XXXVI International Workshop on High Energy Physics

Strong Interactions: Experiment, Theory, Phenomenology

Pomeron in QCD

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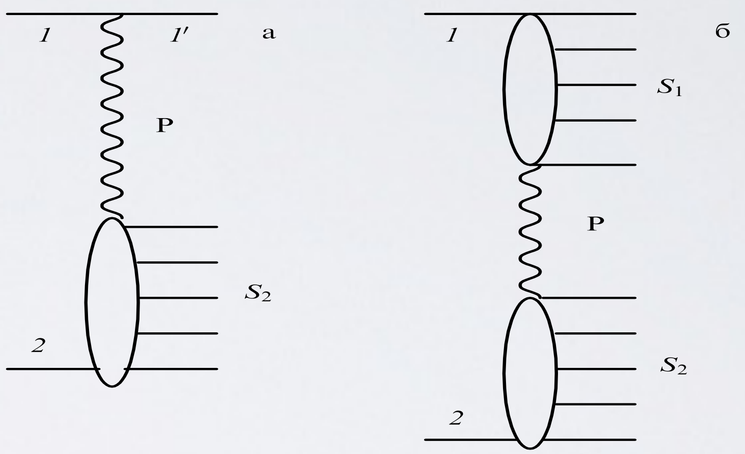
Outline:

- Introduction & Motivation
- Pomeron before QCD
- Pomeron in perturbative QCD
- Pomeron in nonperturbative QCD
- Pomeron beyond QCD

Pomeron: Motivation

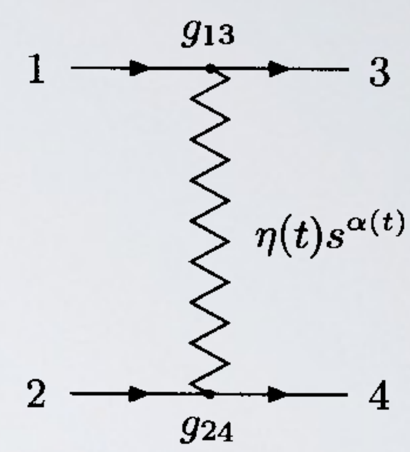
Pomeron at high energies is responsible for:

- elastic scattering
- diffractive scattering
- inelastic scattering
- total x-section



asymptotic theorem: particle and antiparticle x-section equality

I. Pomeranchuk 34 (1958) 725



non-relativistic scattering: Regge poles

T. Regge (1959, 1960)

relativistic scattering: Regge poles

V. Gribov Nucl. Phys. 22 (1961) 249

M. Froissart Phys. Rev. 123 (1961) 1053

Gribov-Froissart representation

Pomeron: vacuum pole and trajectory $\alpha_{IP}(t)=\alpha_{IP}(0)+\alpha'_{IP}\cdot t$

V. Gribov ZhETP 41 (1961) 667 [JETP 14 (1962) 472]

G. Chew, S. Frautschi PRL 7 (1961) 394

$$A(s,t) = \beta(t)\,\eta(t)\,s^{\alpha(t)}$$

$$\frac{d\sigma_{el}}{dt} = F(t)\,s^{2\alpha(0)-2}\,e^{-2\alpha'|t|\ln s}$$

- ➡ **elastic & diffractive cone shrinkage**
- ➡ **x-section: constant with energy** IHEP (Protvino) U70 data since 1967

$$\sigma_{tot} \underset{s\to\infty}{\simeq} \frac{1}{s}\,\mathrm{Im}\,A(s,t=0) \underset{s\to\infty}{\sim} s^{\alpha(0)-1}$$

Pomeron before QCD: developments

Unitarity condition:
Froissart-Martin x-section asymptotic bound $\leq \log^2(s)$

M. Foissart Phys. Rev. 123 (1961) 1053

Reggeon field theory

V.N. Gribov (1967)

multi-Pomeron exchanges

V.N. Gribov, A.A. Migdal (1968-1970)
K.A. Ter-Martirosyan, A.A. Migdal, A.M. Polyakov 1972-1975
A.B. Kaidalov K.A. Ter-Martirosyan 1973-1979

supercritical Pomeron $\alpha_{IP}(0) > 1$

V.N. Gribov, A.A. Migdal, A.M. Polyakov 1970-1975

strongly-interacting supercritical Pomeron

V.N. Gribov, A.A. Migdal, A.M. Polyakov 1969

Pomeron in perturbative QCD

Born approximation: two-gluon Pomeron

F.E. Low, Phys. Rev. D12 (1975) 163

S. Nussinov, Phys. Rev. Lett. 34 (1975) 1286

Leading logarithmic approximation: LL BFKL Pomeron

V.S. Fadin, E.A. Kuraev, L.N. Lipatov, Phys. Lett. B 60 (1975) 50

E.A. Kuraev, L.N. Lipatov, V.S. Fadin, ZhETF 71 (1976) 840 [JETP 45 (1977) 79]

E.A. Kuraev, L.N. Lipatov, V.S. Fadin, ZhETF 72 (1977) 377 [JETP 45 (1977) 79]

I.I. Balitsky, L.N. Lipatov, Yad. Fiz. 28 (1978) 1597

Next-to-leading logarithmic approximation: NLL BFKL Pomeron

V.S. Fadin, L.N. Lipatov, Phys. Lett. B 429 (1998) 127

E.A. Camici, L.N. Ciafaloni, Phys. Lett. (1998)

