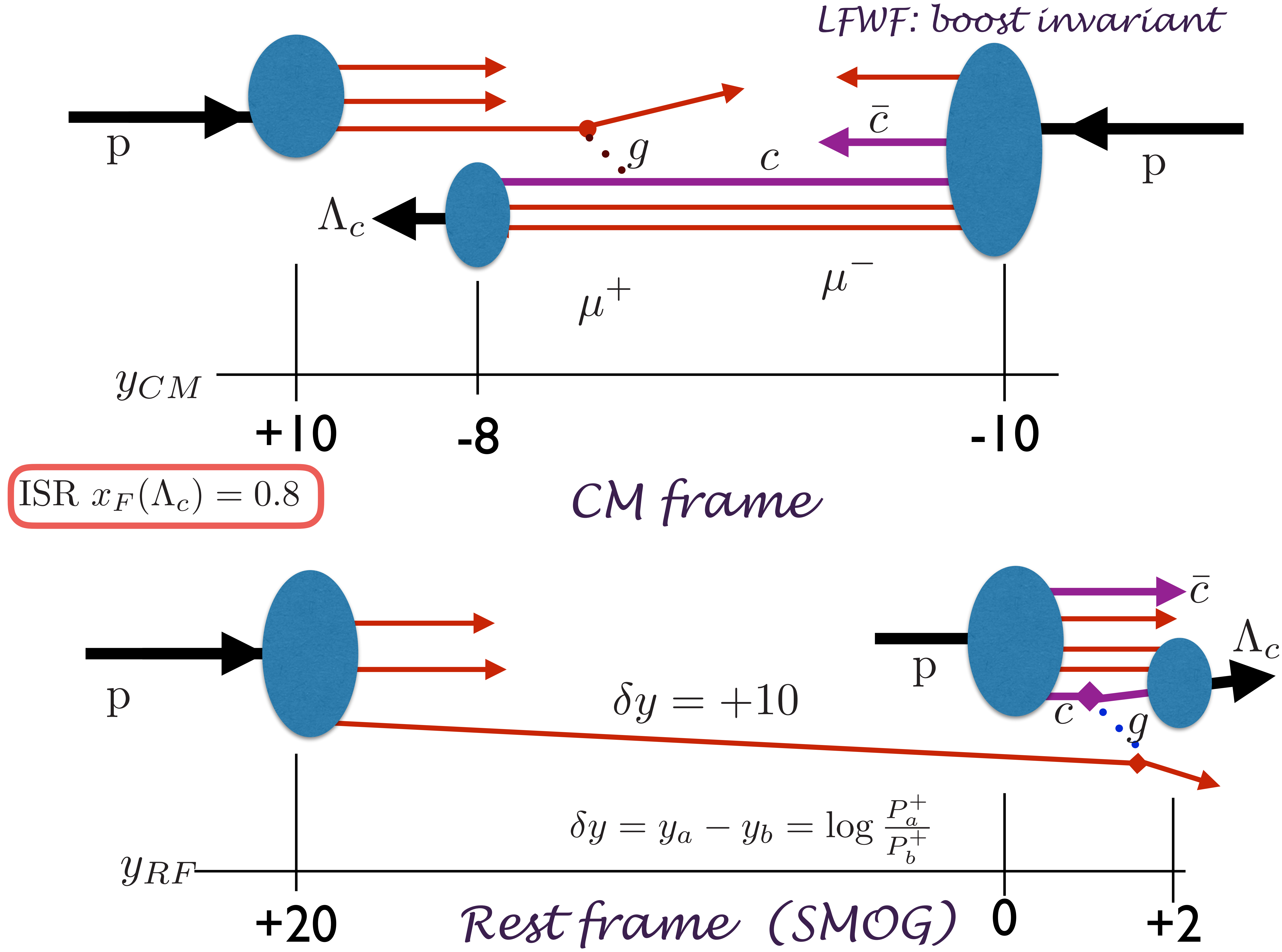
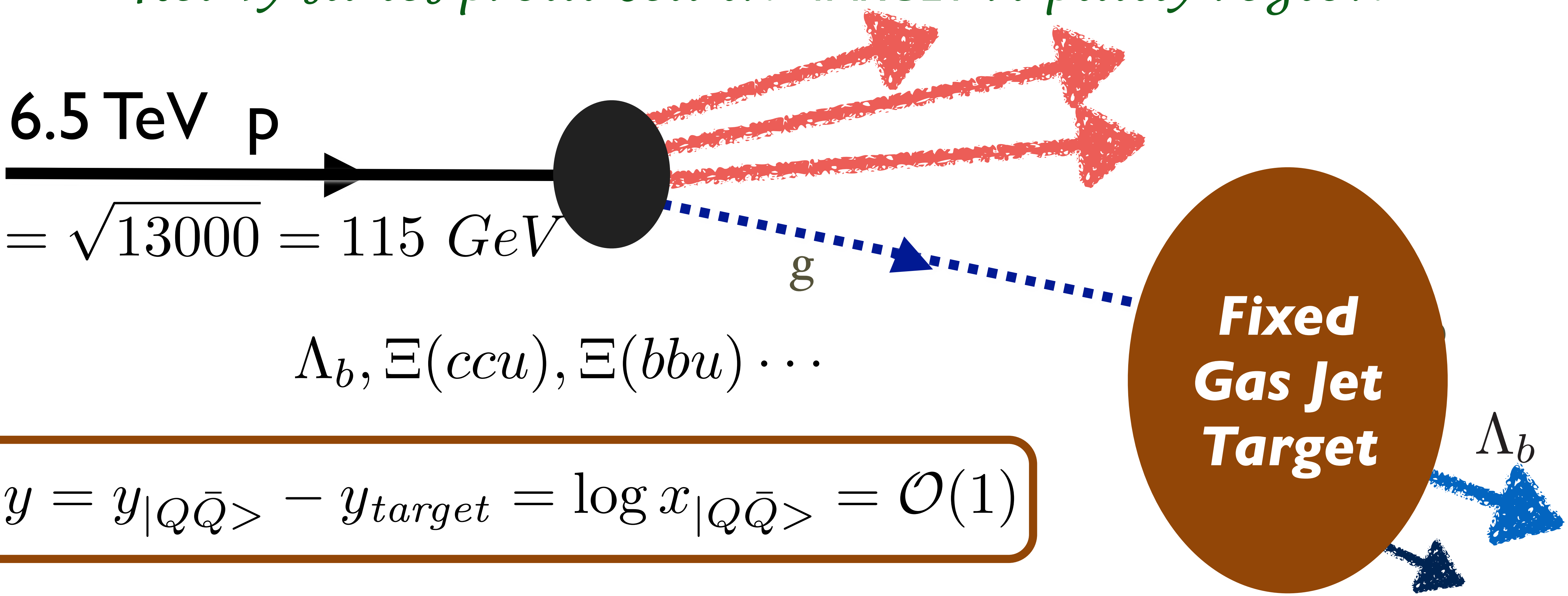

LFWF: boost invariant
p
$\bar{c}$
g
c
p
Λ_c
μ^+
μ^-
y_{CM}
+10
-8
-10
ISR $x_F(\Lambda_c) = 0.8$
CM frame
$\bar{c}$
Λ_c
p
p
$\delta y = +10$
c
g
$\delta y = y_a - y_b = \log \frac{P_a^+}{P_b^+}$
y_{RF}
+20
Rest frame (SMOG)
0
+2

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*



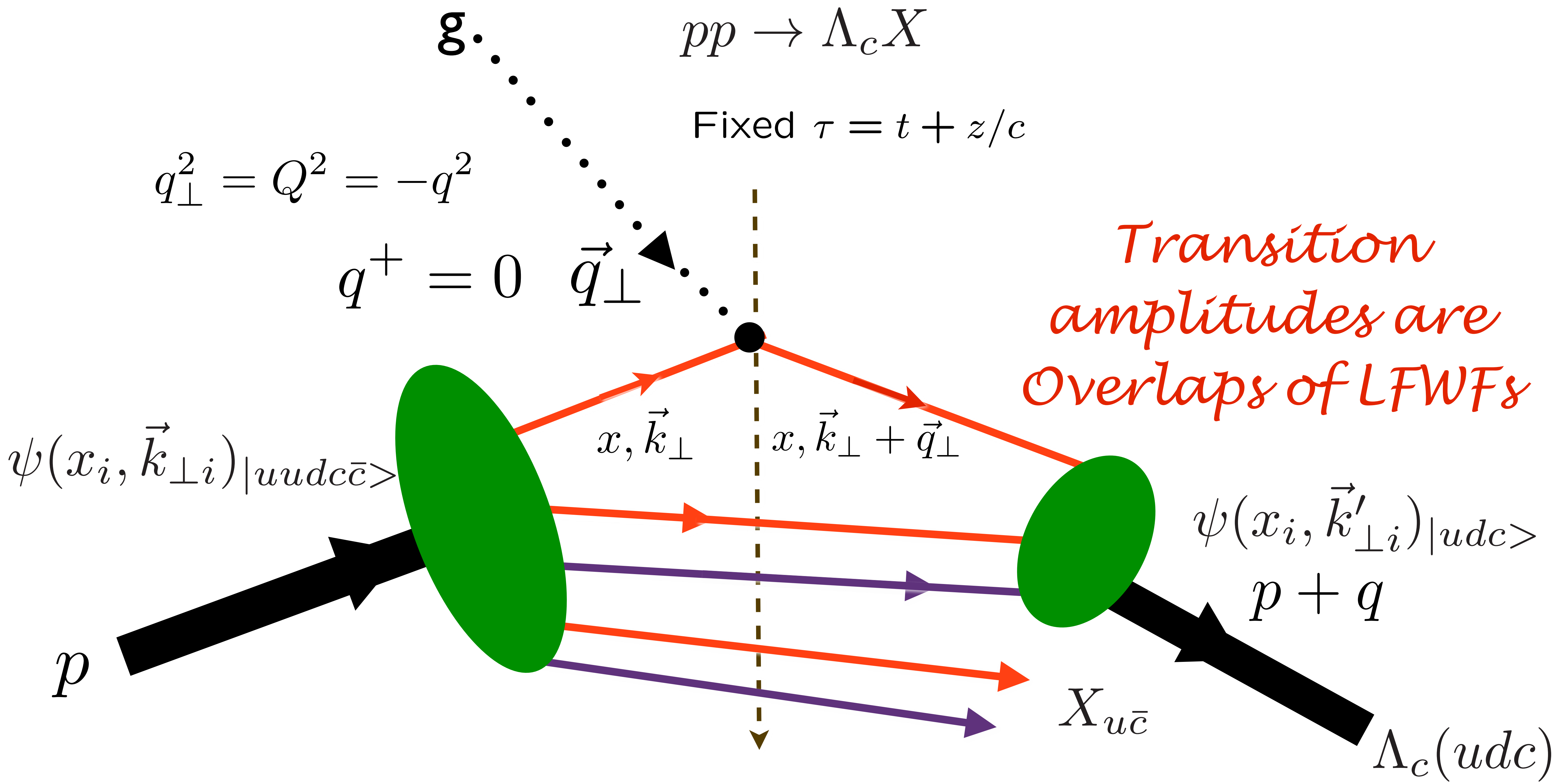
$$\sqrt{s} = \sqrt{13000} = 115\ GeV$$

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

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

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

Test at Smog@LHCb



$$M_{p \to \Lambda_c X_{u\bar{c}}} = \int \Pi_i^3 [d^2 k_{\perp i} dx_i] \psi_{\Lambda_c}(x_i, \vec{k}'_{\perp i})_{|udc>} \psi_p(x_i, \vec{k}_{\perp i})_{|uudc\bar{c}>}$$

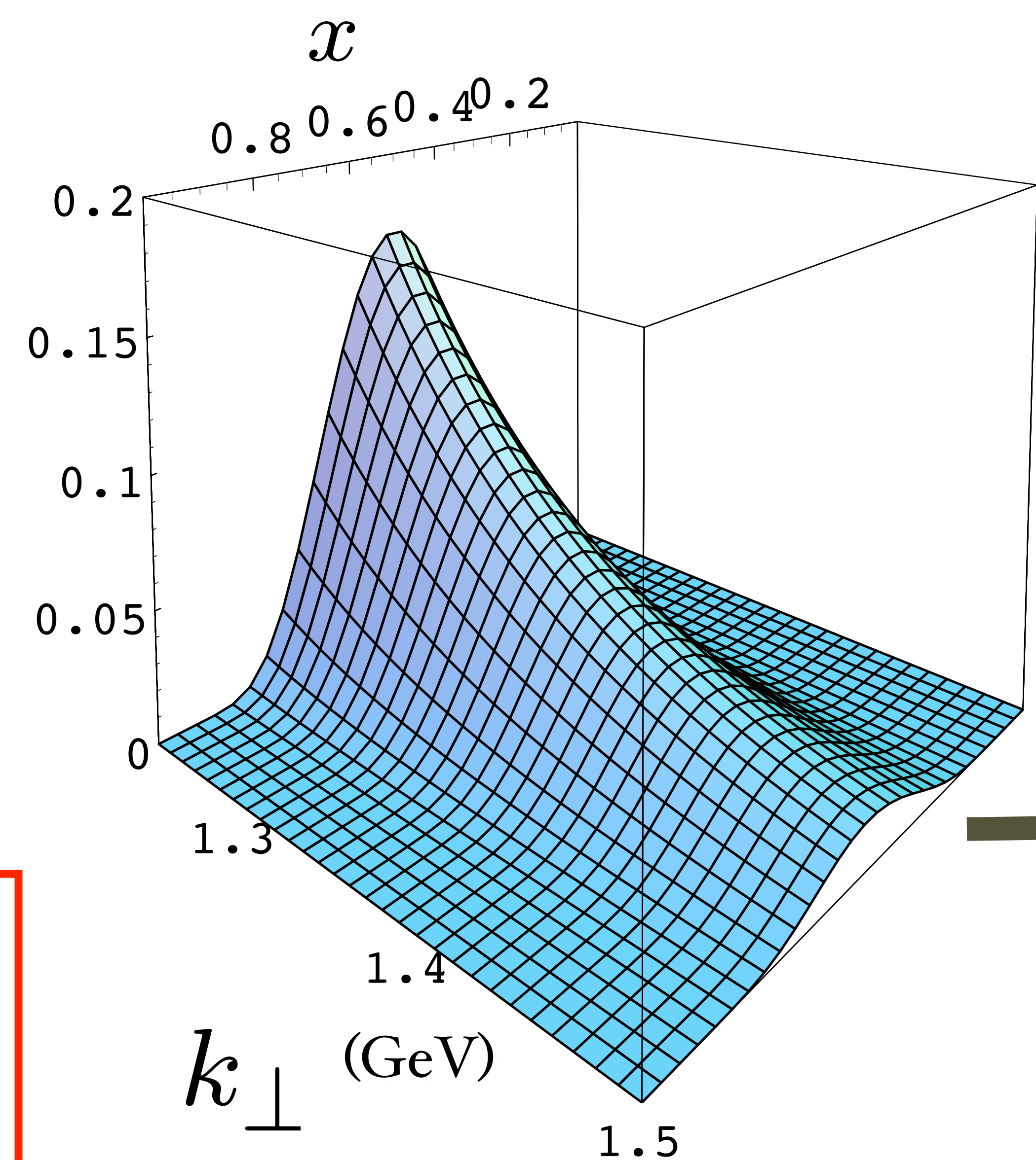
struck $\quad \vec{k}'_{\perp i} = \vec{k}_{\perp i} + (1 - x_i)\vec{q}_\perp$

spectators $\quad \vec{k}'_{\perp i} = \vec{k}_{\perp i} - x_i \vec{q}_\perp$

Drell, sjb

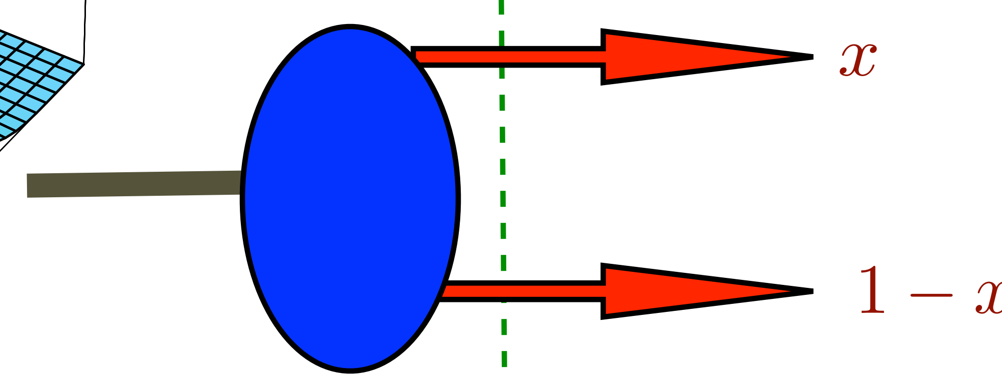
Prediction from AdS/QCD: Meson LFWF

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



de Teramond, Cao, sjb

"Soft Wall" model



Note coupling

$k_\perp^2, x$

massless quarks

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

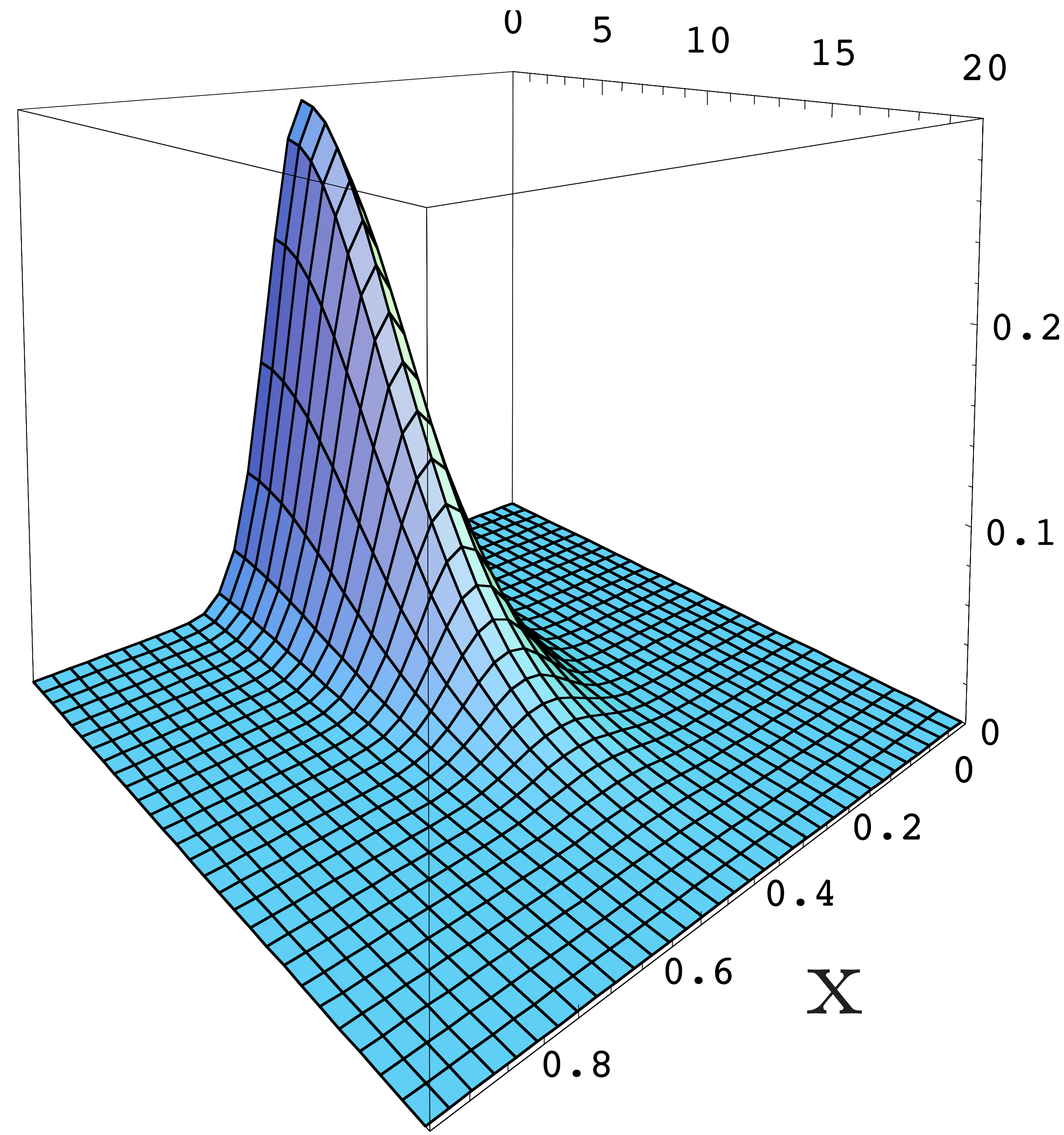
$$\phi_\pi(x) = \frac{4}{\sqrt{3}\pi} f_\pi \sqrt{x(1-x)}$$