S.J. Brodsky V.S. Fadin, VK, L.N. Lipatov, G.B. Pivovarov, Pisma ZhETF 70 (1999) 161 (BFKLP)

High energy asymptotics of pQCD

- Large-angle scattering (hard processes):

QCD in Bjorken limit

- GLAPD: V. Gribov & L. Lipatov (71-72); L. Lipatov (74);
  G. Altarelli & G. Parisi (77); Yu. Dokshitzer (77)

- Small-angle scattering ("semi-hard" processes):

QED in Gribov-Regge limit

- V. Gribov, V. Gorshkov, L. Lipatov & G. Frolov (67-70)
  H. Cheng & T. Wu (66-70)

QCD in Gribov-Regge limit

- BFKL: V. Fadin, E. Kuraev & L. Lipatov (75-78)
  I. Balitsky & L. Lipatov (78)

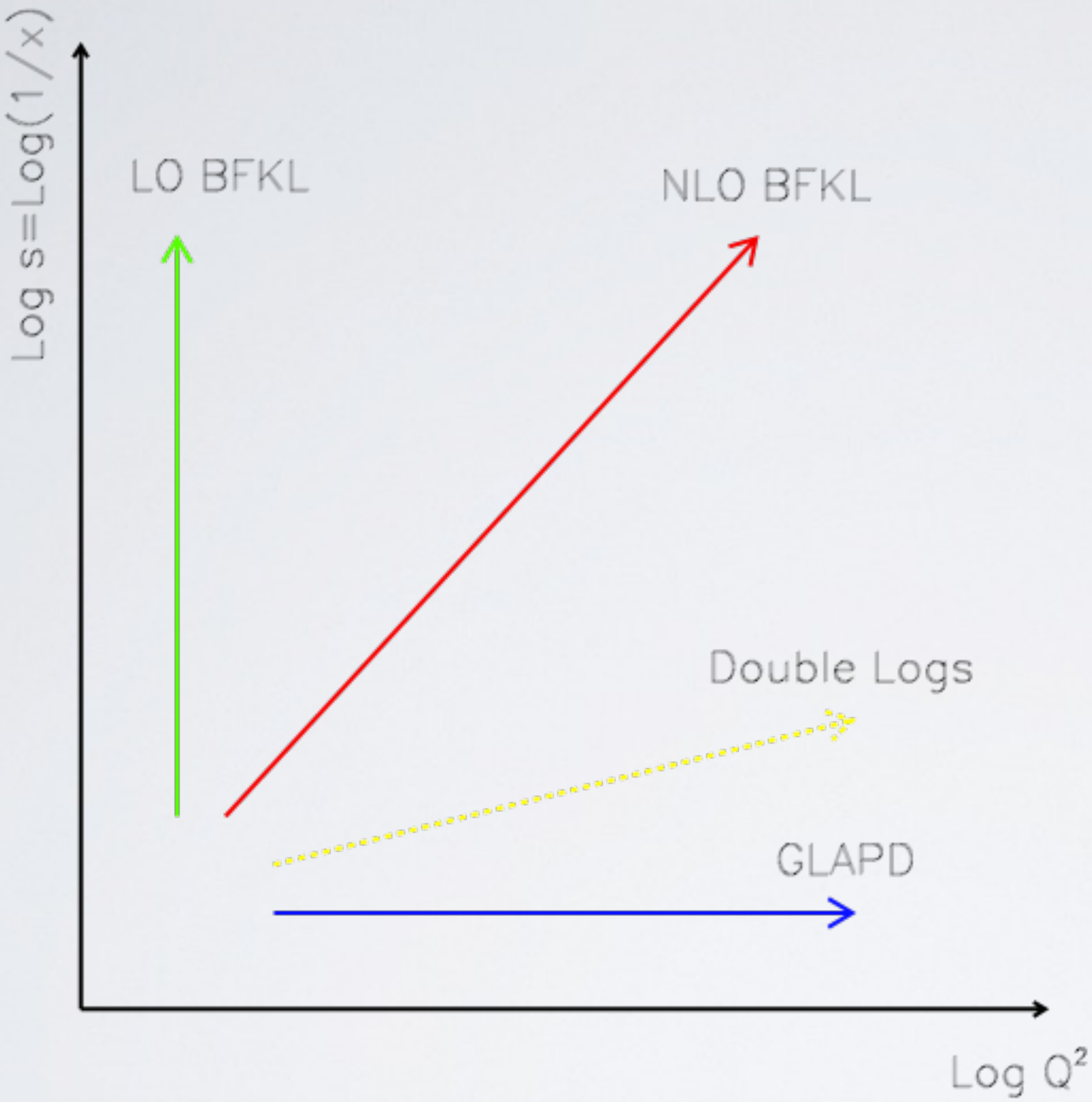
High-energy QCD asymptotics: GLAPD and BFKL

$s=(p_1+p_2)^2$
$t=(p_1-p_3)^2$ $Q^2=-t$
Scattering in the Standard Model (QCD) at high energies:
Large logarithms: $a_s \log(s)$, $a_s \log(Q^2)$