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

Provides Connection of Confinement to Hadron Structure

J/ψ

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



LFWF peaks at

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

where

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

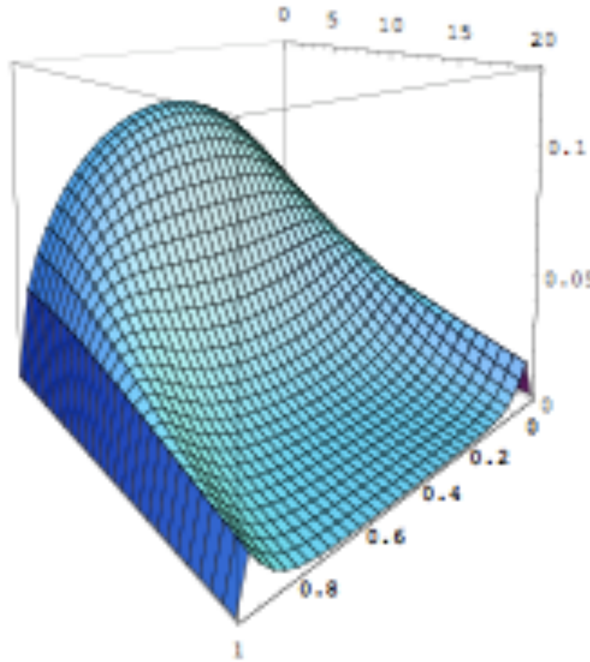
minimum of LF energy denominator

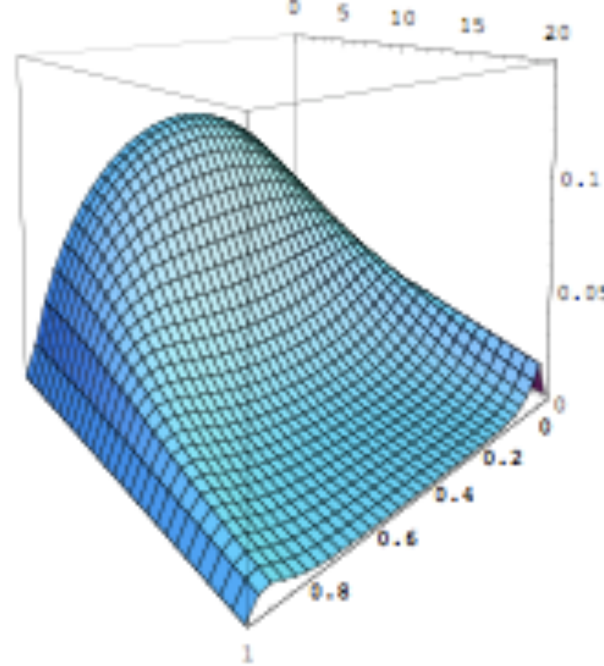
$$\kappa = 0.375 \text{ GeV}$$

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

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

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



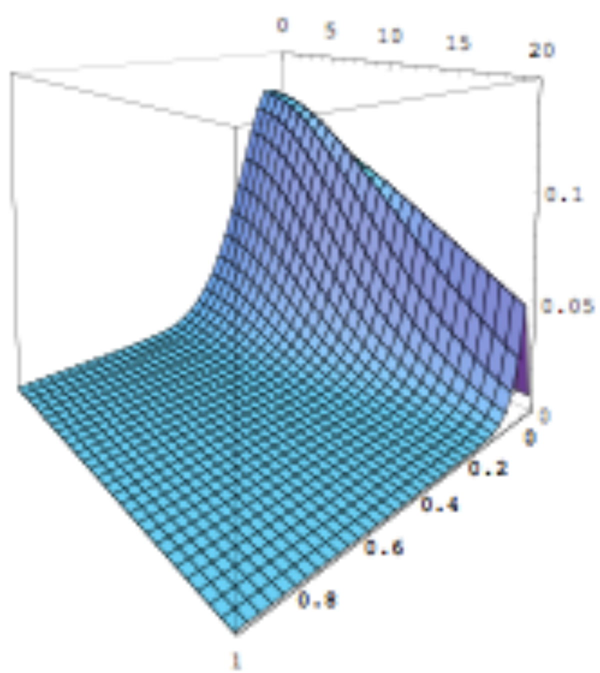


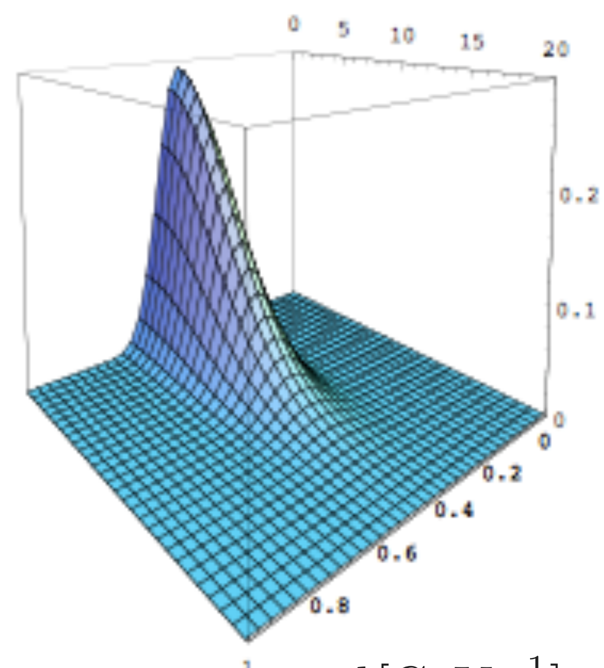
$|K^+ >= |u\bar{s} >$

$m_s = 95\ MeV$

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

$m_c = 1.25\ GeV$

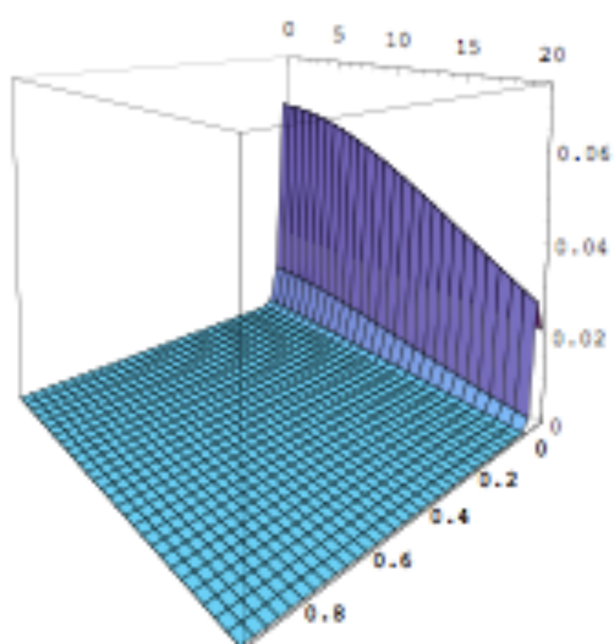


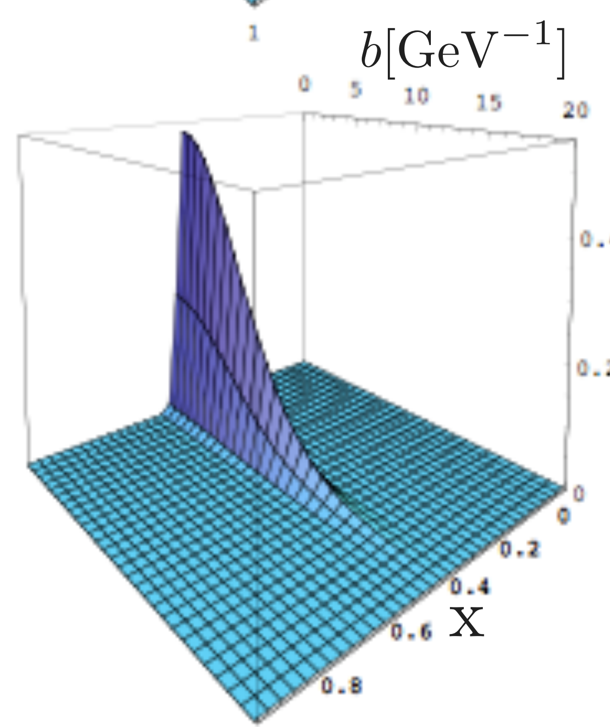


$|\eta_c >= |c\bar{c} >$

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

$m_b = 4.2\ GeV$



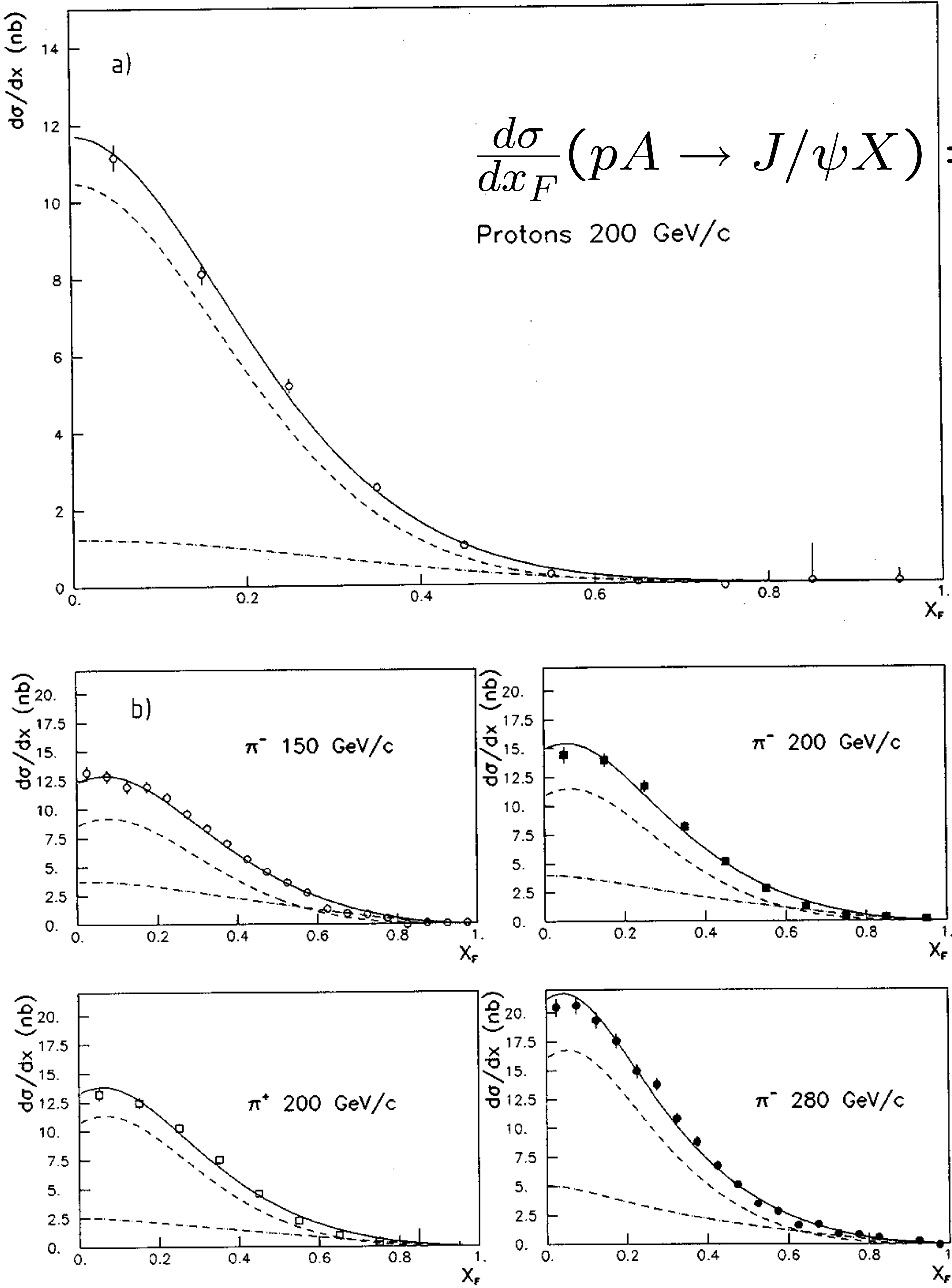


$|\eta_b >= |b\bar{b} >$

$\kappa = 375\ MeV$

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

NA3: Badier et al.

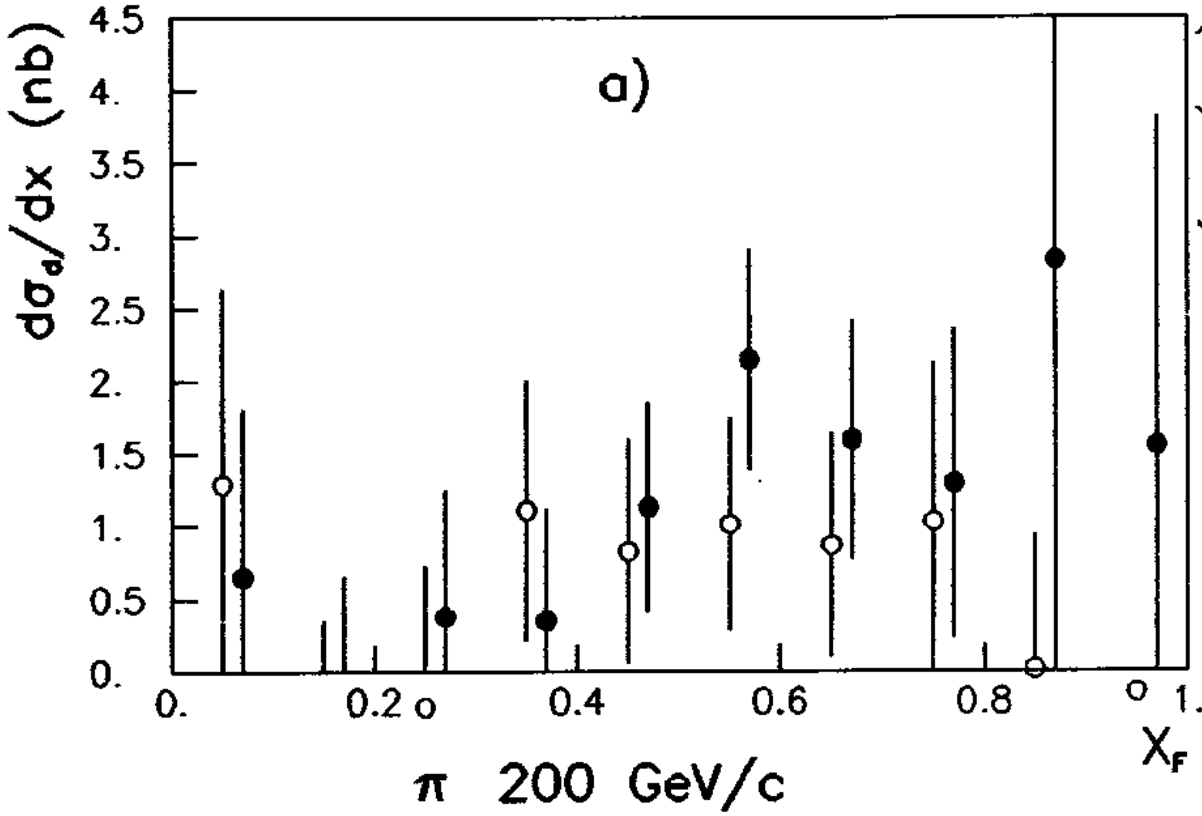


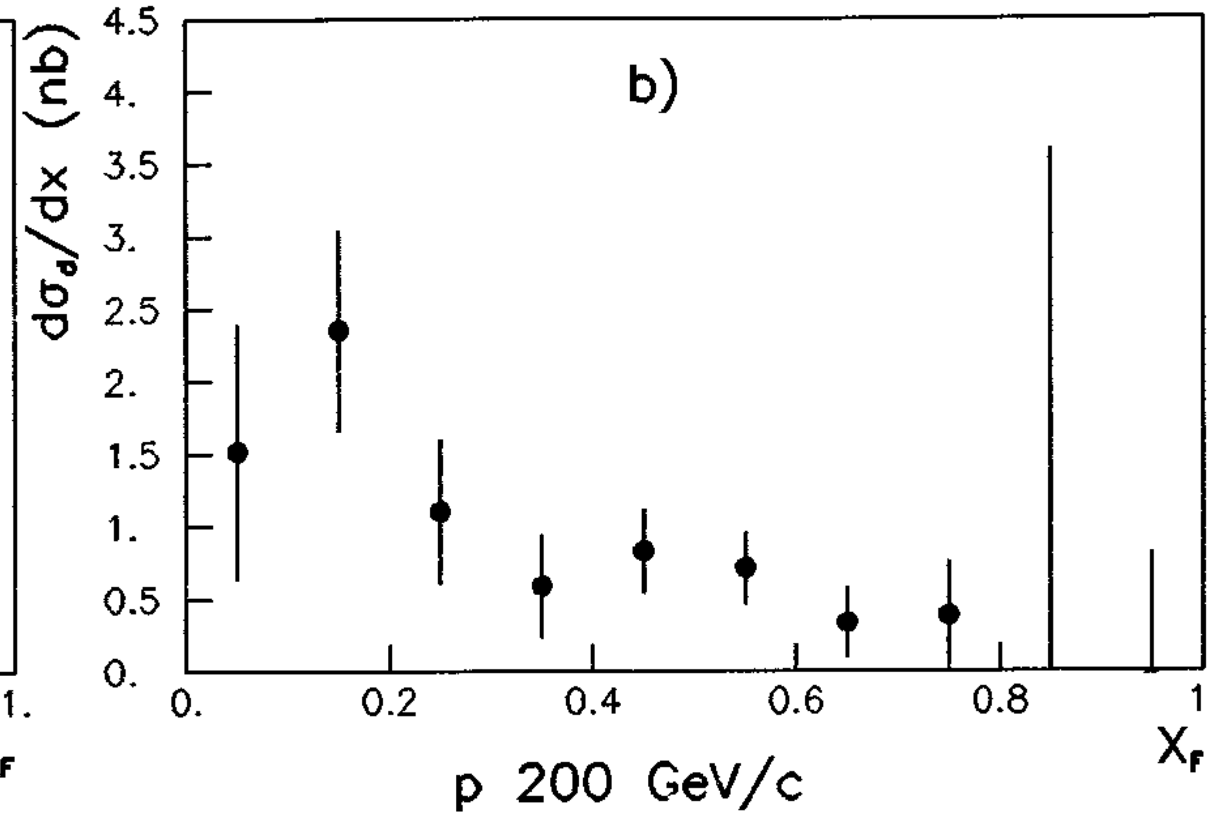
A^1 component consistent with sum of gg and $\bar{q}q$ fusion

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

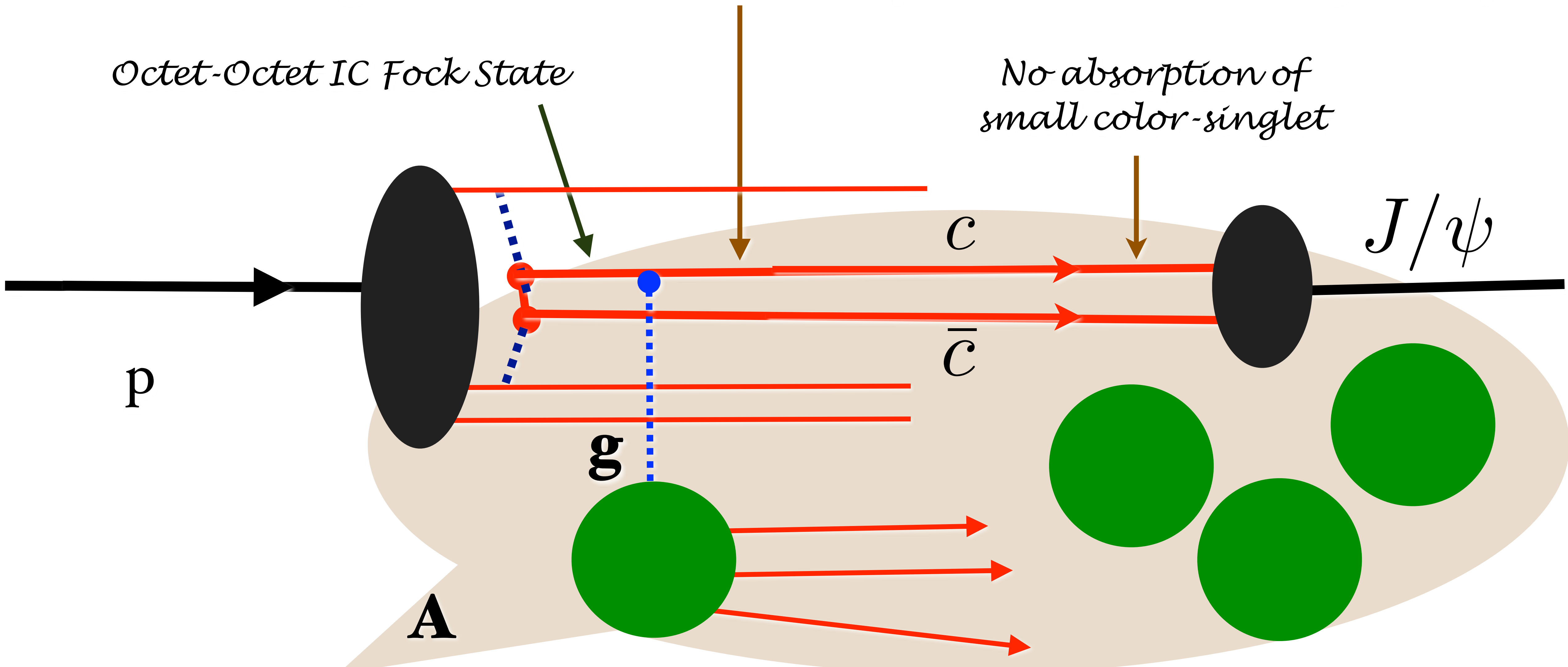
NA3: Badier et al.