Bjorken limit (large-angle scattering):
$s \sim Q^2 >> m^2$
$Q^2/s = x \sim 1$
Gribov-Lipatov-Altarelli-Parisi-Dokshitzer (GLAPD):
$(a_S \log(Q^2))^n$ resummation
Inclusive cross section $\sim 1/Q^4$

Gribov-Regge limit (small-angle scattering):
$s>>Q^2 >> m^2$
$Q^2/s = x \Rightarrow 0$
Balitsky-Fadin-Kuraev-Lipatov (BFKL):
$(a_S \log(s))^n$ resummation
Total cross section $\sim s^{(a_P-1)}$
a_P – Pomeron intercept soft scattering data: $a_P = 1.1$

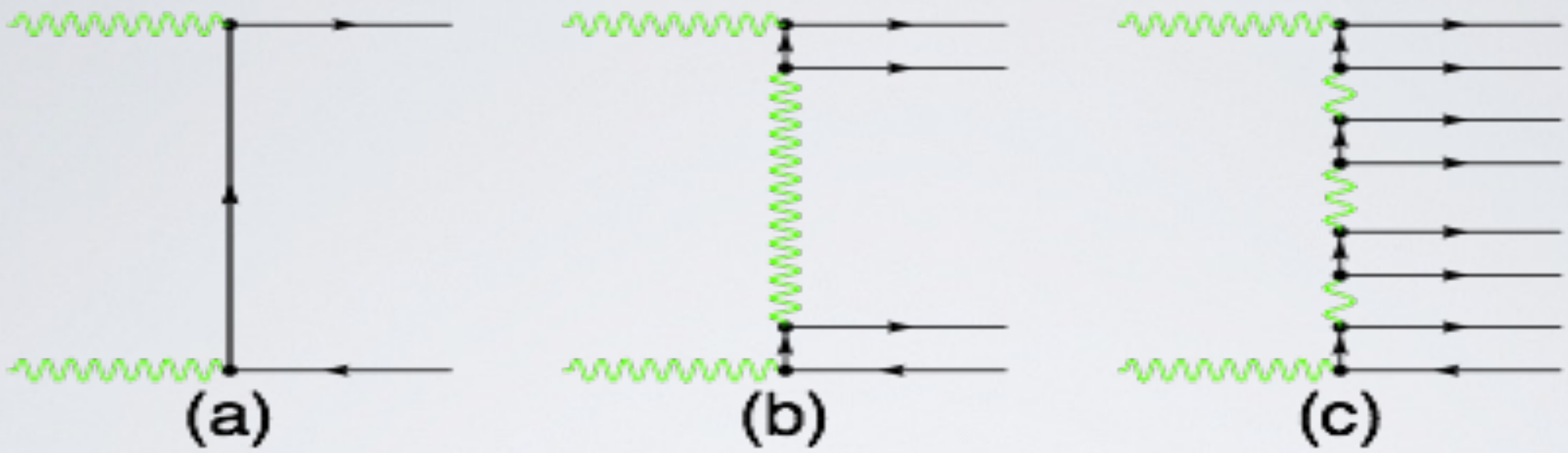
pQCD x-section asymptotics



Bjorken limit (GLAPD):
$s \sim Q^2 >> m^2$
$Q^2/s = x \sim 1$
Large-angle (large-x) scattering

Gribov-Regge limit (BFKL):
$s>>Q^2 >> m^2$
$Q^2/s = x \to 0$
Small-angle (small-x) scattering

Asymptotics of QED cross sections



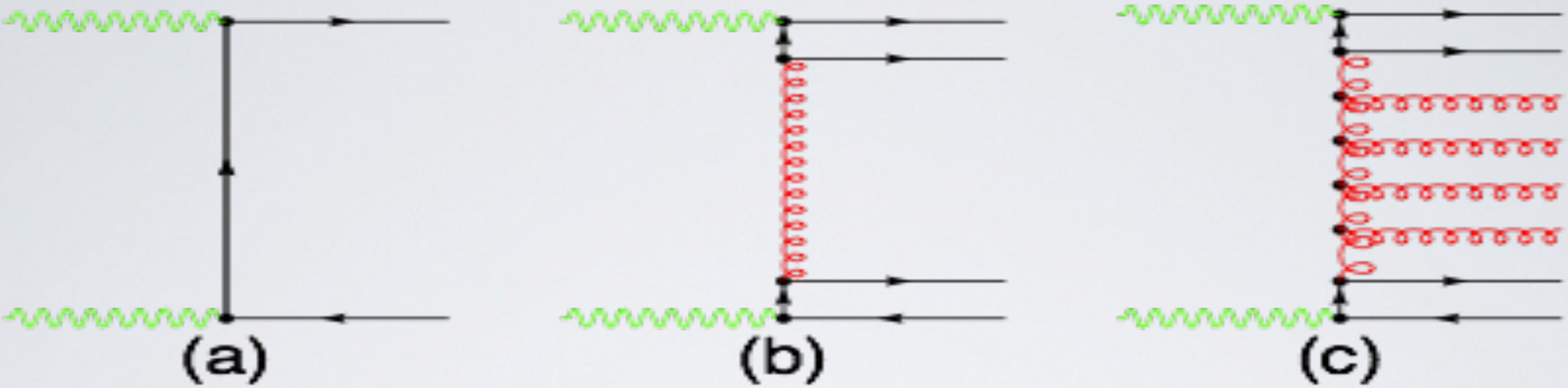
$\sigma \sim (\alpha_{QED})^2 \log(s)/s$ $\sigma \sim (\alpha_{QED})^4 \text{const}(s)$

All orders: **V.N. Gribov, L.N. Lipatov, G.V. Frolov & V.G. Gorshkov (69-71)**
H. Cheng & T.T. Wu (69-70)

Cross section at s -> ∞: $\sim (\alpha_{QED})^4 (S/S_0)^{(aP-1)}$
$a_P = 1 + C (\alpha_{QED})^2 \approx 1.002$

photon: no reggeization!