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

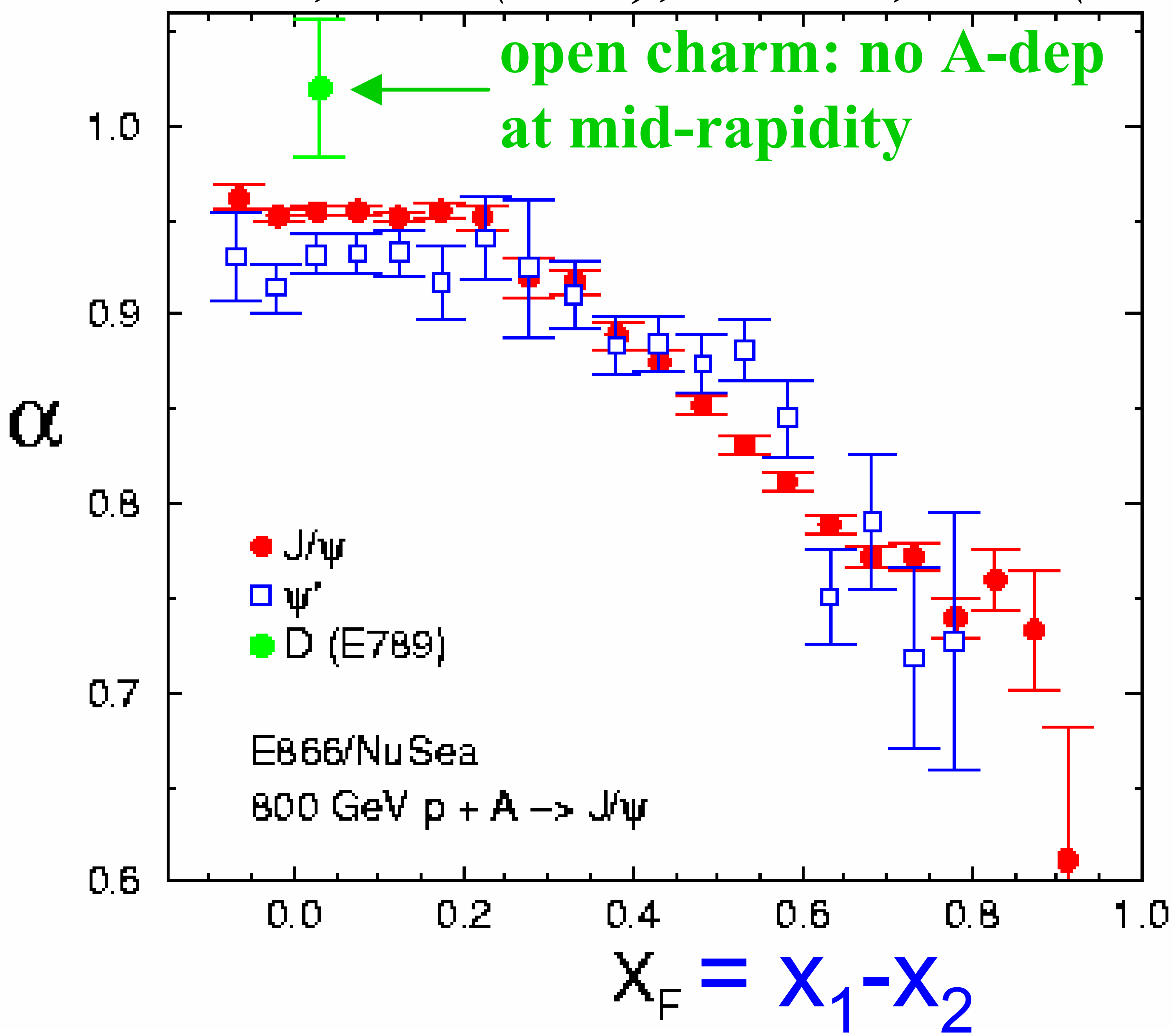


$$\frac{d\sigma}{dx_F}(pA \to J/\psi X) = A^{2/3} \times \frac{d\sigma}{dx_F}(pN \to J/\psi X)$$

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.

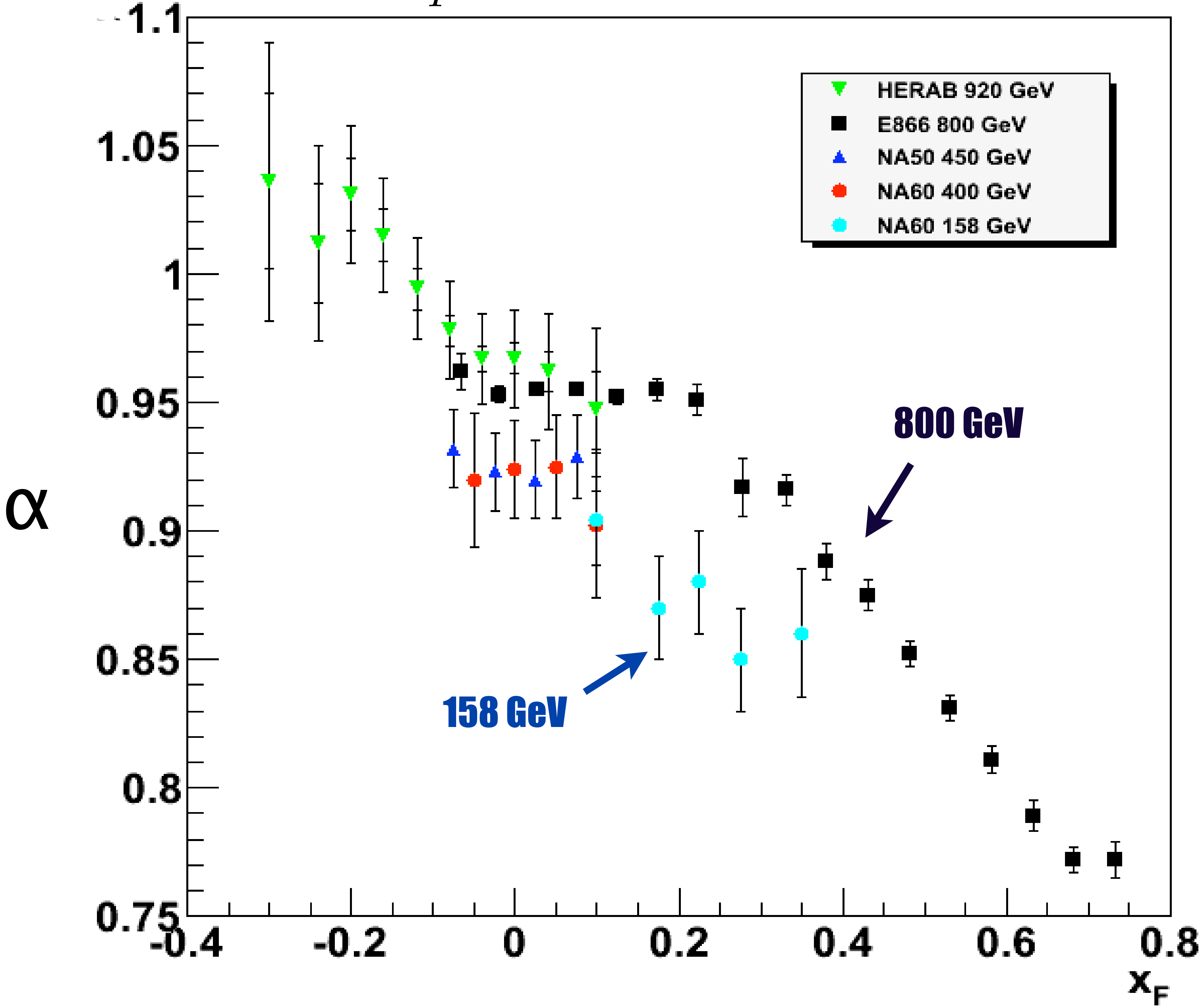
P. Hoyer, **M. Vanttinen** (**Helsinki U.**) , **U. Sukhatme** (**Illinois U., Chicago**) . **HU-TFT-90-14, May 1990. 7pp.**

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

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

NA60 pA data @ 158GeV

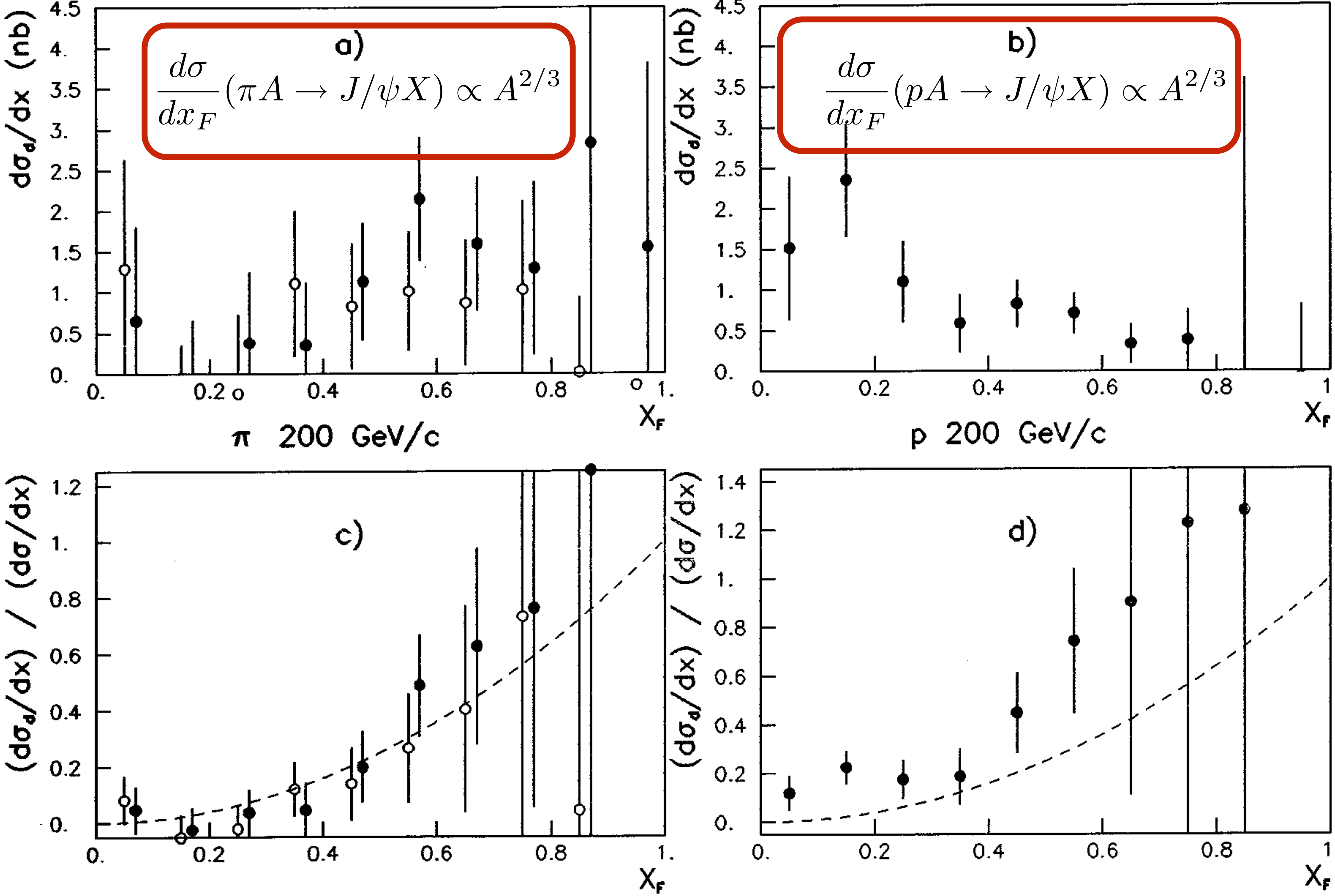
$$\frac{d\sigma}{dx_F}(pA \to J/\psi X) \propto A^{\alpha}$$



Clear dependence on x_F and beam energy

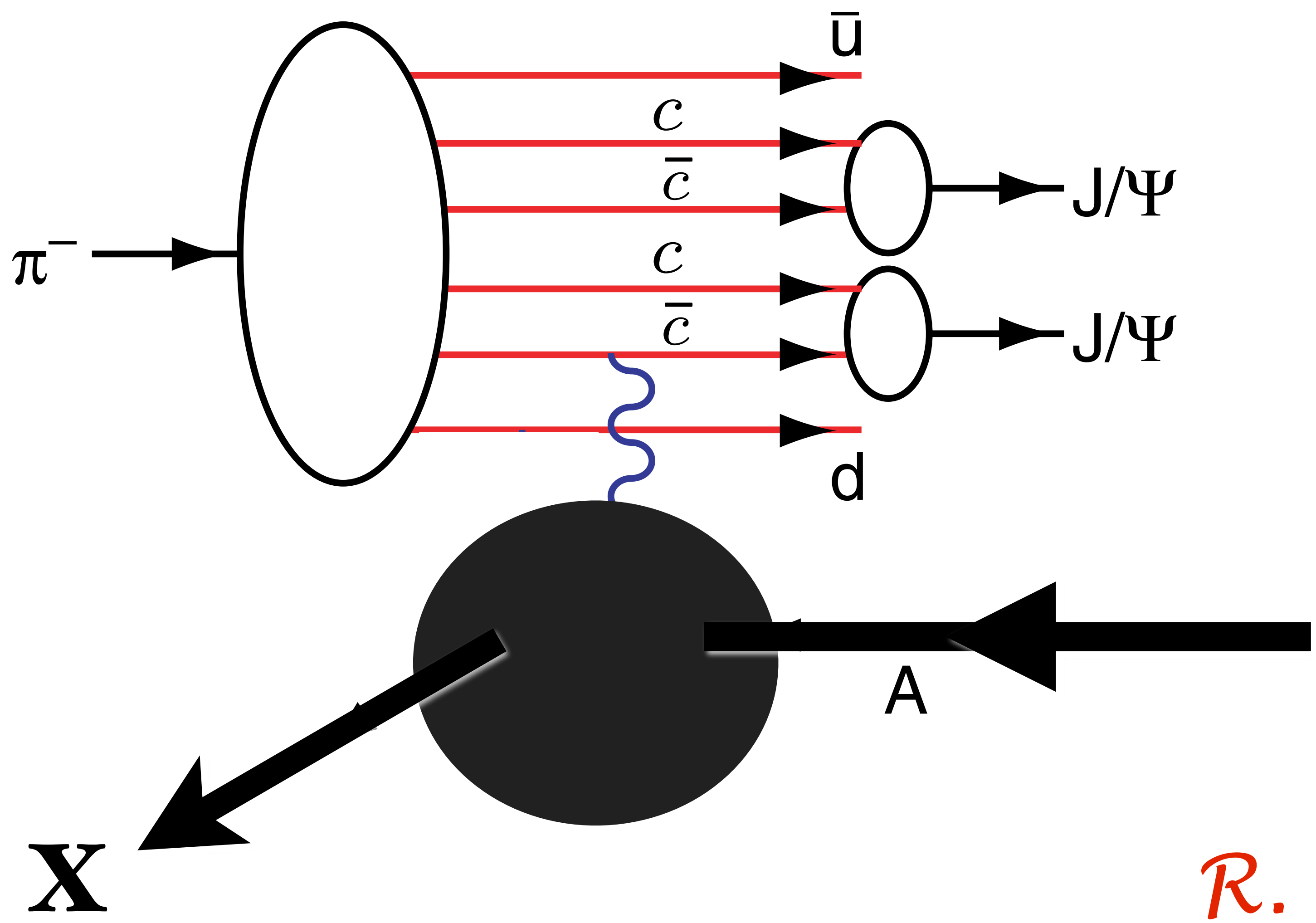
Dramatic change in nuclear dependence

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

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

R. Vogt, sjb

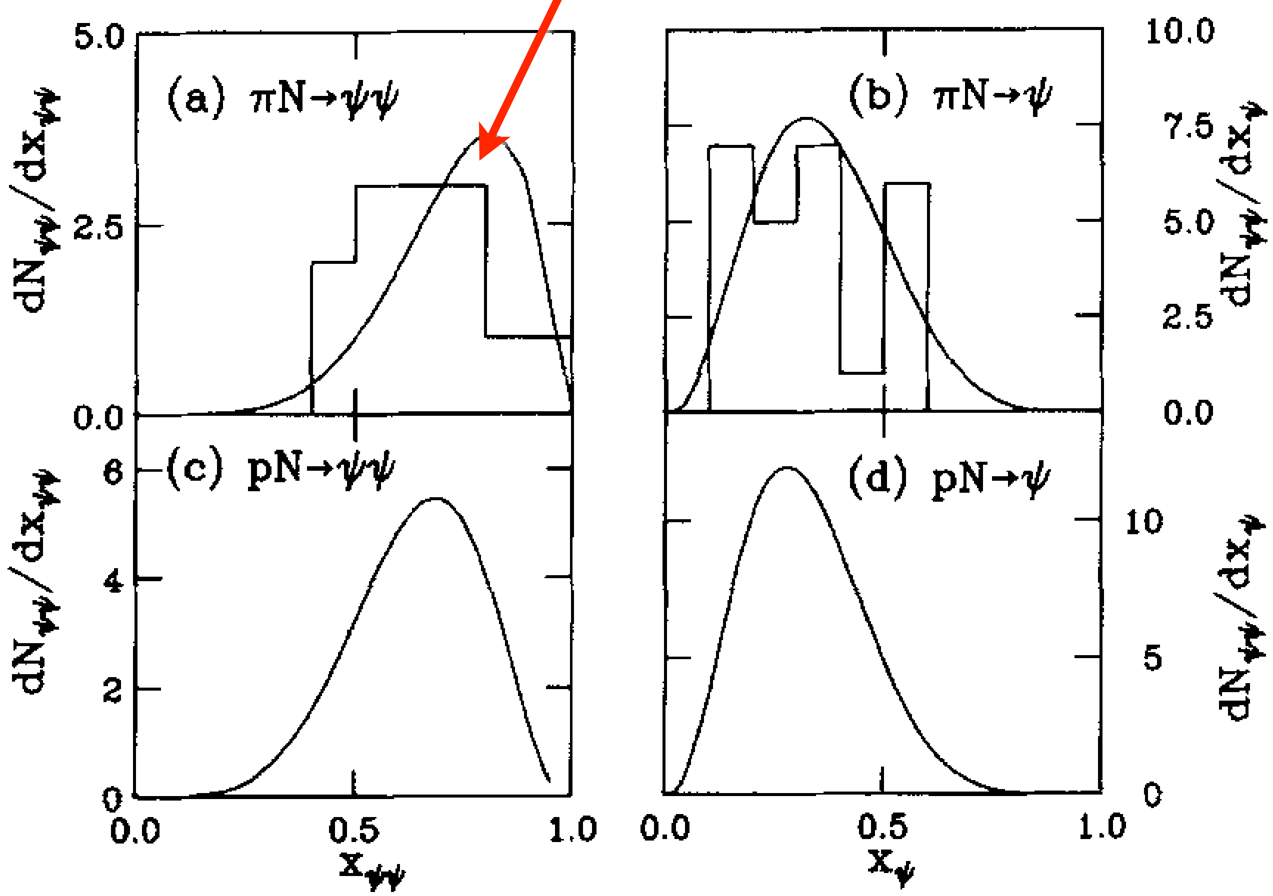
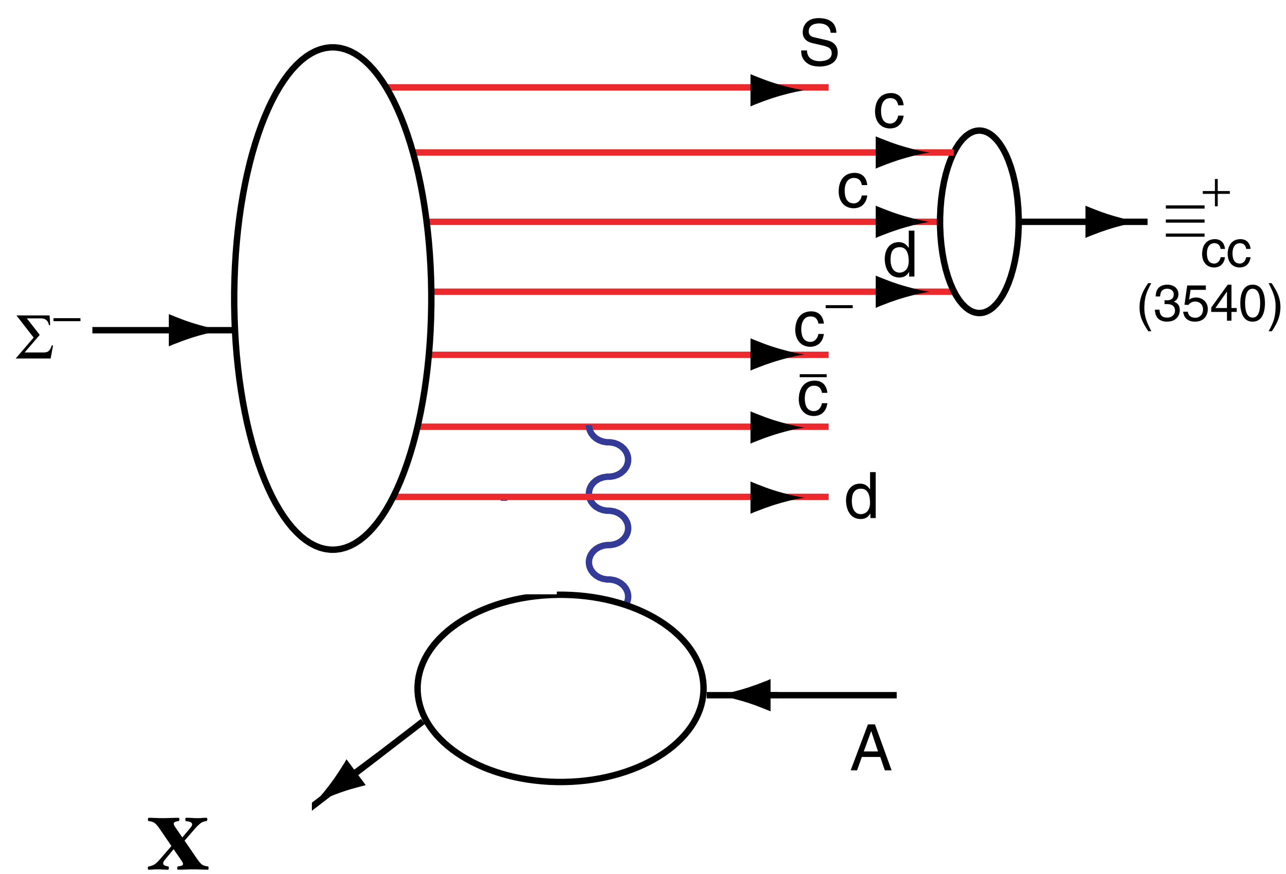


Fig. 3. The $\psi\psi$ pair distributions are shown in (a) and (c) for the pion and proton projectiles. Similarly, the distributions of J/ψ's from the pairs are shown in (b) and (d). Our calculations are compared with the $\pi^- N$ data at 150 and 280 GeV/c [1]. The $x_{\psi\psi}$ distributions are normalized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

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



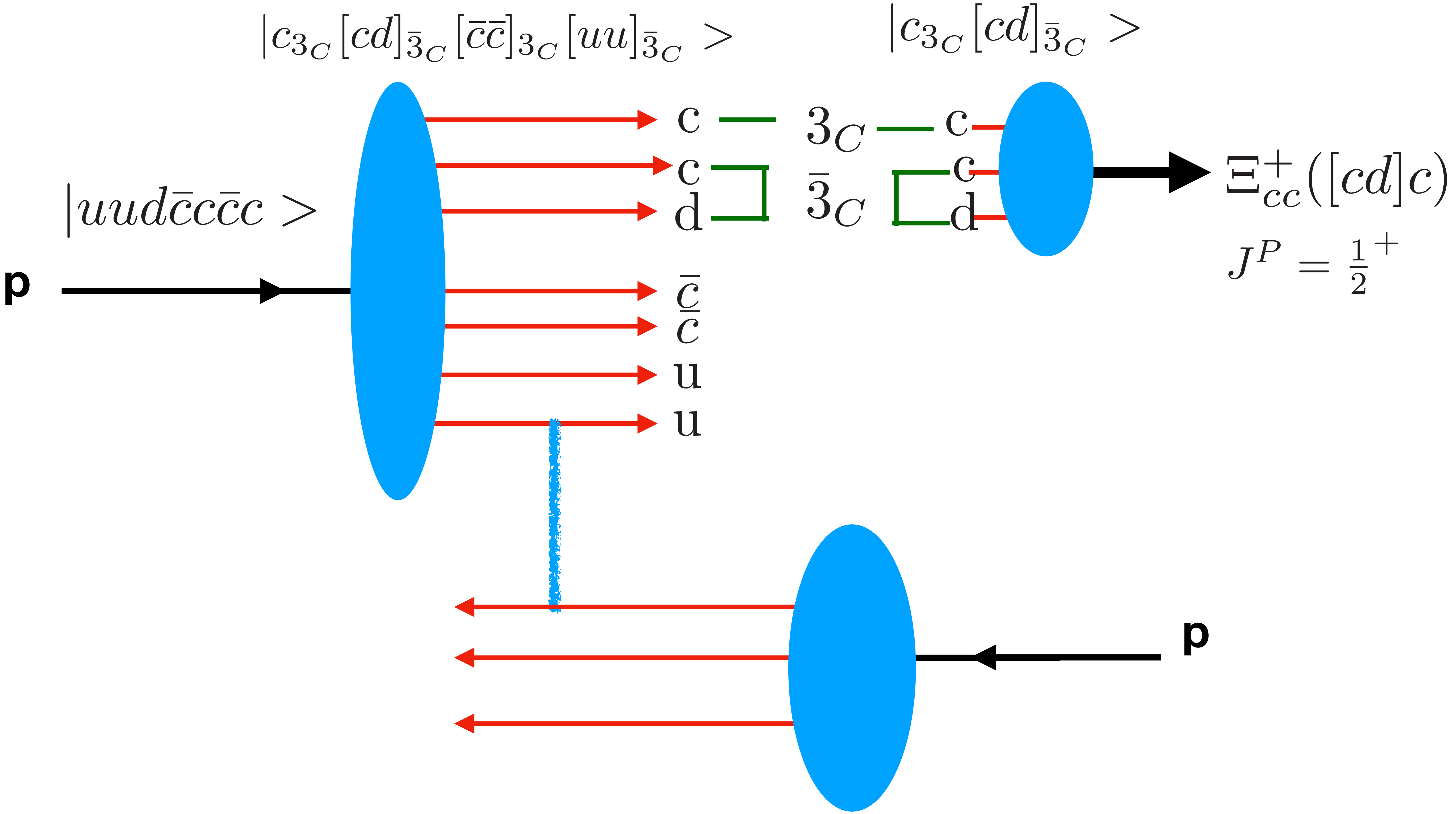
Production of a Double-Charm Baryon

SELEX high x_F $< x_F >= 0.33$

Hadroproduction of the Double-Charm Baryon at High X_F

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

Double Intrinsic Charm Fock State of proton



$$\text{SELEX: } \Xi(ccd)^+(3510 \pm 2) \rightarrow \Lambda_c^+ K^- \pi^+$$

SLAC-PUB-17156

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]

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[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 $pp \to J/\psi X$

Rules out color drag (Pythia)

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

- High x_F $pp \to \Lambda_c X$

Evidence for IQ

- High x_F $pp \to \Lambda_b X$

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

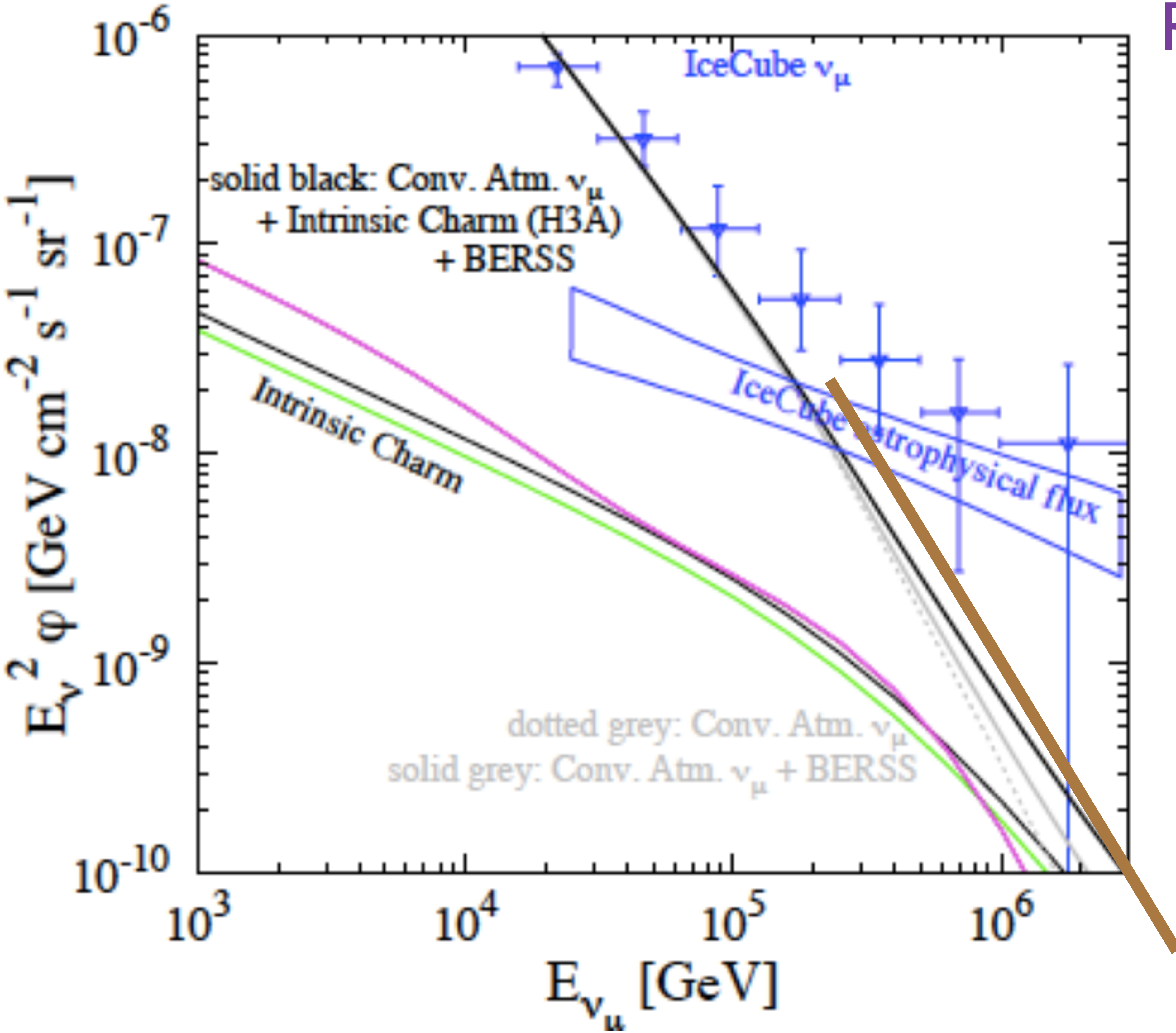
Explain Tevatron anomalies: $p\bar{p} \to \gamma c X, Z c X$

Interesting spin, charge asymmetry, threshold, spectator effects

Important corrections to B decays; Quarkonium decays

Gardner, Karliner, sjb

R.Laha, sjb

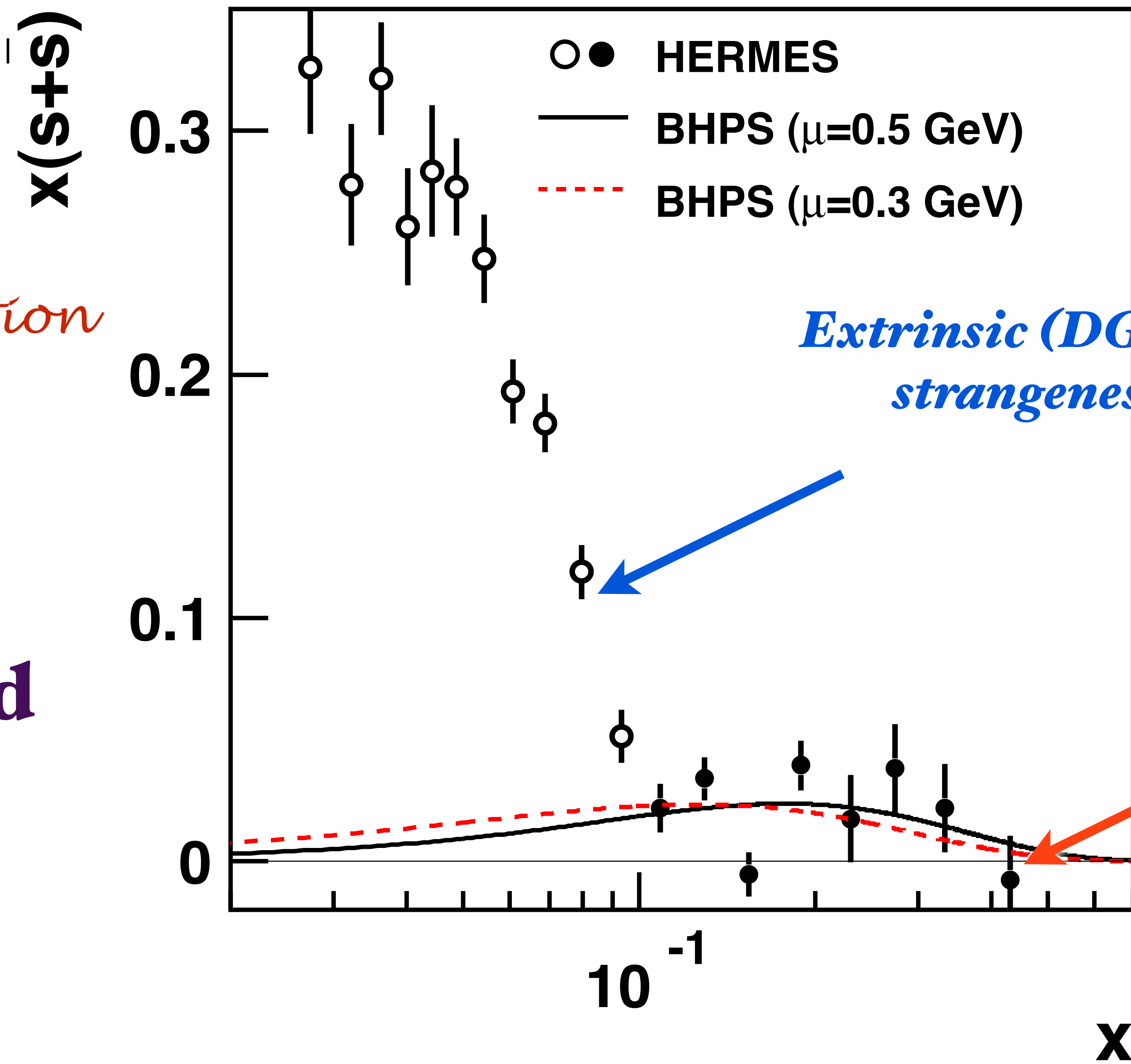


IC: doubles conventional estimates because of rapidly falling proton distribution

HERMES: Two components to s(x,Q²)!

BHPS: Hoyer, Sakai, Peterson, sjb

Sensitive to Fragmentation Function



Intrinsic strangeness!

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

arXiv:1105.2381

Consistent with intrinsic charm data

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.

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

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

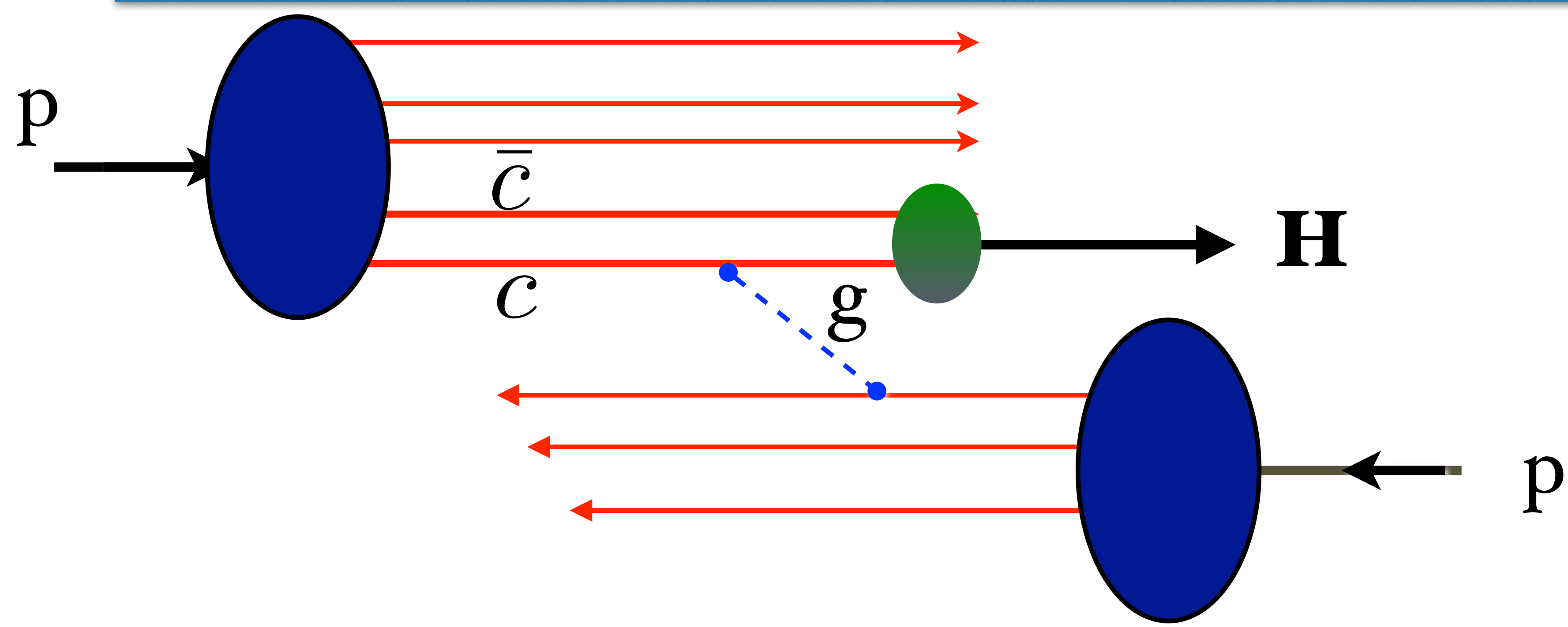
- IC Explains $J/\psi \to \rho\pi$ puzzle
(Karliner, SJB)