High-energy limit pQCD as LL BFKL: γγ



$\sigma \sim (\alpha_{QED})^2 \log(s)/s$ $\sigma \sim (\alpha_{QED})^2 (\alpha_S)^2 \mathrm{const}(s)$

Resummation of all leading logarithms: LL BFKL

gluon: reggeization!

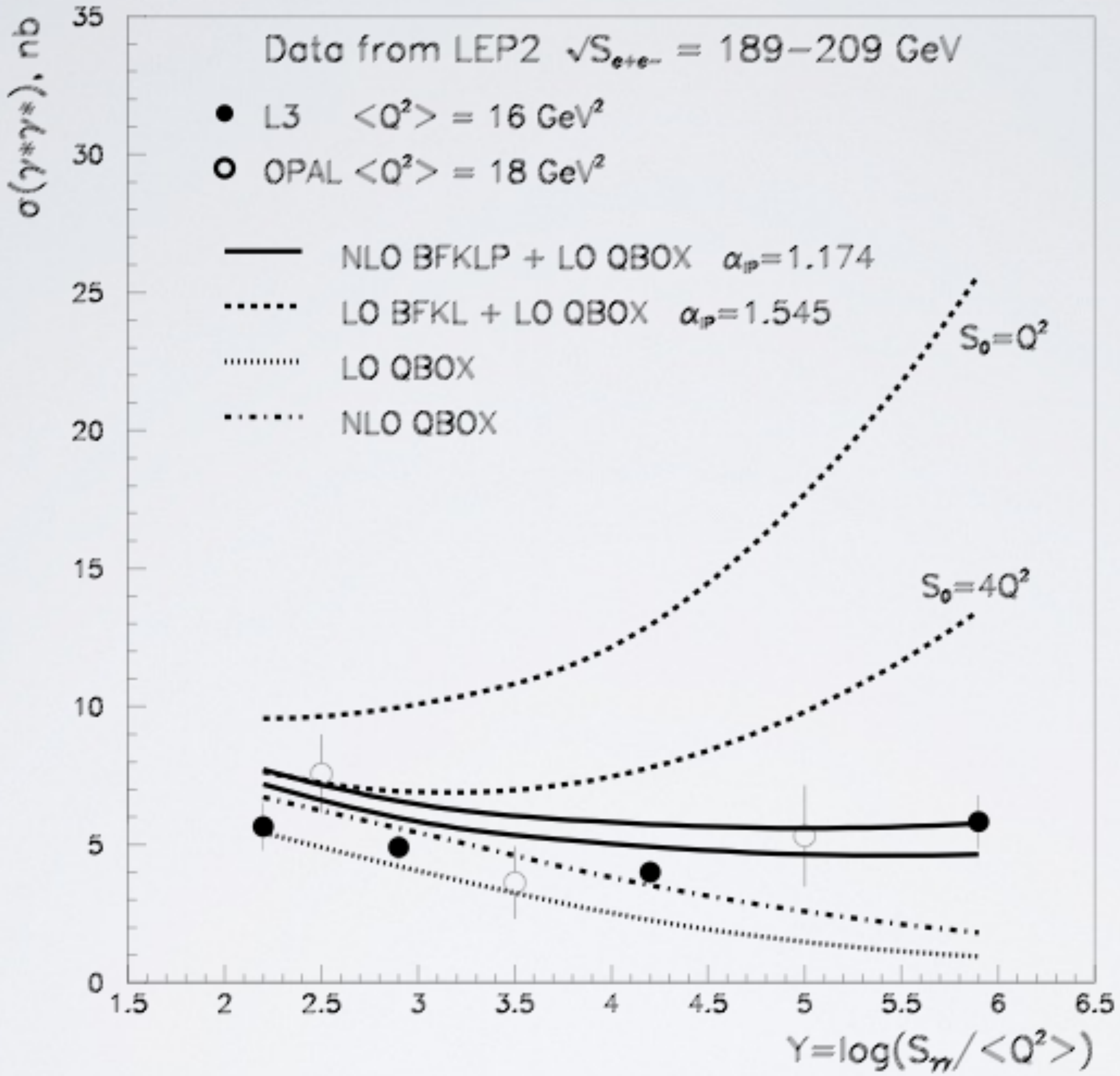
Cross section at s -> ∞: $\sim (\alpha_{QED})^2 (\alpha_S)^2 (S/S_0)^{(a_P - 1)}$

$a_P = 1 + C\,\alpha_S \approx 1.5$ **LL BFKL** S. Brodsky & F. Hautmann (96)

$a_P = 1 + C\,\alpha_S \approx 1.2$ **NLL BFKL**

S.Brodsky, V Fadin, VK,L. Lipatov, G. Pivovarov (2001-02)

Highly virtual photon scattering at LEP-2



S.J Brodsky, VK, L.N. Lipatov, V.S. Fadin & G.B. Pivovarov (2002)

BFKLP: NLL BFKL + generalized BLM

LO Impact factor

Full NLL BFKL calculations: require extra studies

LL BFKL: problems

LL BFKL: designed for infinite collision energies
multi-Regge-kinematics

LL BFKL problems (at finite energies):
- fixed (non-running) coupling α_s
- energy-momentum conservation
- transverse momentum conservation

Cross section in LL BFKL:

$\sigma = \sigma_0 \, (S/S_0)^{(\alpha_P - 1)}$ $\alpha_P = 1 + C\,\alpha_s \approx 1.5\text{-}1.6$

Data: $\alpha_P \approx 1.2\text{-}1.3$

BFKL: next-to-leading logs (NLL) improved by running α_s

next-to-leading log approximation (NLL) BFKL
MSbar-renormalization scheme: large corrections
V.S. Fadin & L.N. Lipatov (89-98)
C.Camici & M. Ciafaloni (96-98)

BFKLP: NLL BFKL + resummation of running coupling α_s
generalized for the case with non-Abelian LO
S.J. Brodsky, V.S. Fadin, VK, L.N. Lipatov, G.B. Pivovarov(98-99) BFKLP

→ **BLM approach** Brodsky, Lepage & Mackenzie – 1983
→ **works only (!) for the case with Abelian LO**

BFKLP: generalized BLM for non-Abelian case

S.Brodsky, P. Lepage, P.Mackenzie (1983) BLM

$$\beta_0 = \frac{11}{3} N_C - \frac{2}{3} n_F$$

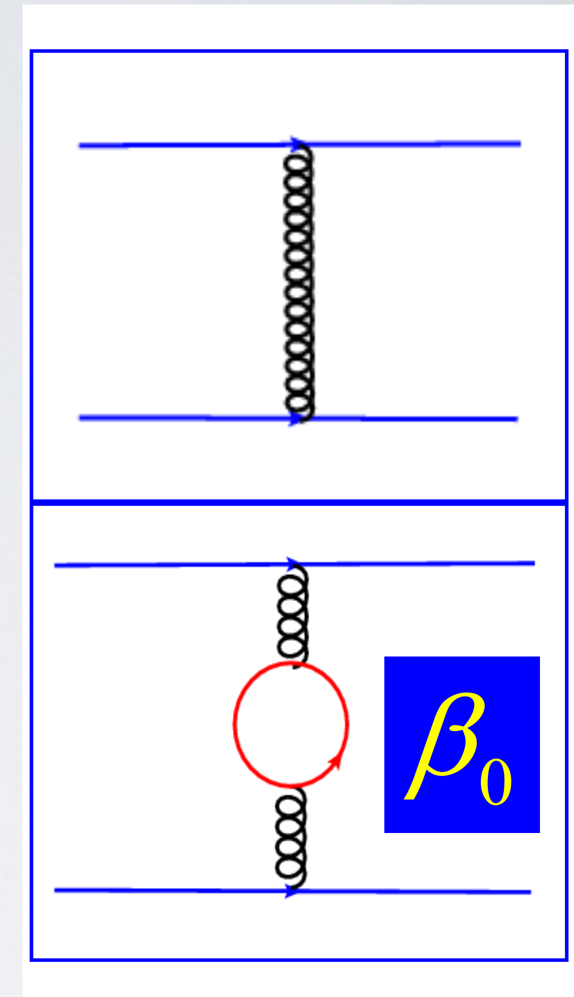
$$\rho = C_0 \alpha_{\overline{\rm MS}}(Q) \left[1 + \frac{\alpha_{\overline{\rm MS}}(Q)}{\pi} \left(-\tfrac{3}{2}\beta_0 A_{\rm VP} + \tfrac{33}{2} A_{\rm VP} + B \right) \right.$$

$$\mu^2 \frac{da_s}{d\mu^2} = \beta(a_s) = -\sum_{i \geq 0} \beta_i(n_f) a_s^{i+2}$$

$$\rho = C_0 \alpha_{\overline{\rm MS}}(Q^*) \left[1 + \frac{\alpha_{\overline{\rm MS}}(Q^*)}{\pi} C_1^* + \cdots \right]$$

$$Q^* = Q \exp(3A_{\rm VP})$$

$$C_1^* = \tfrac{33}{2} A_{\rm VP} + B \ .$$



LO Abelian -> LO non-Abelian
MSbar-scheme -> MOM scheme 3g-vertex

S.Brodsky, V.Fadin, VK, L.Lipatov, G. Pivovarov(99) BFKLP

BFKLP (generalized BLM) works for non-Abelian cases
NLL BFKL and Y->ggg decay

Naïve BLM application does not work (!):

- **NLL BFKL in Msbar scheme**
- **Upsilon ->ggg decay in NLO in MSbar scheme**

MSbar-scheme: nonphysical RG scheme (!)
numerically close to V-scheme (heavy quark potential) – Abelian in LO

physical RG scheme: MOM scheme (gauge dependent)