- 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



$$pp \to H\,X$$

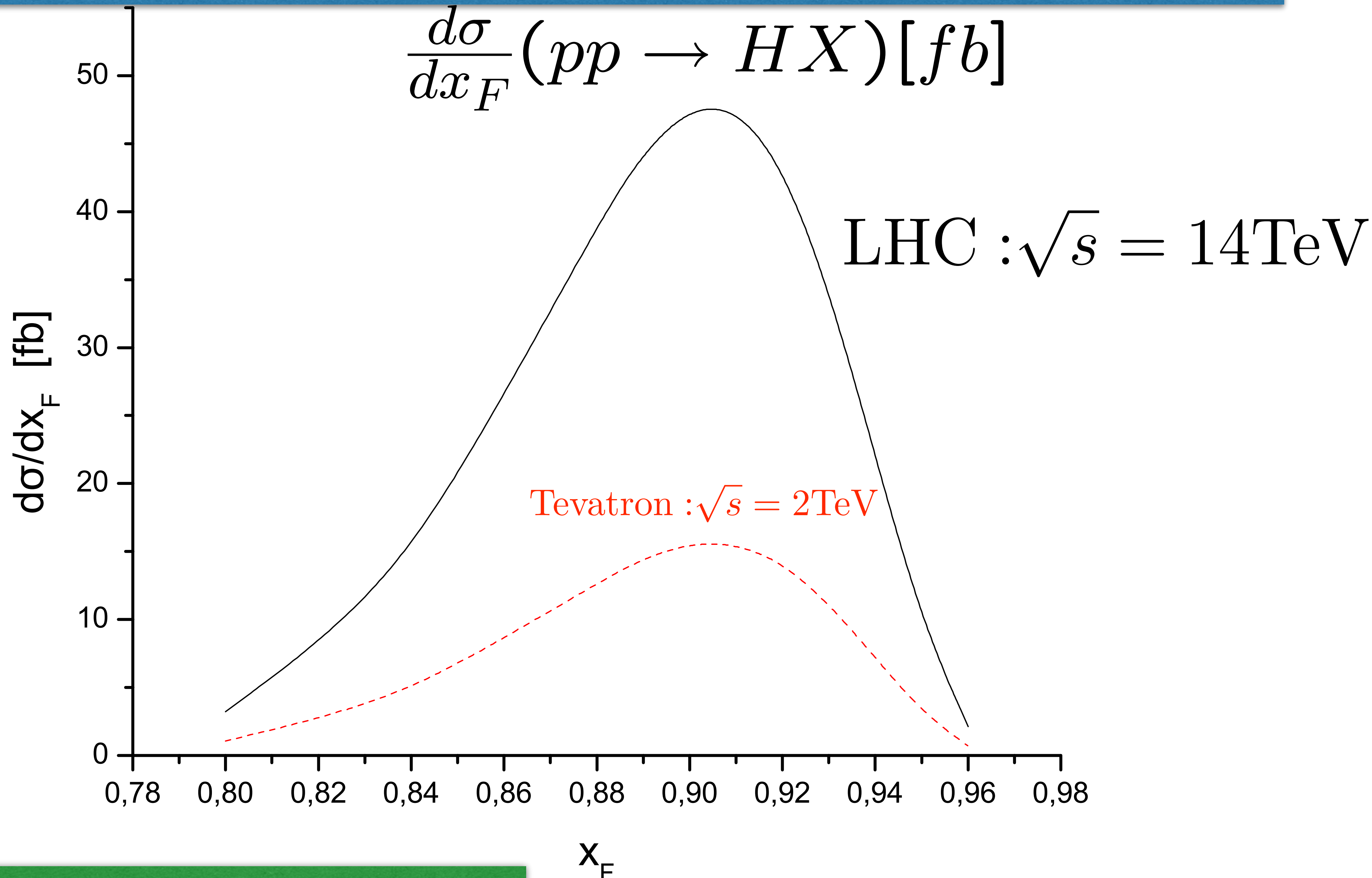
Also: intrinsic strangeness, bottom, top

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



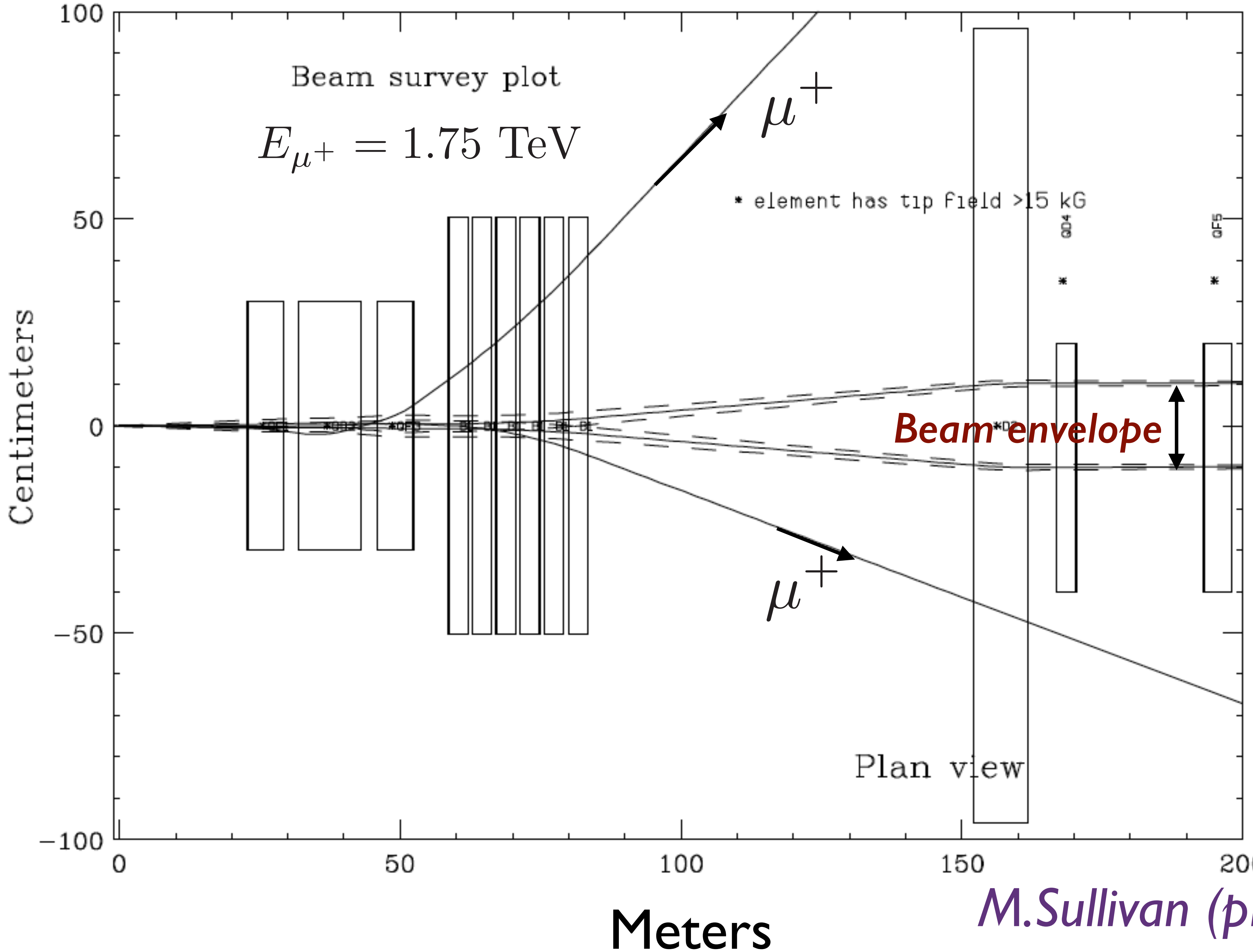
Need High x_F Acceptance

Most practical: Higgs to 4 muons

Goldhaber, Kopeliovich, Schmidt, Soffer, sjb

Use LHC Magnetic Field as Downstream Muon Spectrometer

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

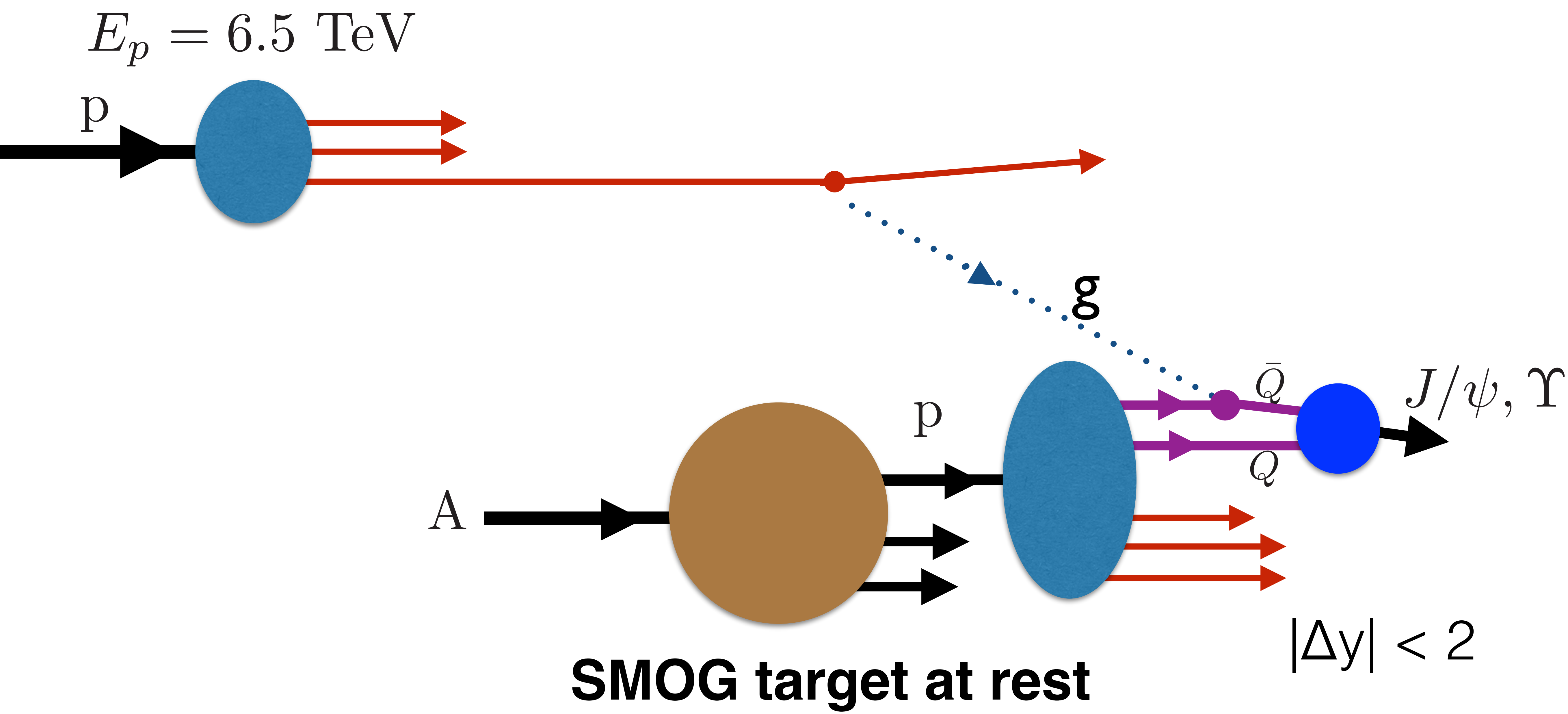


M.Sullivan (preliminary)

Measure exotic events at SMOG@LHCb such as

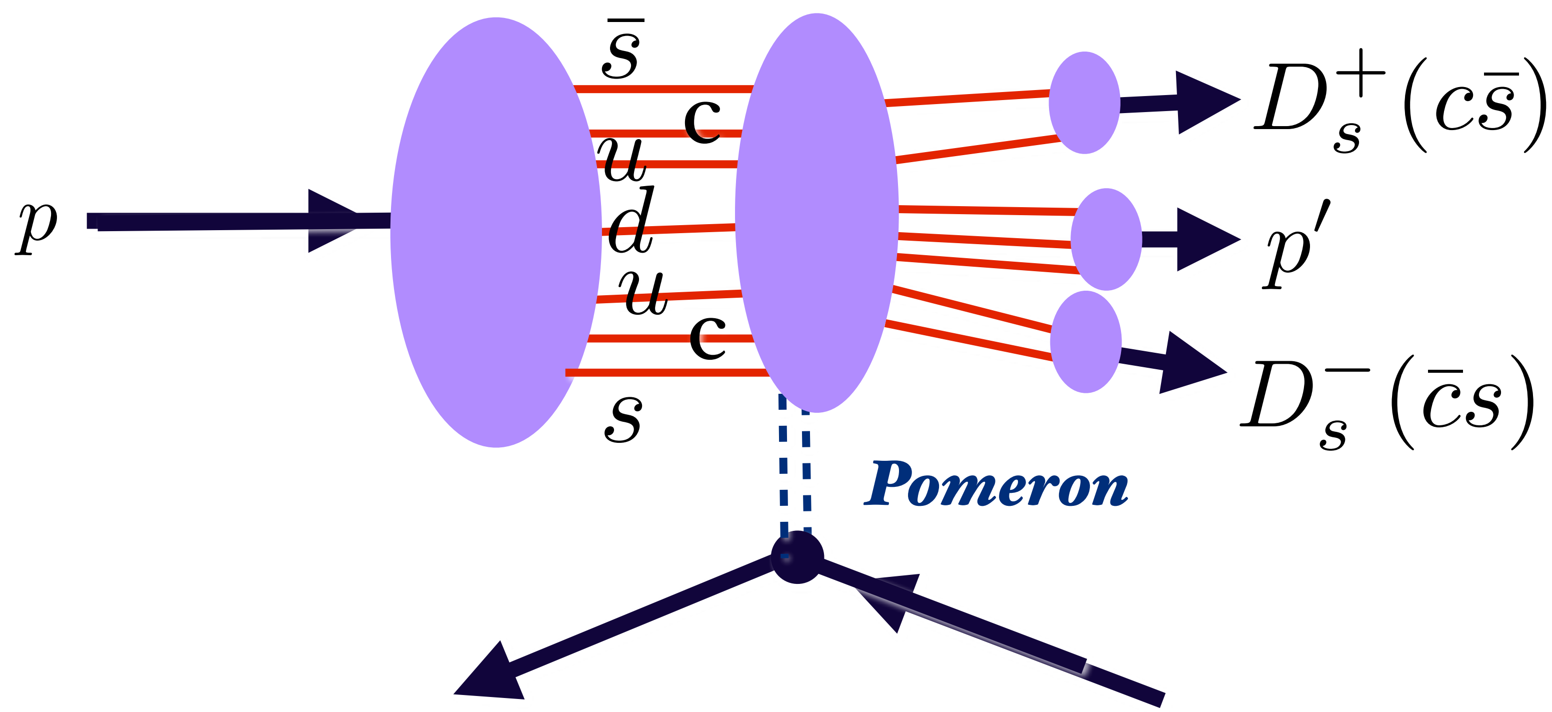
$$pA \to \Upsilon + J/\psi X \to \mu^+\mu^-\mu^+\mu^- X$$

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



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

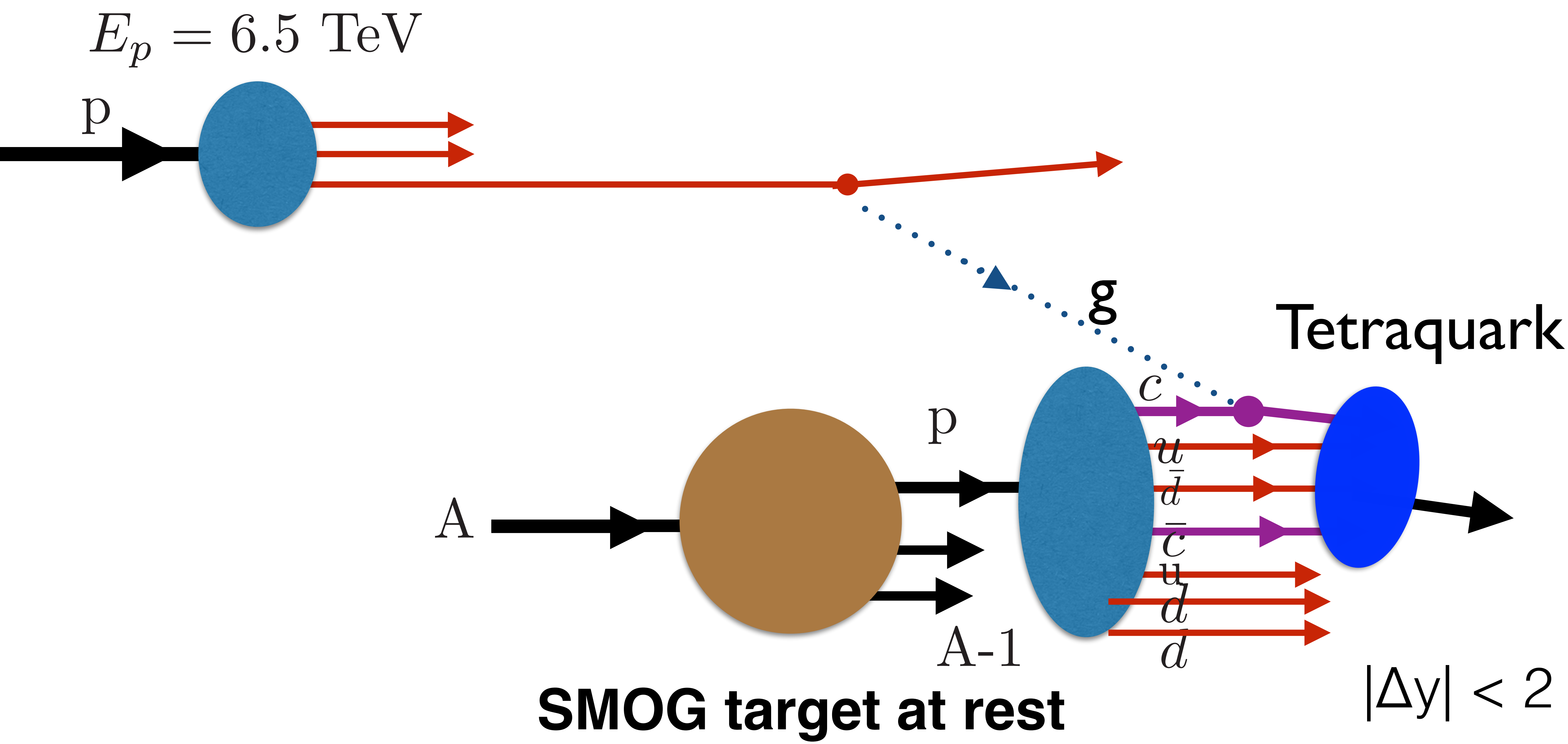
Quarkonium produced nearly at rest — has small rapidity y < 2 in target rest frame



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.

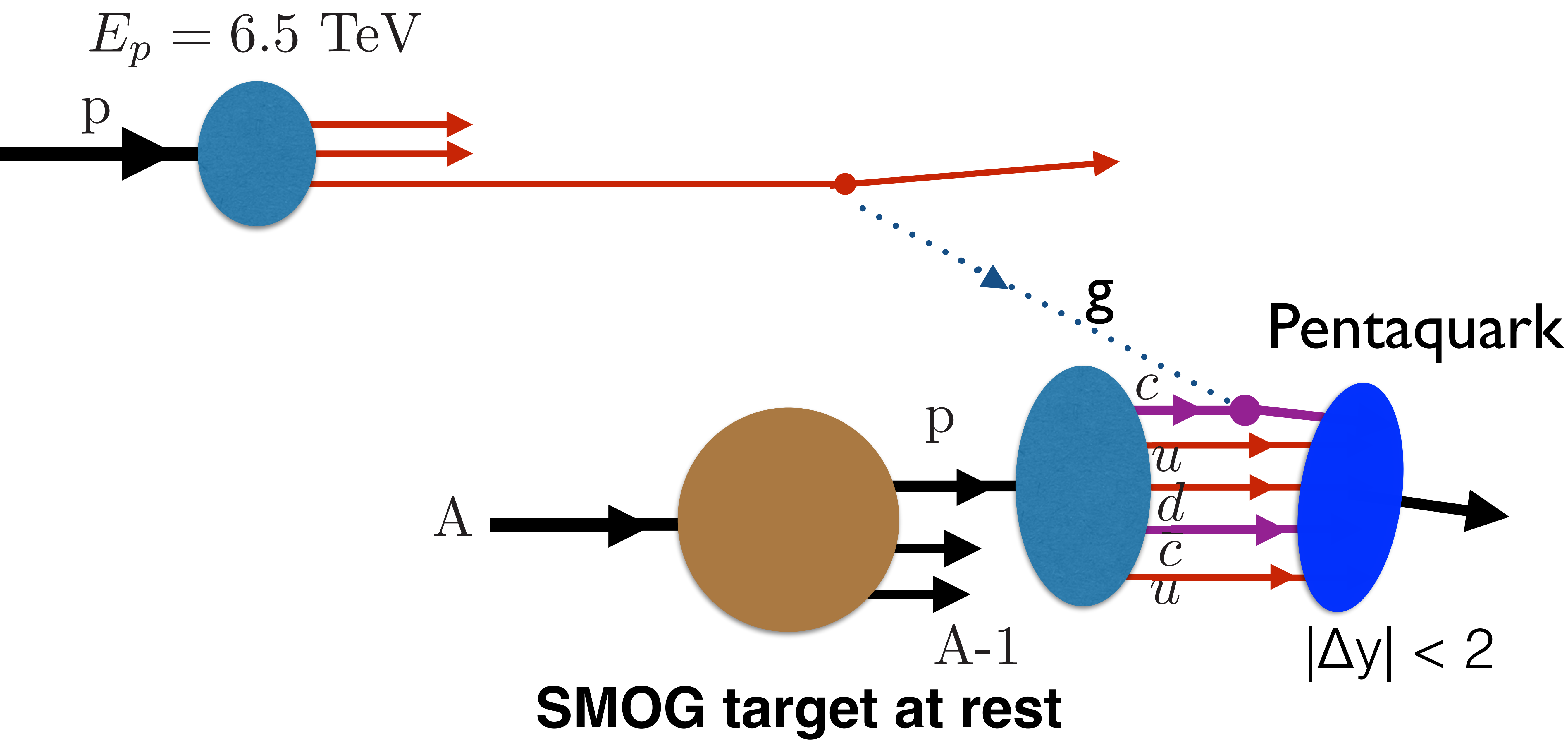
$$pA \rightarrow Tetraquark(|cu\bar{c}\bar{d}>)X$$



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

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

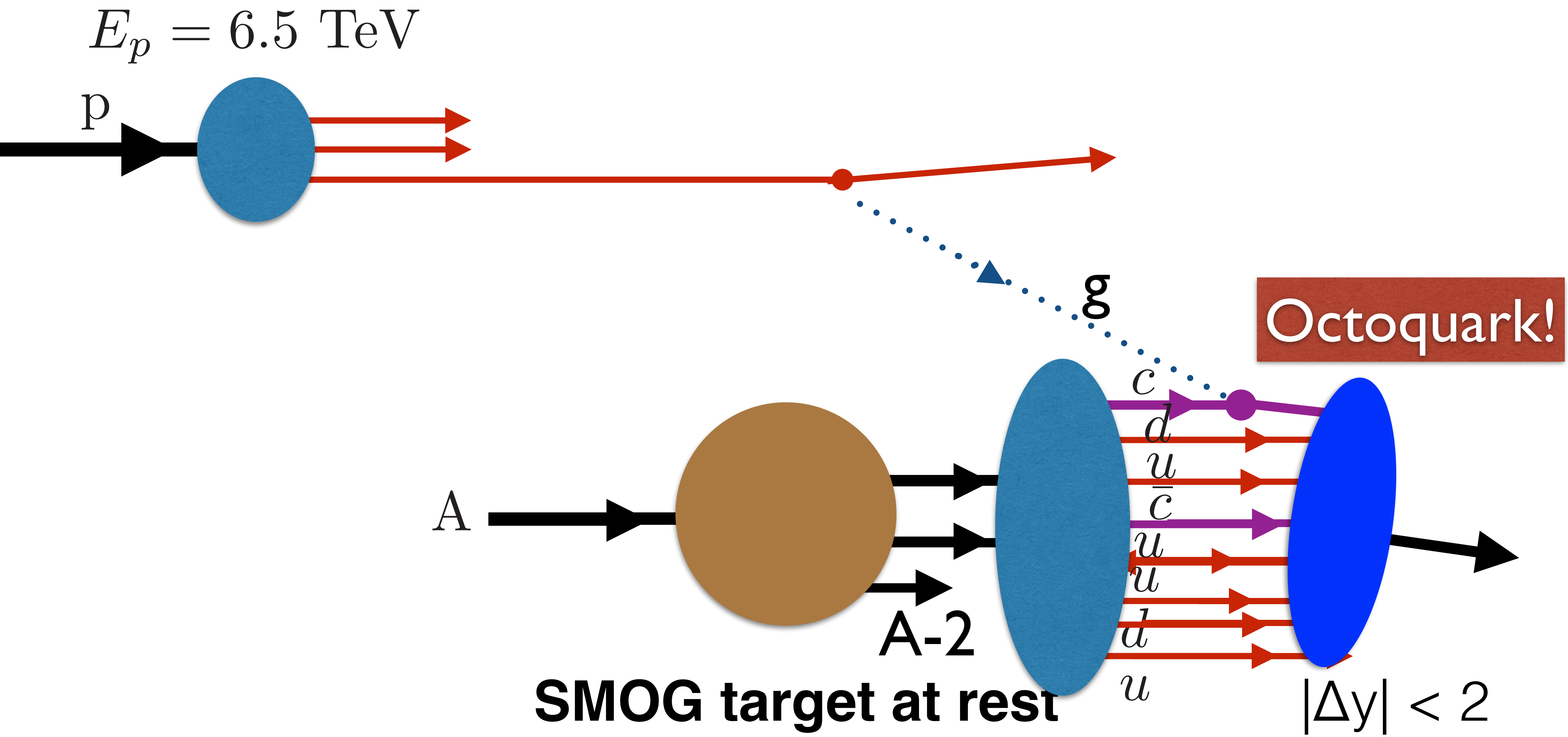
$$pA \to Pentaquark(|uudc\bar{c} >)X$$



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

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

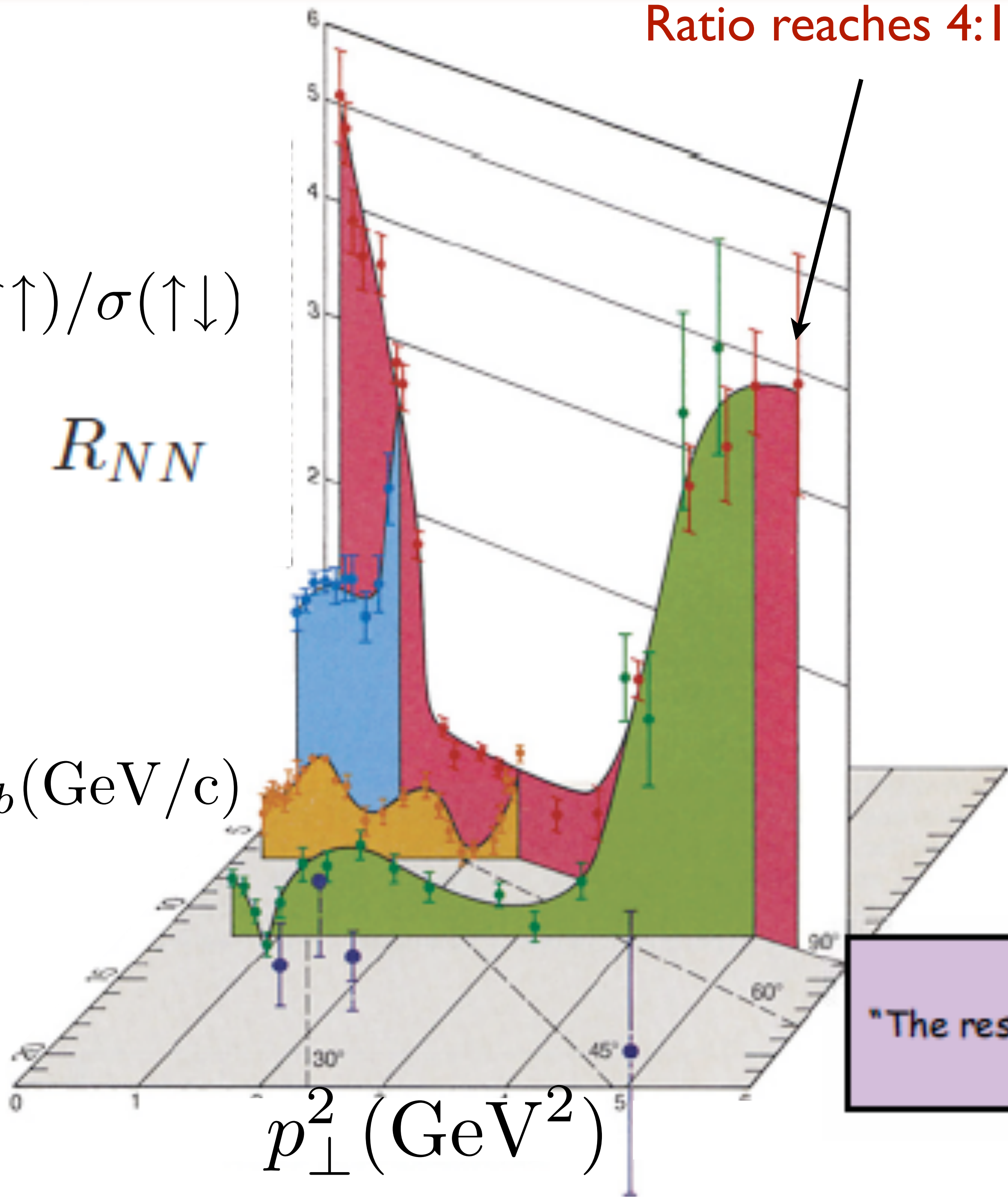
$$pA \to Octoquark(|uuduudc\bar{c}>)X$$

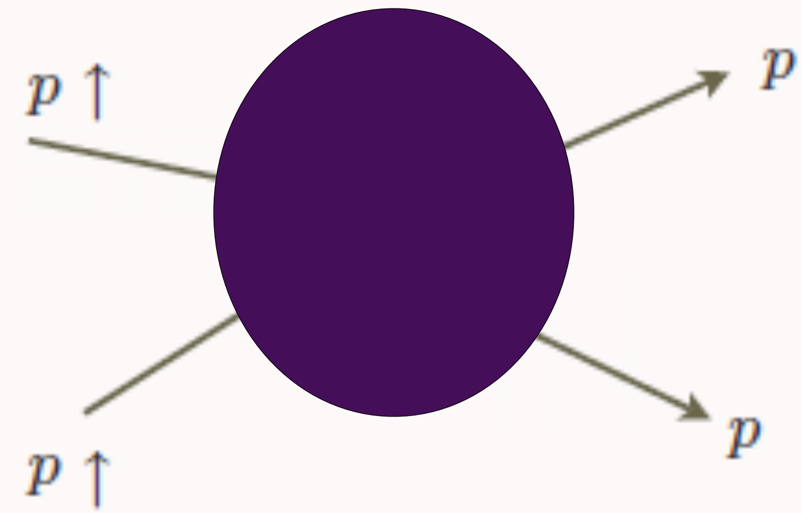


Intrinsic heavy quark probability in the nucleon maximal at minimum off-shellness

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

Spin Correlations in Elastic $p - p$ Scattering





polarization normal to scattering plane

$$|uud\ uud\ c\bar{c}\rangle$$

B=2 Octoquark

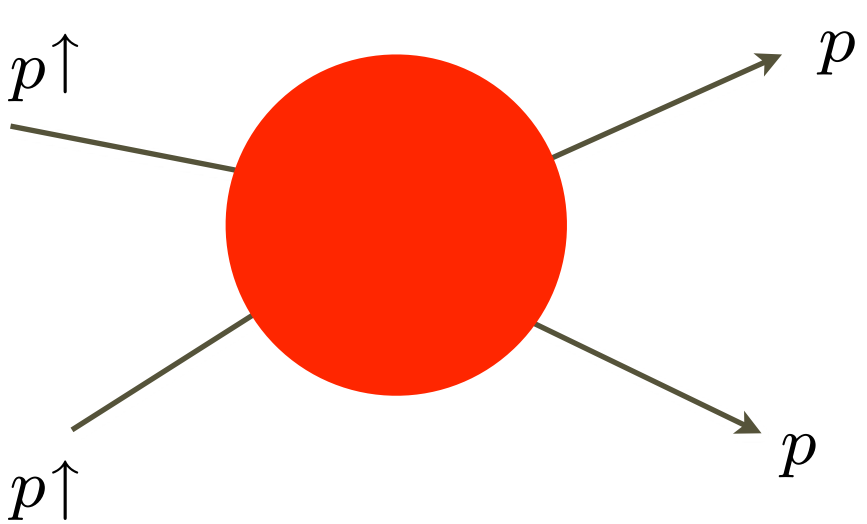
A. Krisch, Sci. Am. 257 (1987)
"The results challenge the prevailing theory that describes the proton's structure and forces"

Large R_{NN} in $pp \to pp$ explained by
$B = 2, J = L = 1$ $|uuduudc\bar{c} >$ resonance
at $\sqrt{s} \sim 5$ GeV

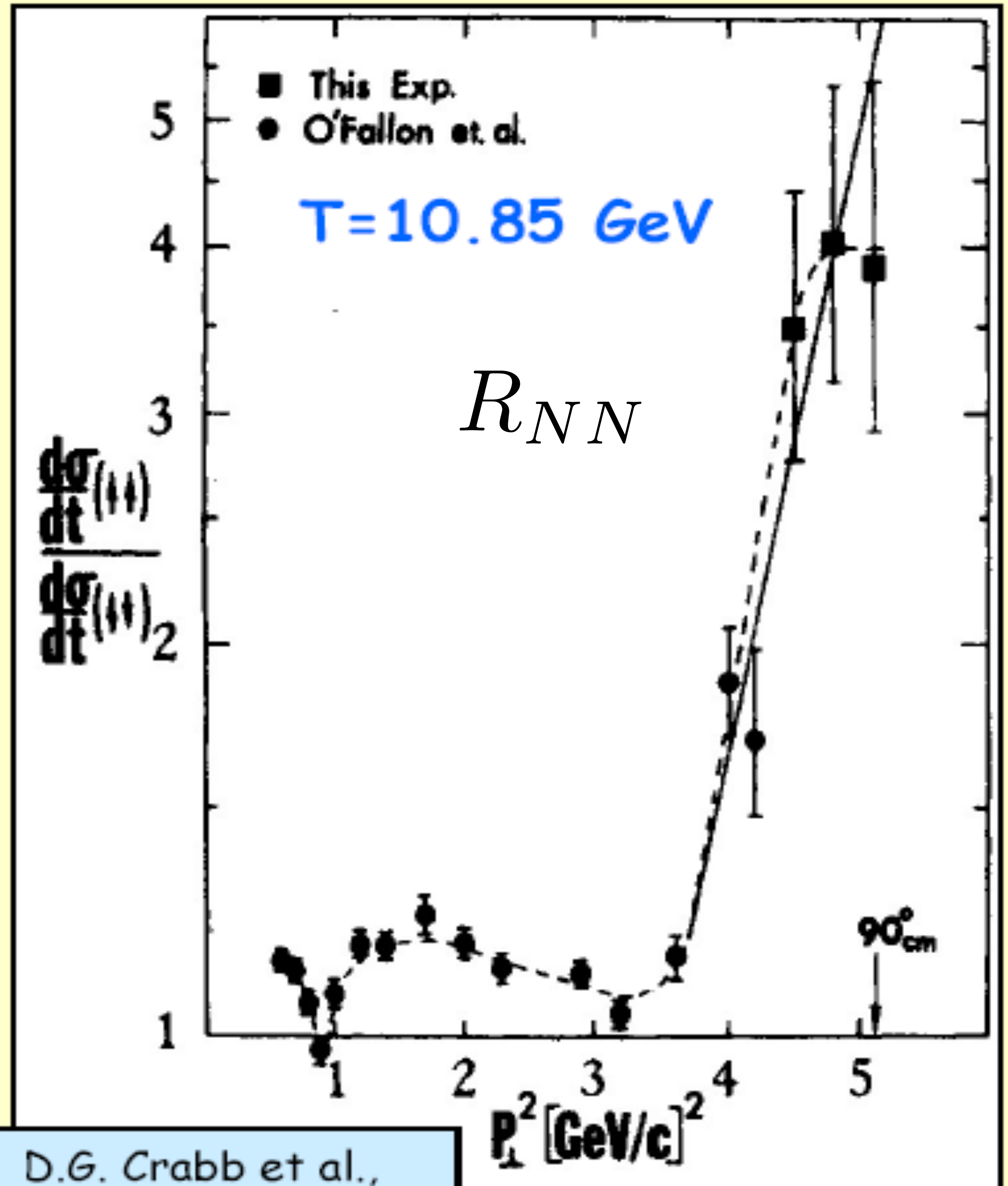
de Teramond and sjb

Krisch, Crabb, et al

Unexpected spin-spin correlation in pp elastic scattering

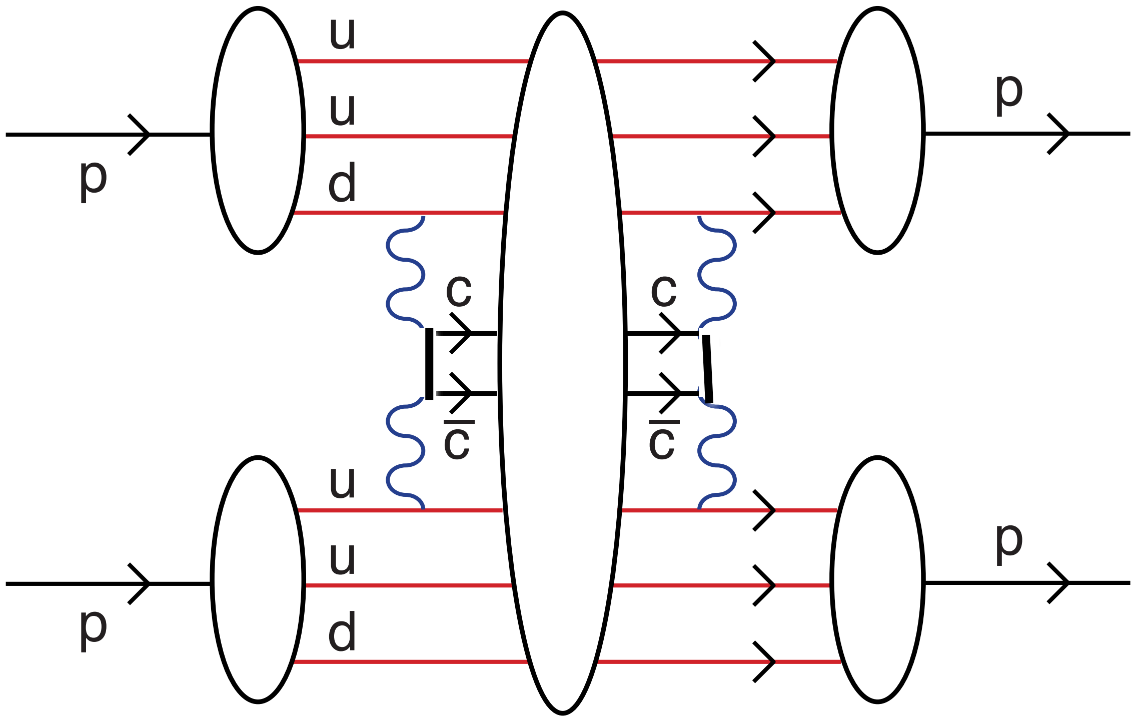


polarizations normal to scattering plane



D.G. Crabb et al., PRL 41, 1257 (1978)

$$A_{nn} = 1!$$



Production of
uud $\bar{c}$ c uud
octoquark resonance

J=L=S=1, C=-, P=- state

QCD
Schwinger-Sommerfeld
Enhancement at Heavy
Quark Threshold

Hebecker, Kuhn, sjb

S. J. Brodsky and G. F. de Teramond, "Spin Correlations, QCD Color Transparency And Heavy Quark Thresholds In Proton Proton Scattering," Phys. Rev. Lett. **60**, 1924 (1988).