- **NLL BFKL <- non-Abelian in LO**
- **Upsilon ->ggg decay <- non-Abelian in LO**

one can use MOM-scheme based on ggg-vertex non-Abelian in LO

BLM generalized for non-Abelian case:

S.J. Brodsky, V.S. Fadin, VK, L.N. Lipatov, G.B. Pivovarov(98-99) BFKLP

BFKLP: NLL BFKL + resummation of running coupling as

BLM resummation depends on non-Abelian structure in LO

BFKLP: NLL BFKL within generalized BLM

S.J. Brodsky, V.S. Fadin, VK, L.N. Lipatov, G.B. Pivovarov(98-99) BFKLP

$$\sigma \sim s^{\alpha_{IP}-1} = s^{\omega^{\max}}$$

$$\omega_{\overline{MS}}(Q_1^2,\nu) = \int d^2 Q_2 \ K_{\overline{MS}}(\mathbf{Q}_1,\mathbf{Q}_2)\left(\frac{Q_2^2}{Q_1^2}\right)^{-\frac{1}{2}+i\nu}$$

$$= N_C \chi_L(\nu)\frac{\alpha_{\overline{MS}}(Q_1^2)}{\pi}\left[1 + r_{\overline{MS}}(\nu)\frac{\alpha_{\overline{MS}}(Q_1^2)}{\pi}\right],$$

$$\chi_L(\nu) = 2\psi(1) - \psi(1/2+i\nu) - \psi(1/2-i\nu)$$

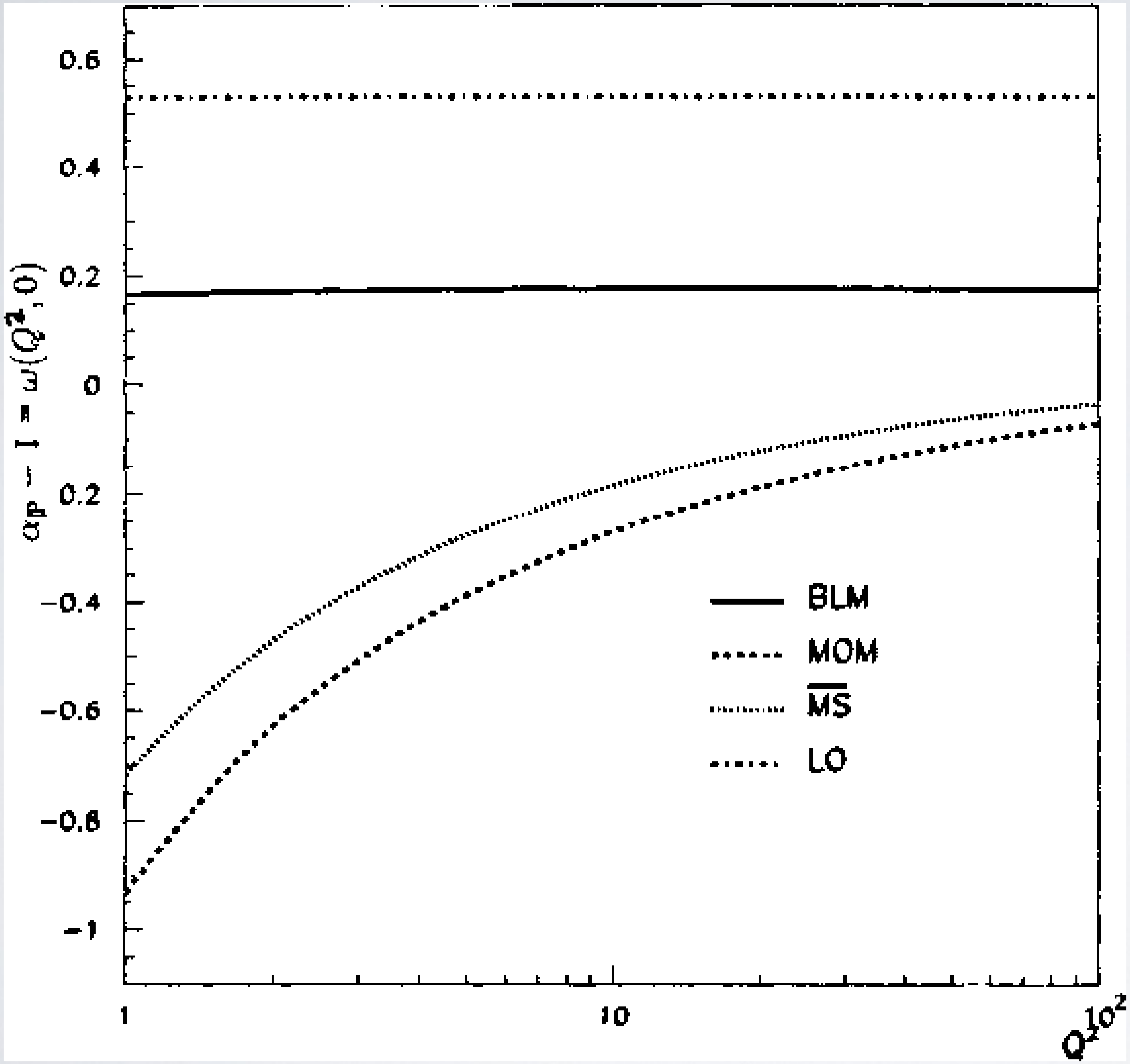
$$r_{\overline{MS}}(\nu) = r^{\beta}_{\overline{MS}}(\nu) + r^{\mathrm{conf}}_{\overline{MS}}(\nu)$$