8 quarks in S-wave: odd parity

$$|uud\ uud\ c\bar{c}\rangle$$

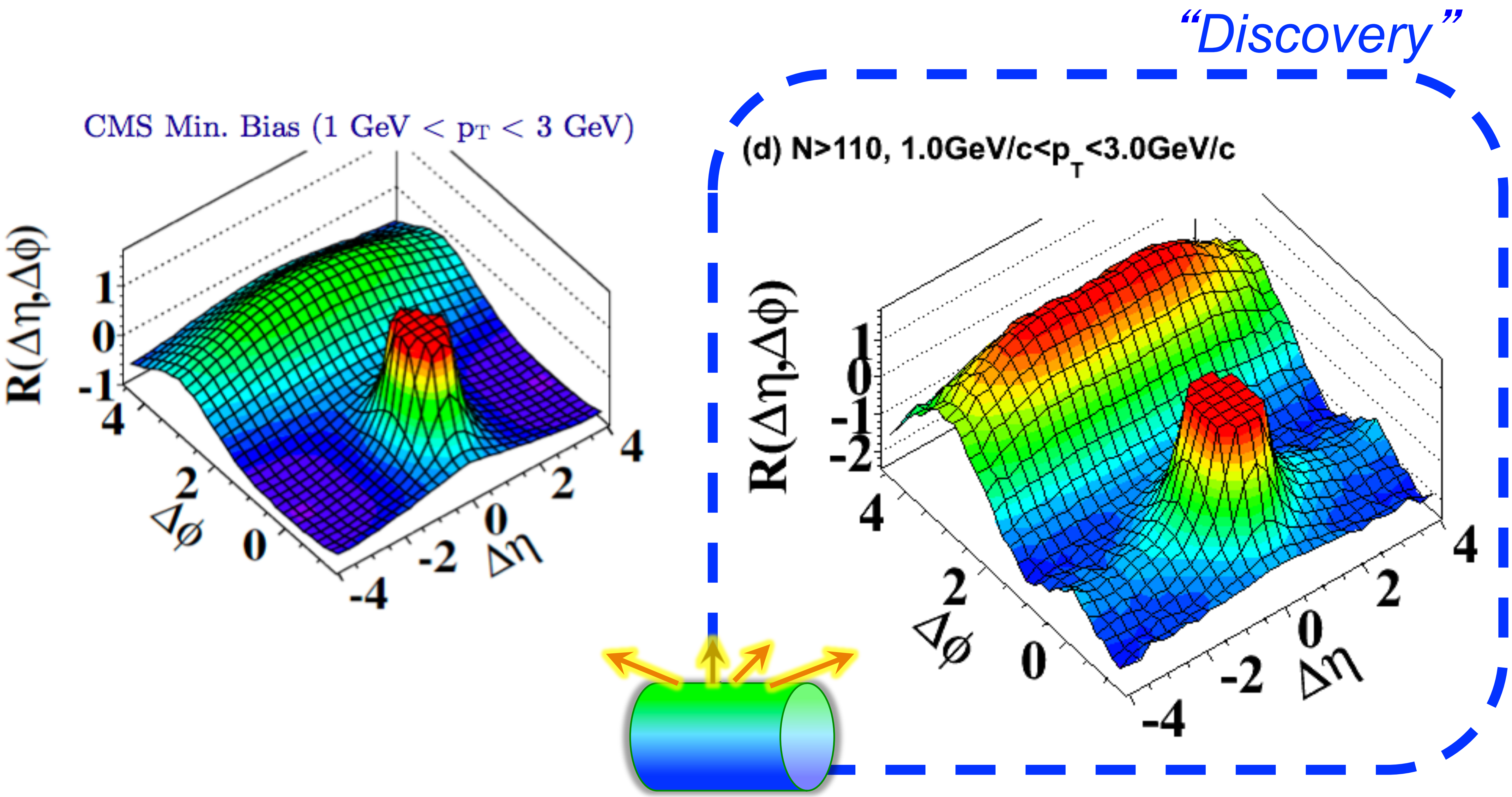
B=2 Octoquark

$\sigma(pp \to c\bar{c}X) \simeq 1\ \mu b$ at threshold

$\sigma(\gamma p \to c\bar{c}X) \simeq 1\ nb$ at threshold

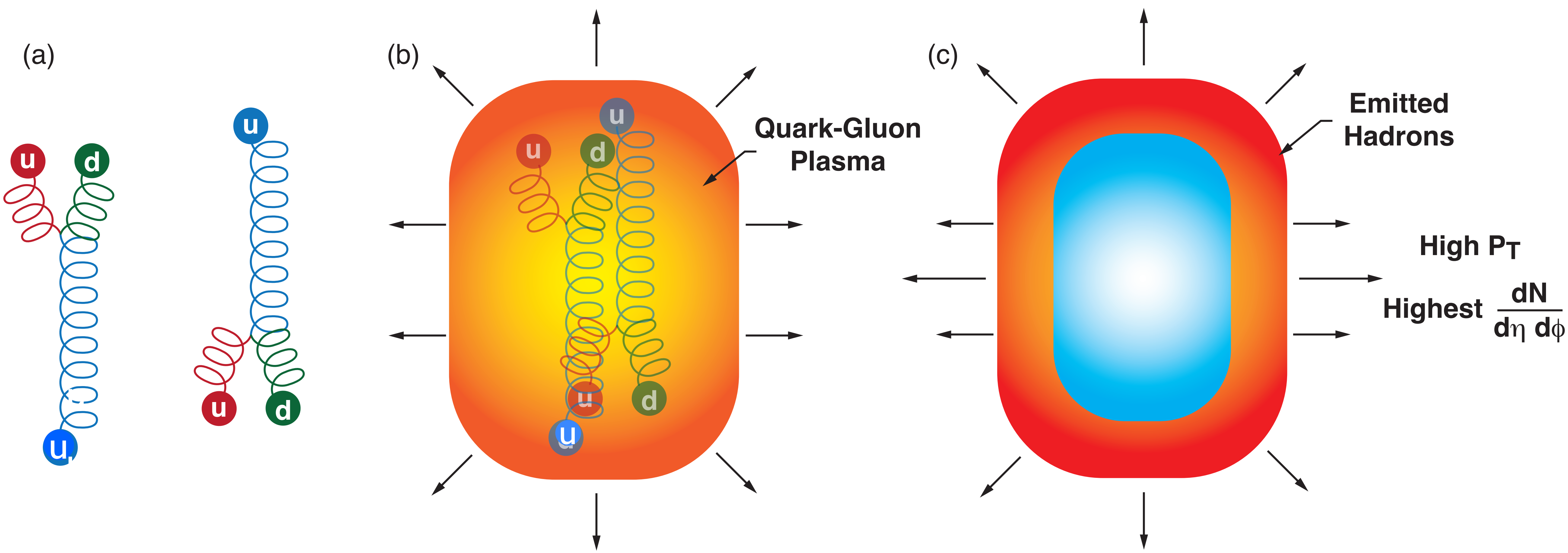
Raju Venugopalan

Two particle correlations: CMS results



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

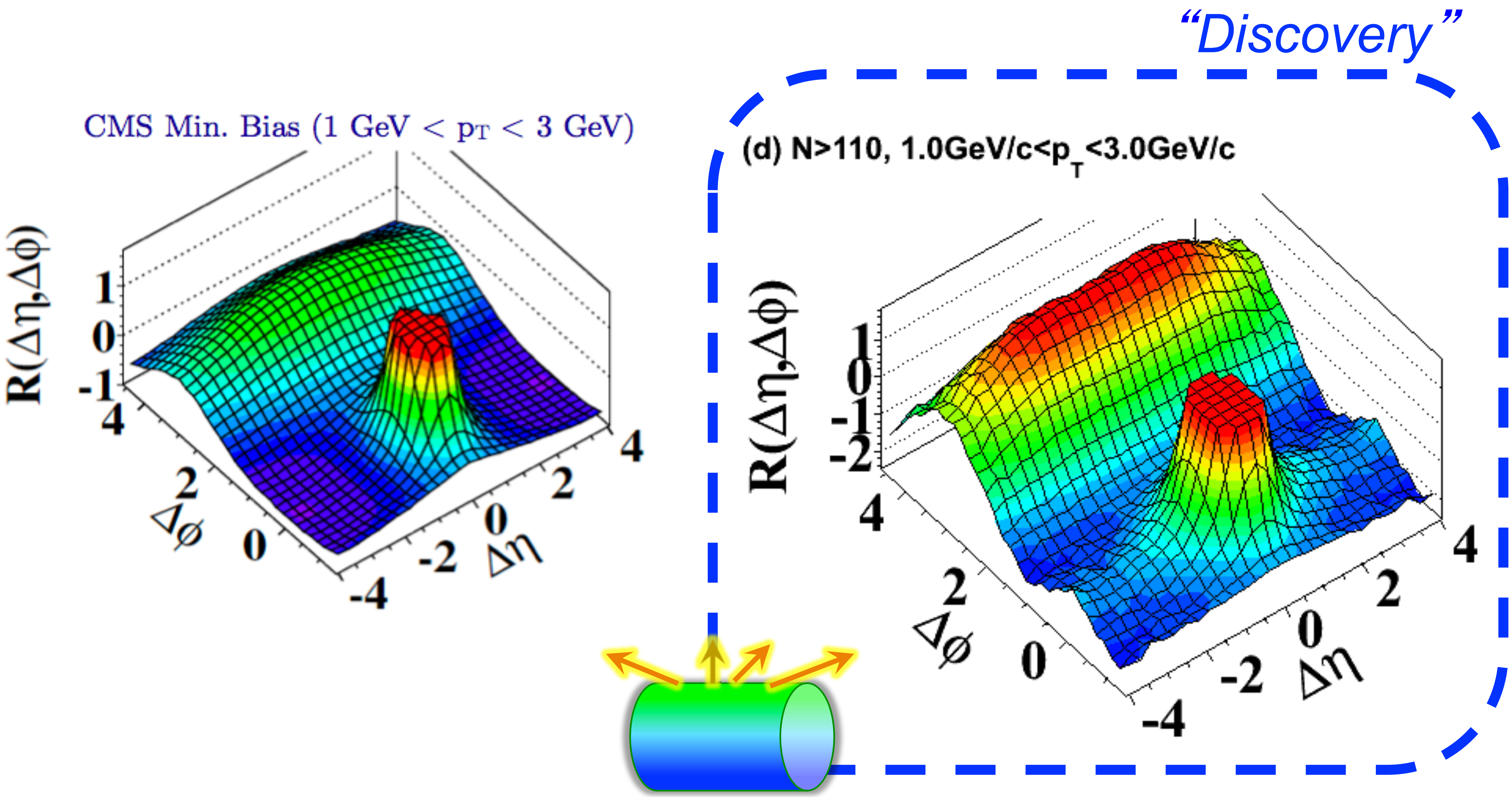
Ridge may reflect collision of aligned flux tubes



Bjorken, Goldhaber, sjb

Raju Venugopalan

Two particle correlations: CMS results



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

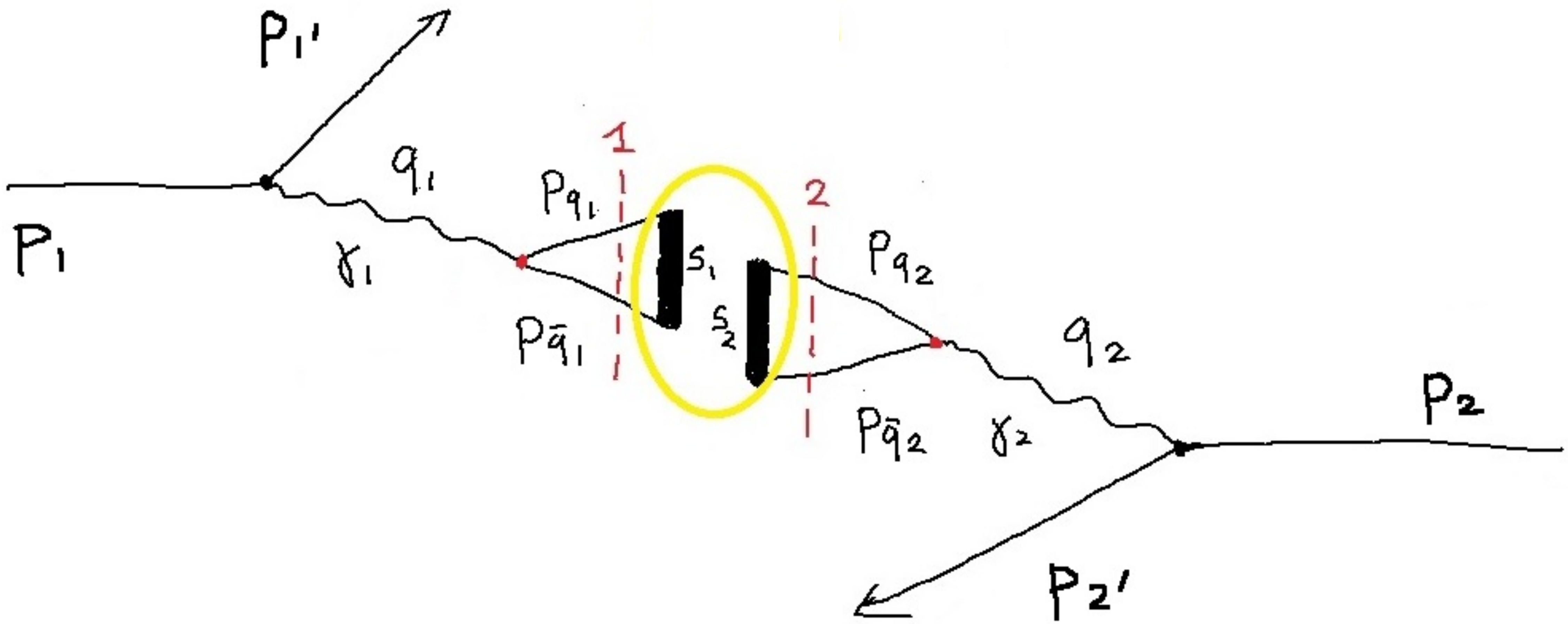
Bjorken, Goldhaber, sjb

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

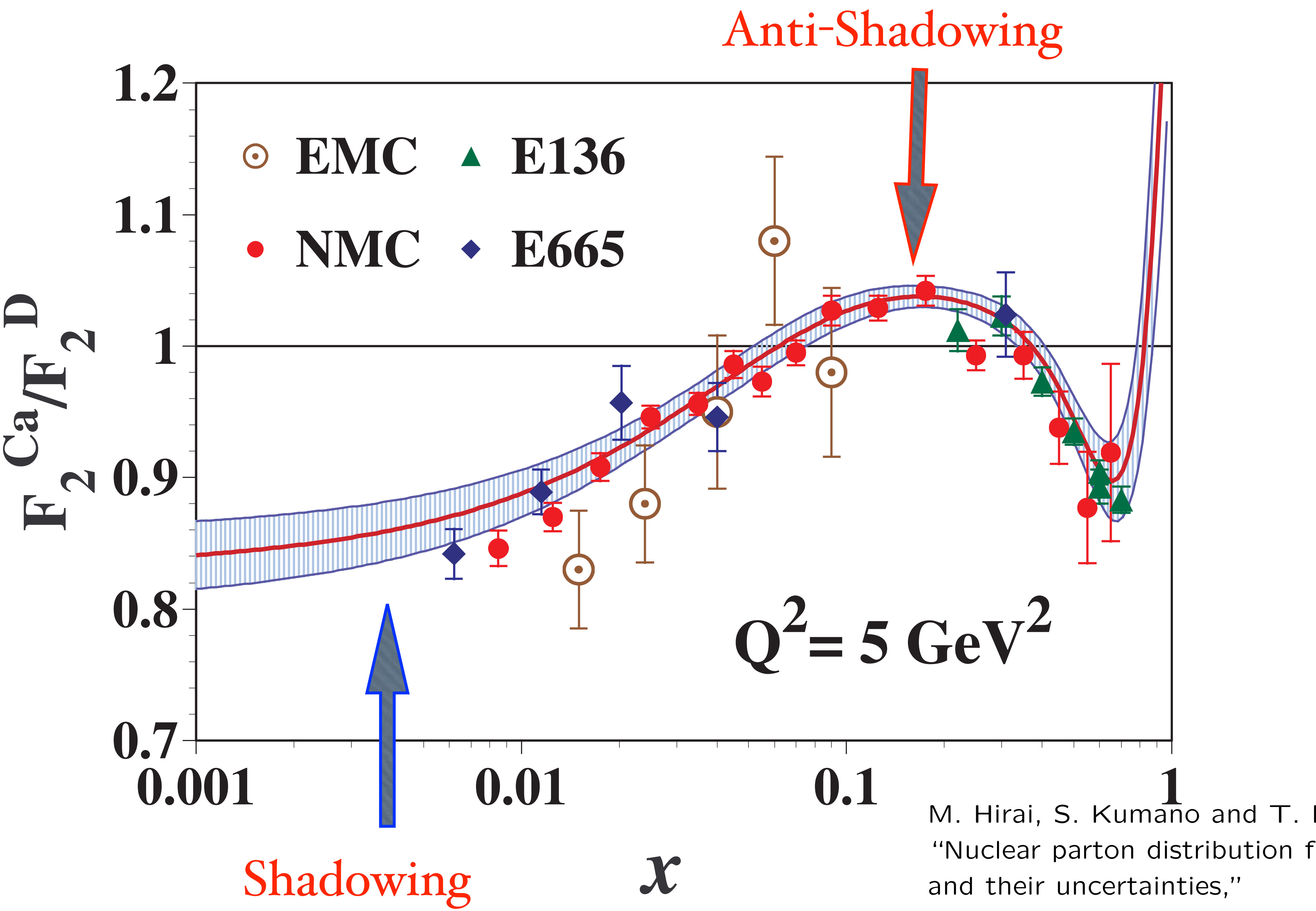
Brown, Glazek, Goldhaber, sjb



Ridges correlate with scattering plane of proton!

Challenge Conventional Wisdom

- **Nuclear Structure Functions obey QCD sum rules**
- **ISI and FSI are higher twist effects and universal**
- **High transverse momentum hadrons arise only from jet fragmentation -- baryon anomaly!**
- **Heavy quarks in hadrons only arise from gluon splitting: ``*Intrinsic Charm, Bottom*"**
- **Renormalization scale cannot be fixed : BLM/PMC**
- **QCD gives 10^{42} to the cosmological constant**
- **Colliding Pancakes**
- **Nuclei are only Composites of Nucleons: "*Hidden Color*"**
- **Hadronic Interactions are Static: ``*Color Transparency*"**

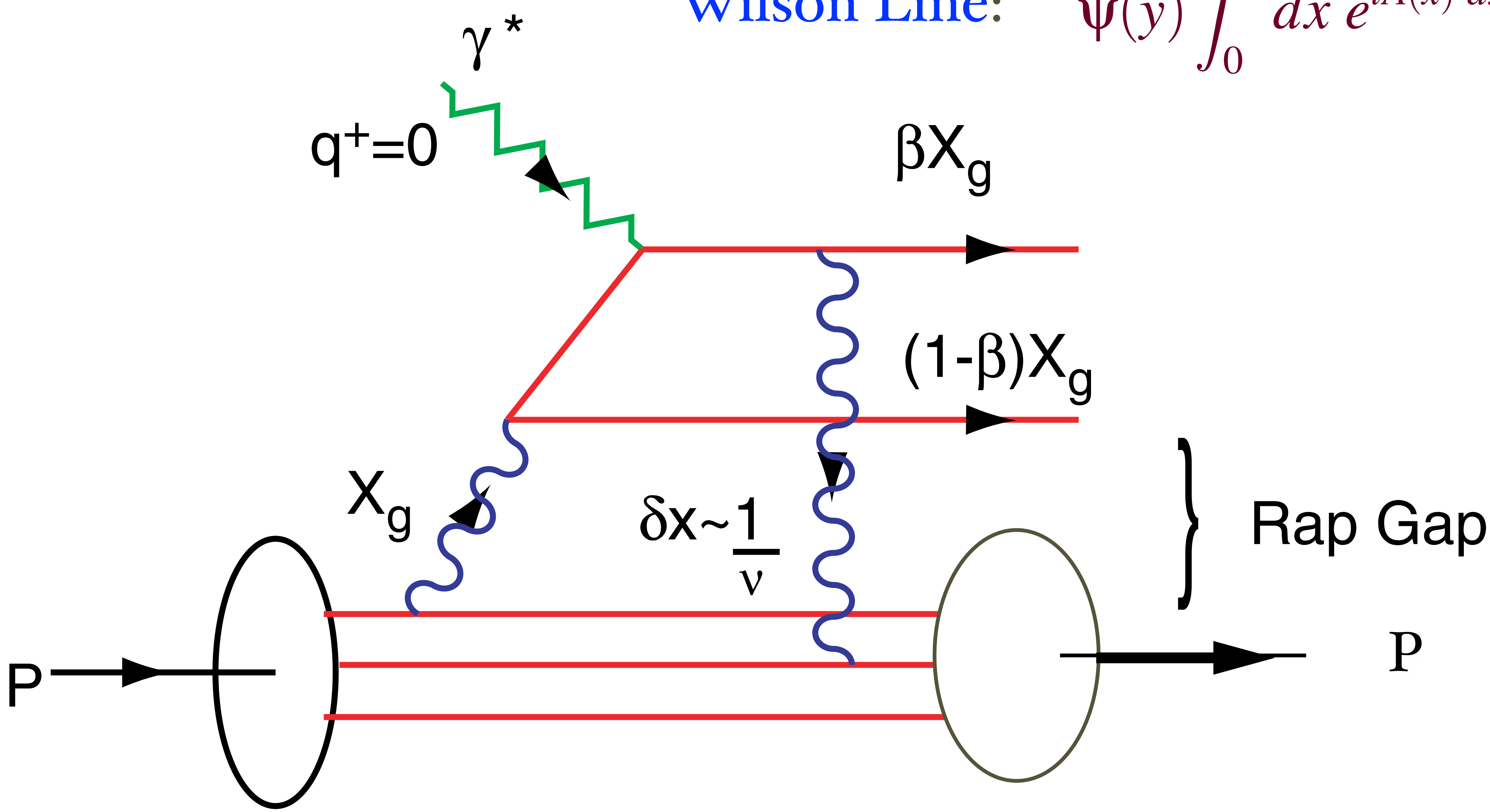


M. Hirai, S. Kumano and T. H. Nagai, "Nuclear parton distribution functions and their uncertainties," Phys. Rev. C **70**, 044905 (2004) [arXiv:hep-ph/0404093].