$$r^{\beta}_{\overline{MS}}(\nu) = -\frac{\beta_0}{4}\left[\frac{1}{2}\chi_L(\nu) - \frac{5}{3}\right]$$

$$r^{\mathrm{conf}}_{\overline{MS}}(\nu) = -\frac{N_C}{4\chi_L(\nu)}\left[\frac{\pi^2 \sinh(\pi\nu)}{2\nu\cosh^2(\pi\nu)}\left(3 + \left(1 + \frac{N_F}{N_C^3}\right)\frac{11+12\nu^2}{16(1+\nu^2)}\right) - \chi_L''(\nu) + \frac{\pi^2-4}{3}\chi_L(\nu) - \frac{\pi^3}{\cosh(\pi\nu)} - 6\zeta(3) + 4\varphi(\nu)\right]$$

QCD N=4 A.V. Kotikov, L.N. Lipatov (2000)

BFKLP: NLL BFKL within generalized BLM



$$\sigma \sim s^{\alpha_{IP} - 1} = s^{\omega^{\max}}$$

BFKLP: NLL BFKL within generalized BLM

V.S. Fadin & L.N. Lipatov (89-98)
C.Camici & M. Ciafaloni (96-98)
next-to-leading log approximation (NLL) BFKL
MSbar-renormalization scheme: large corrections

S.J. Brodsky, V.S. Fadin, VK, L.N. Lipatov, G.B. Pivovarov(98-99) BFKLP
BFKLP: NLL BFKL + resummation of running coupling a_S
in physical renormalization scheme

BFKLP: Conformal BFKL kernel in NLL -> SUSY N=4
Pomeron intercept: a_P=1.2 - 1.3
Cross section: $\sigma_0 \, (S/S_0)^{(a_P-1)}$ $a_P = 1 + C \, a_S$

L.N. Lipatov, A.V. Kotikov et al. (2000-06)
SUSY N=4 BFKL Pomeron
Anomalous dimensions: test of AdS/CFT

BFKL observables

Heavy quark production
I.I. Balitsky, L.N. Lipatov (1978)

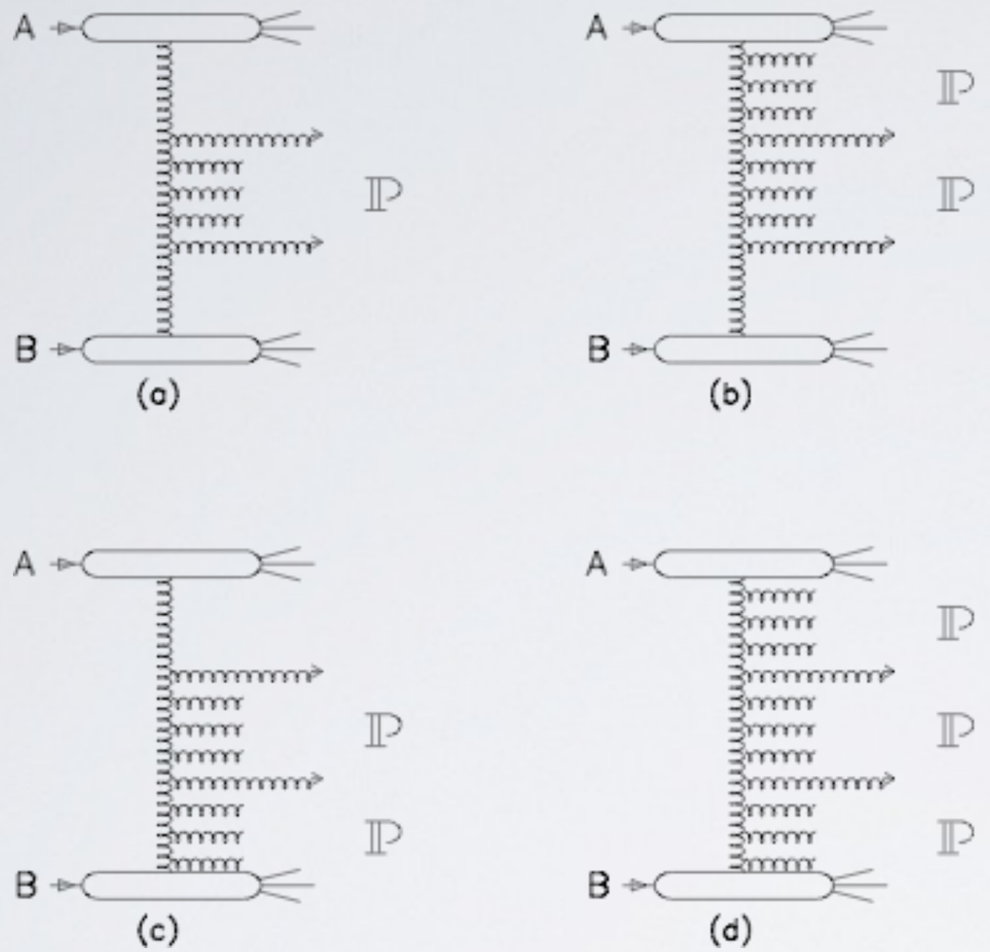
Inclusive jet
M.G. Ryskin (1980)