Hoyer, Marchal, Peigne, Sannino, sjb

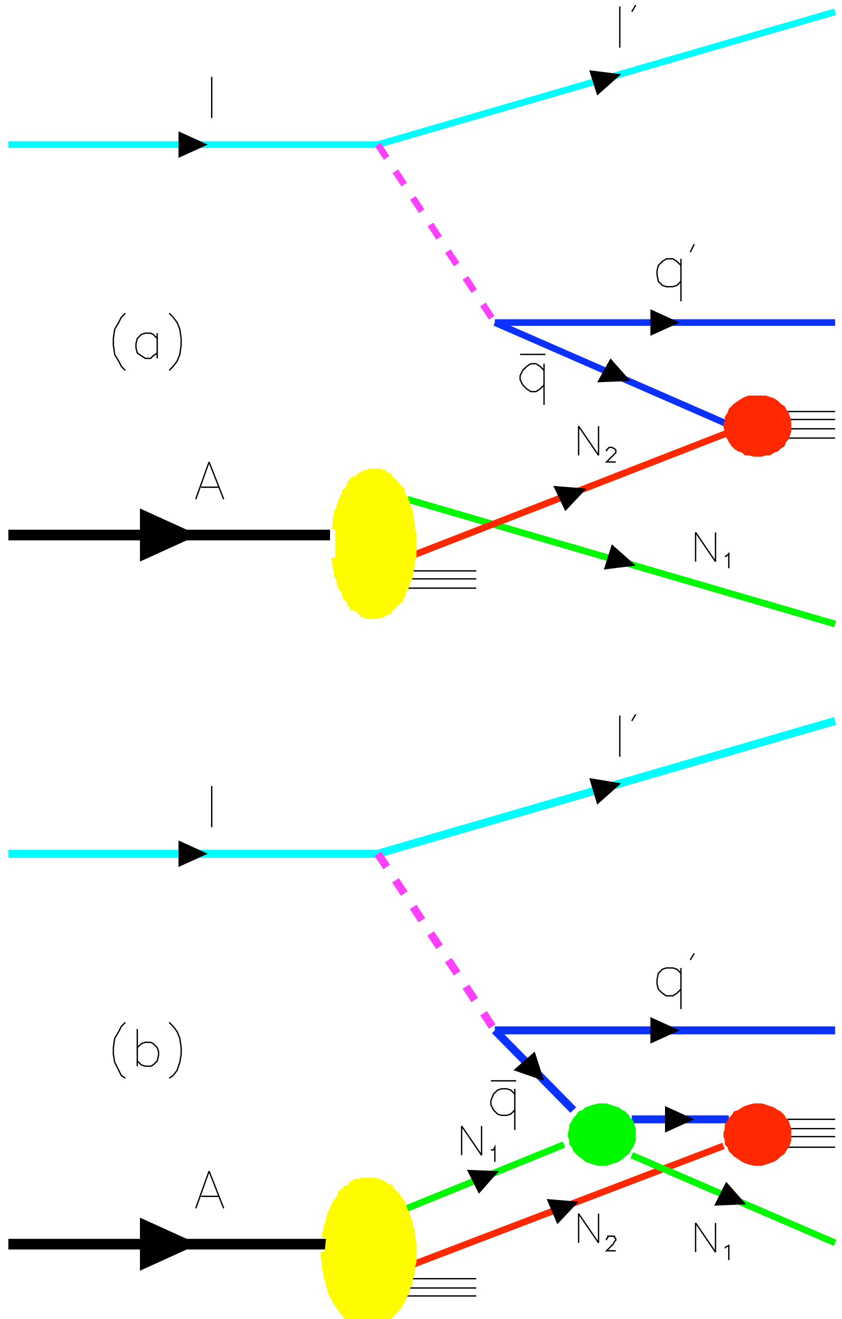
QCD Mechanism for Rapidity Gaps

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



Reproduces lab-frame color dipole approach
DDIS: Input for leading twist nuclear shadowing

DDIS: Diffractive Deep Inelastic Scattering



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

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

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

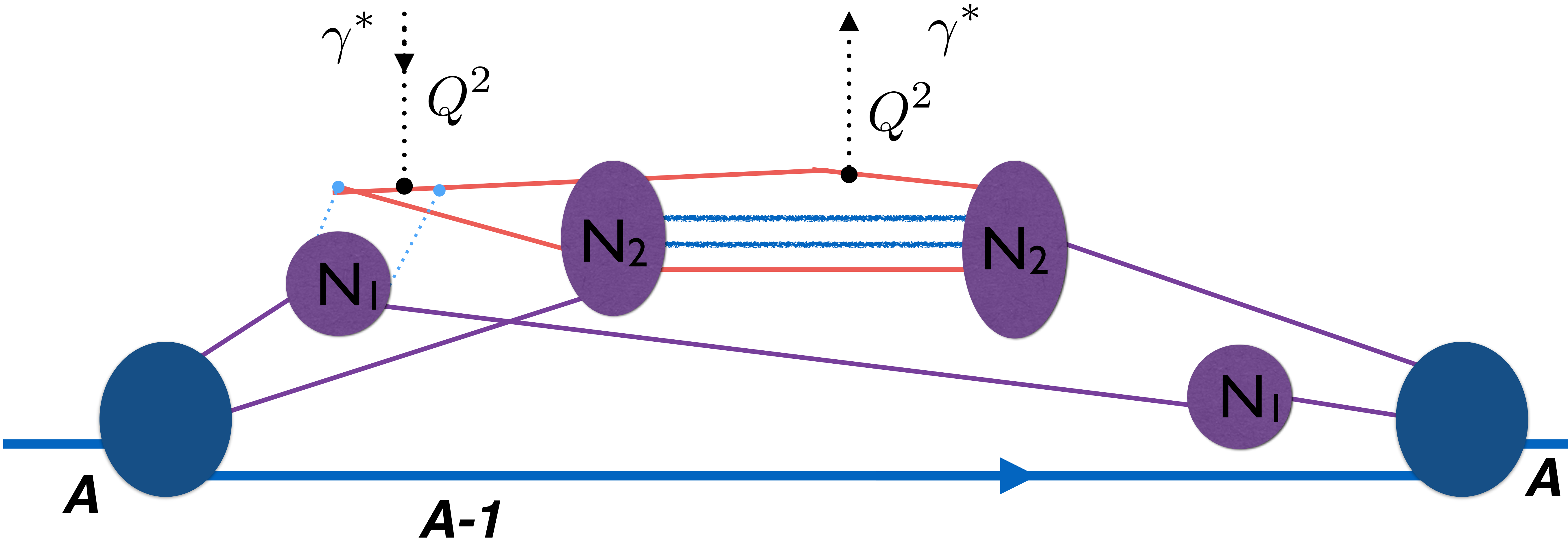
Interior nucleons shadowed

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

Observed HERA DDIS produces nuclear shadowing

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, sjb

LFWFs are real for stable hadrons, nuclei

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

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

Matin Mojaza*

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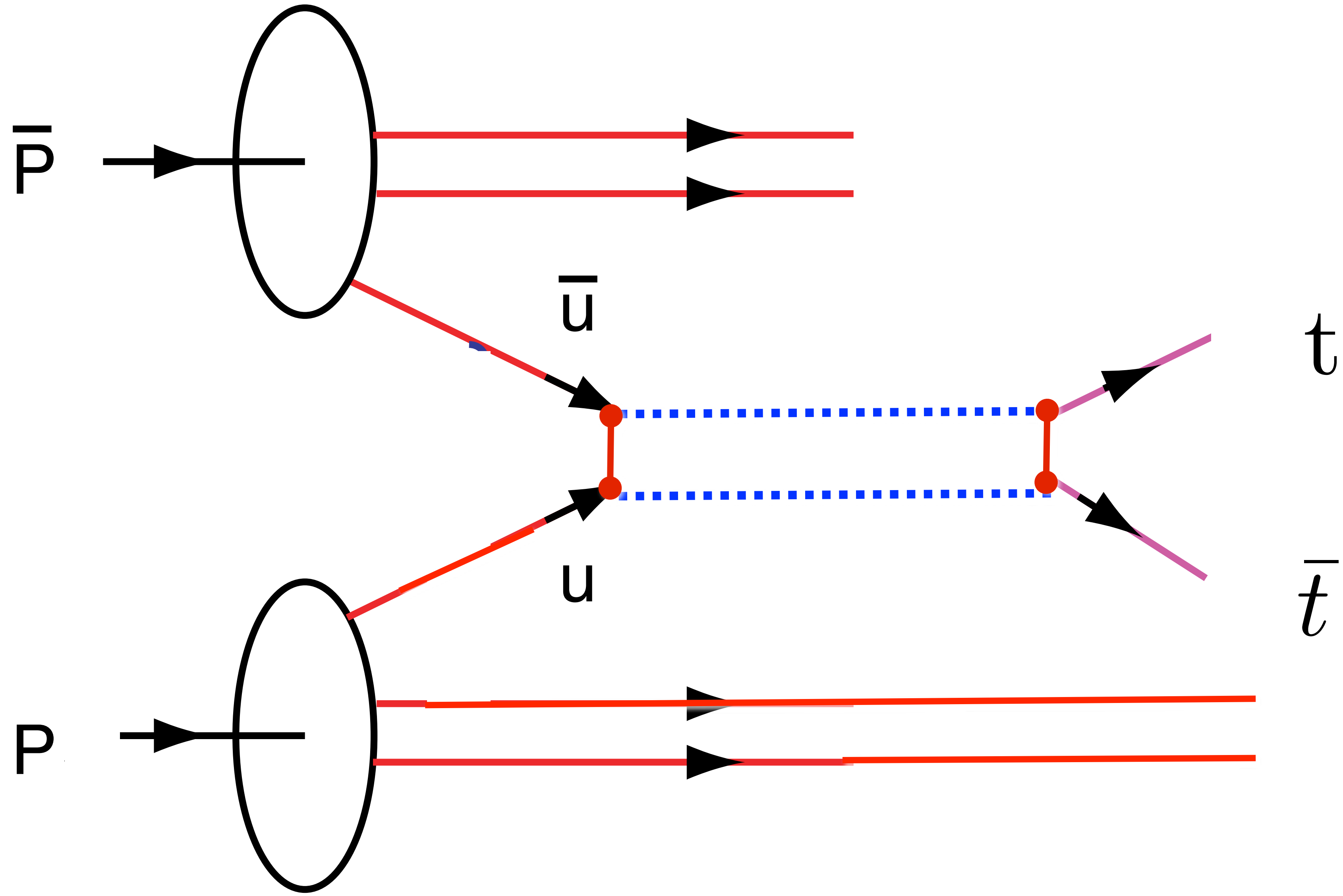
(Received 13 January 2013; published 10 May 2013)

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



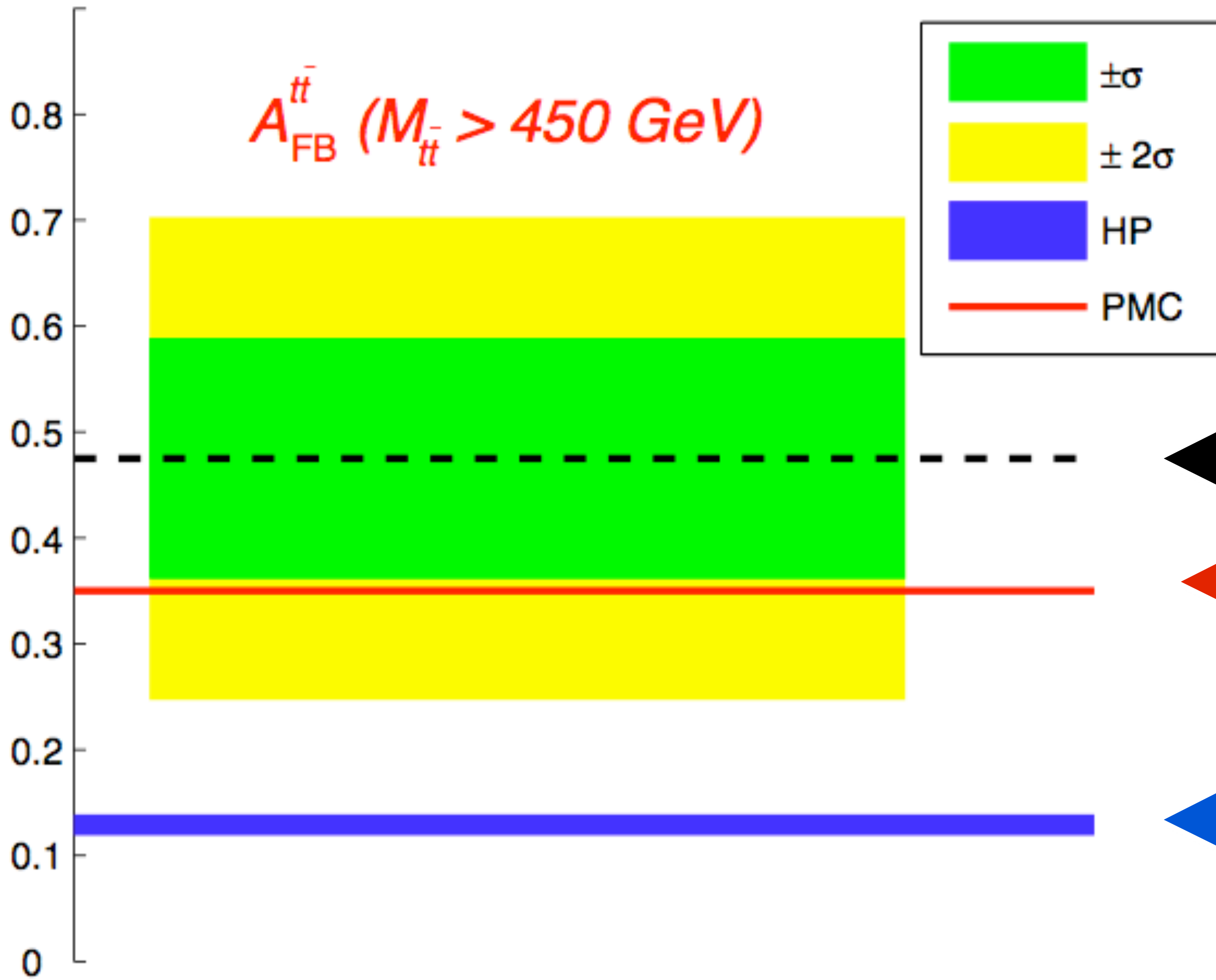
Interferes with Born term.

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)

Xing-Gang Wu
SJB



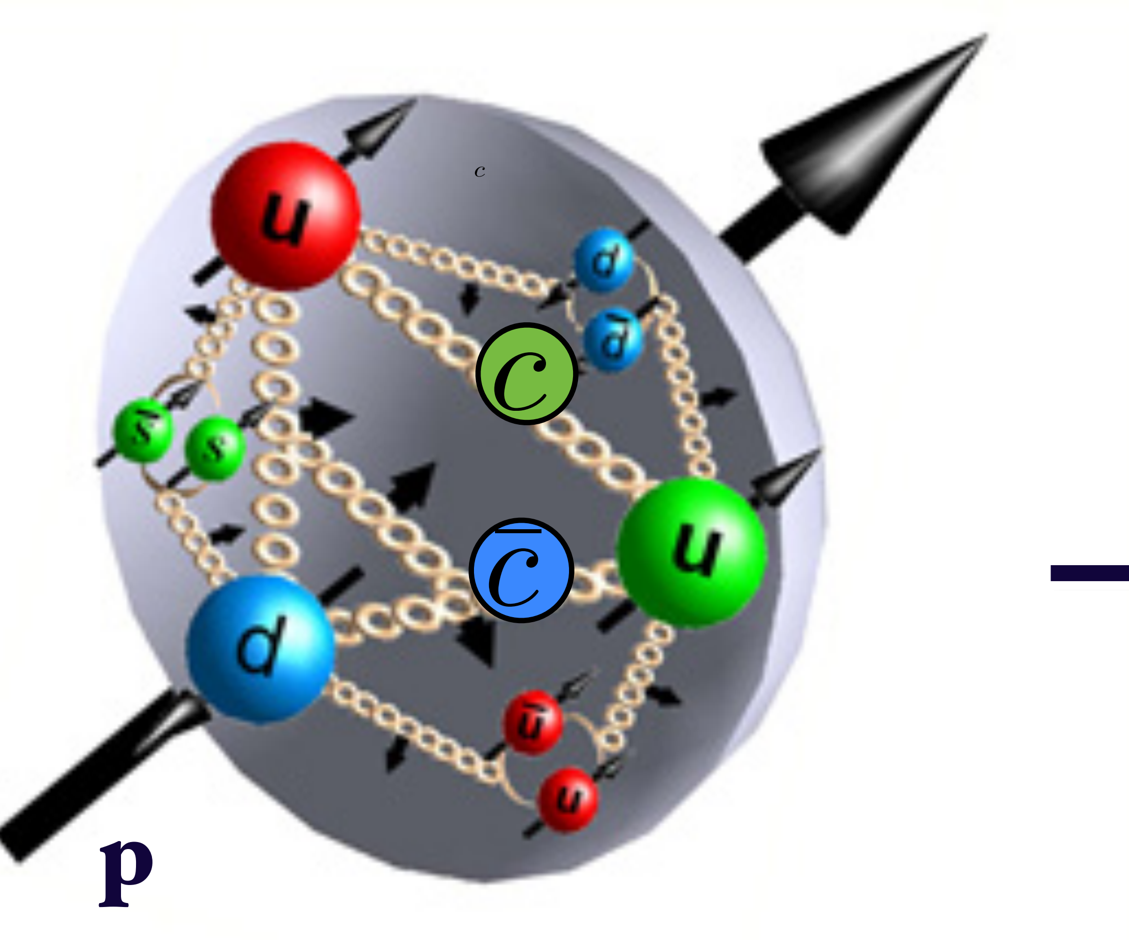
Experimental asymmetry

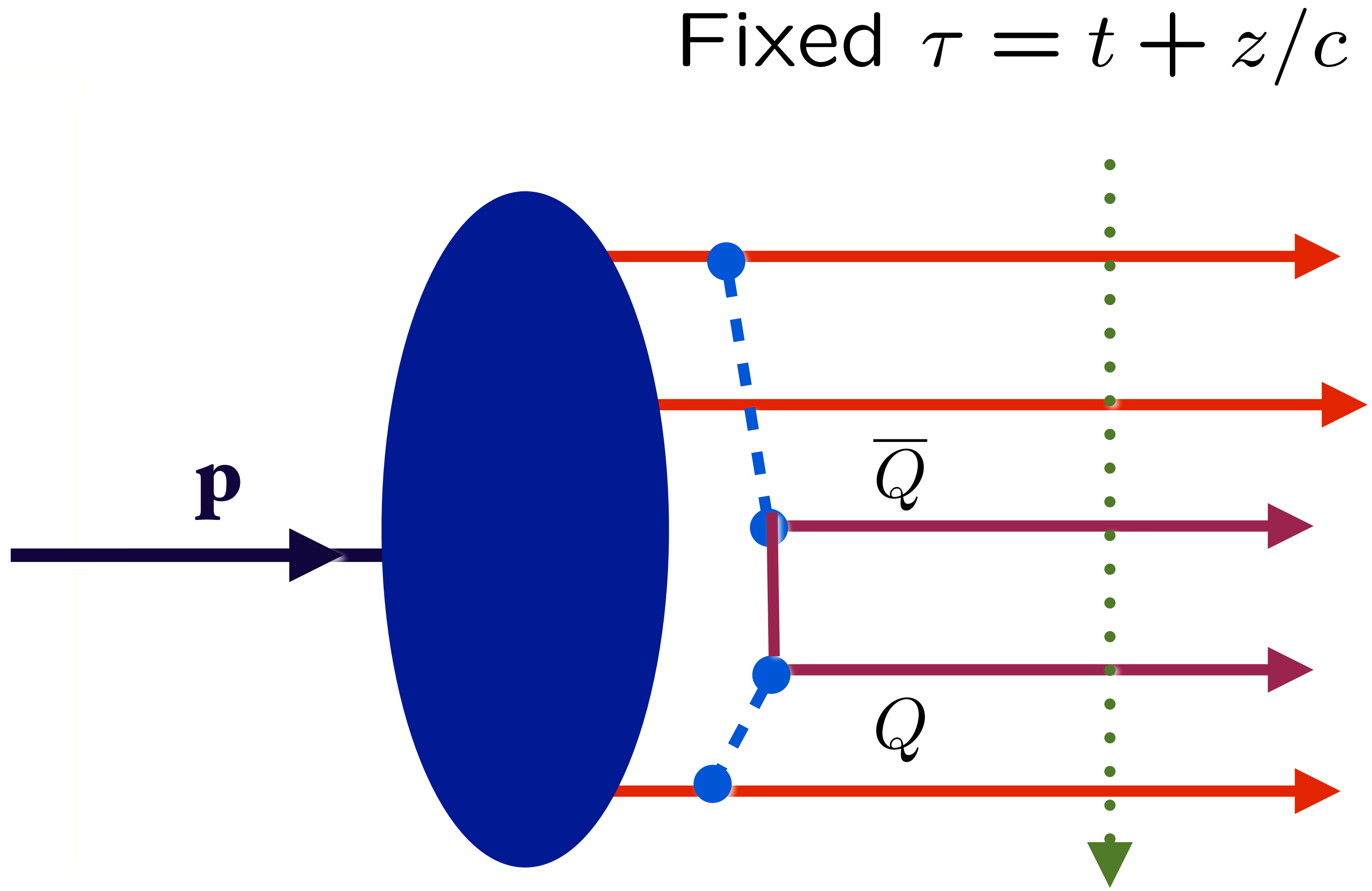
PMC Prediction

Conventional guess for renormalization scale and range

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

Novel Features of QCD Phenomenology at the LHC





LHC Working Group Workshop on Forward Physics and Diffraction

Instituto de Física Teórica
UAM-CSIC

Madrid
March 22, 2018

Stan Brodsky

SLAC NATIONAL ACCELERATOR LABORATORY