Lepton pair production
M.G. Ryskin, E.M. Levin (1981)

Deep inelastic processeses -> small-x physics
unitarization -> small-x shadowing
L.V. Gribov, M.G. Ryskin, E.M. Levin (1981-83)

Most forward/backward (Mueller-Navelet) dijets:
x-section ~ exp(|Δ|y)
A. Mueller & H. Navelet, Nucl. Phys. B (1987)

BFKL direct observable: dijet with large rapidity separation between jets



Jet production

GLAPD: ordering on κT
y – no ordering

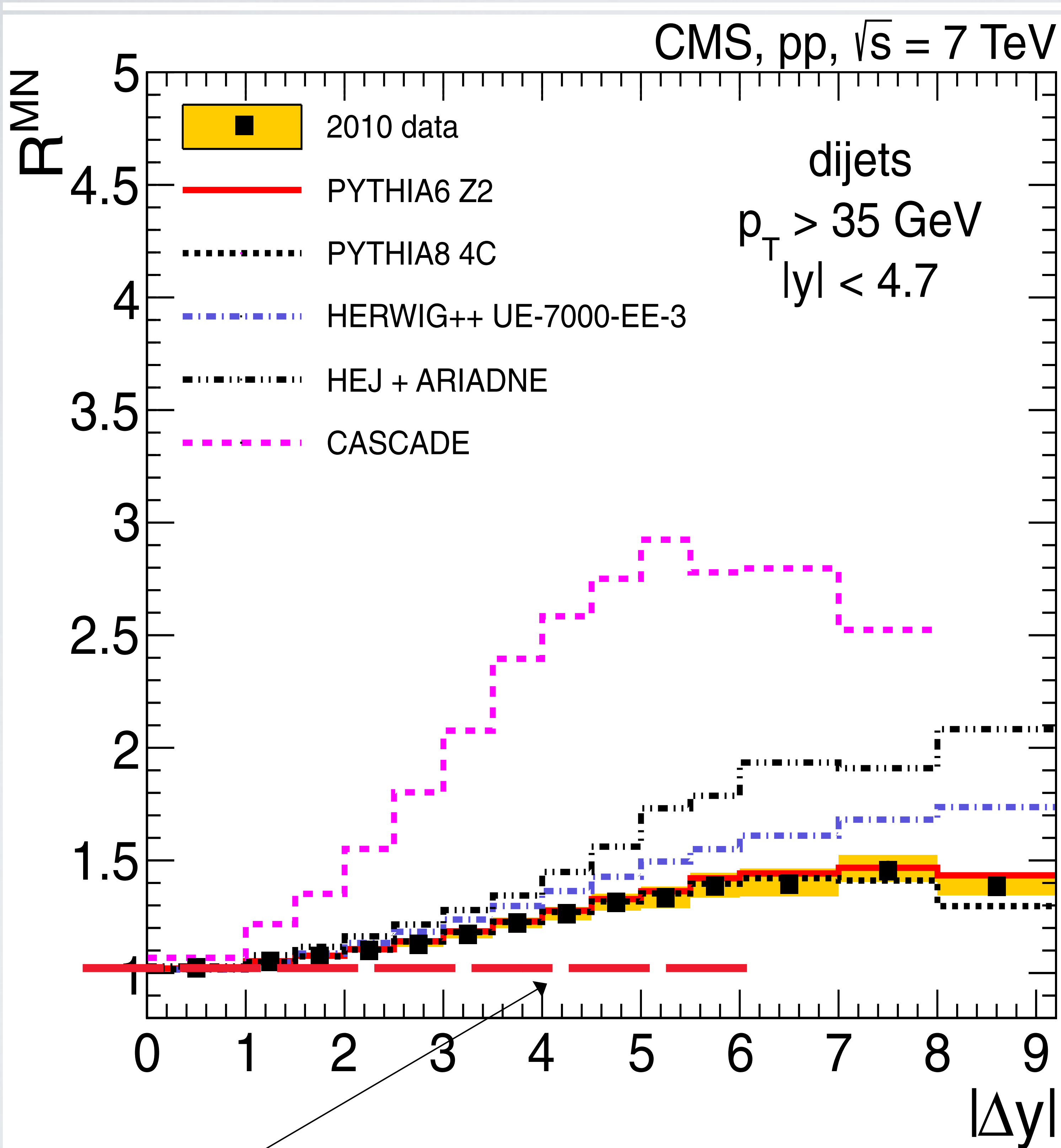
BFKL: ordering on y
κT – no ordering

Most forward/backward (Mueller-Navelet) dijets: x-section ~ exp(|Δ|y)
A. Mueller & H. Navelet, Nucl. Phys. B (1987)

Most forward/backward (Mueller-Navelet) dijets: azimuthal decorrelations
V. Del Duca & C. Schmidt, Phys. Rev. D (1994)
W.J. Stirling, Nucl. Phys. B (1994)

Inclusive dijets
VK & G.B. Pivovarov, Phys. Rev. D (1996)

CMS: dijet "K-factor"

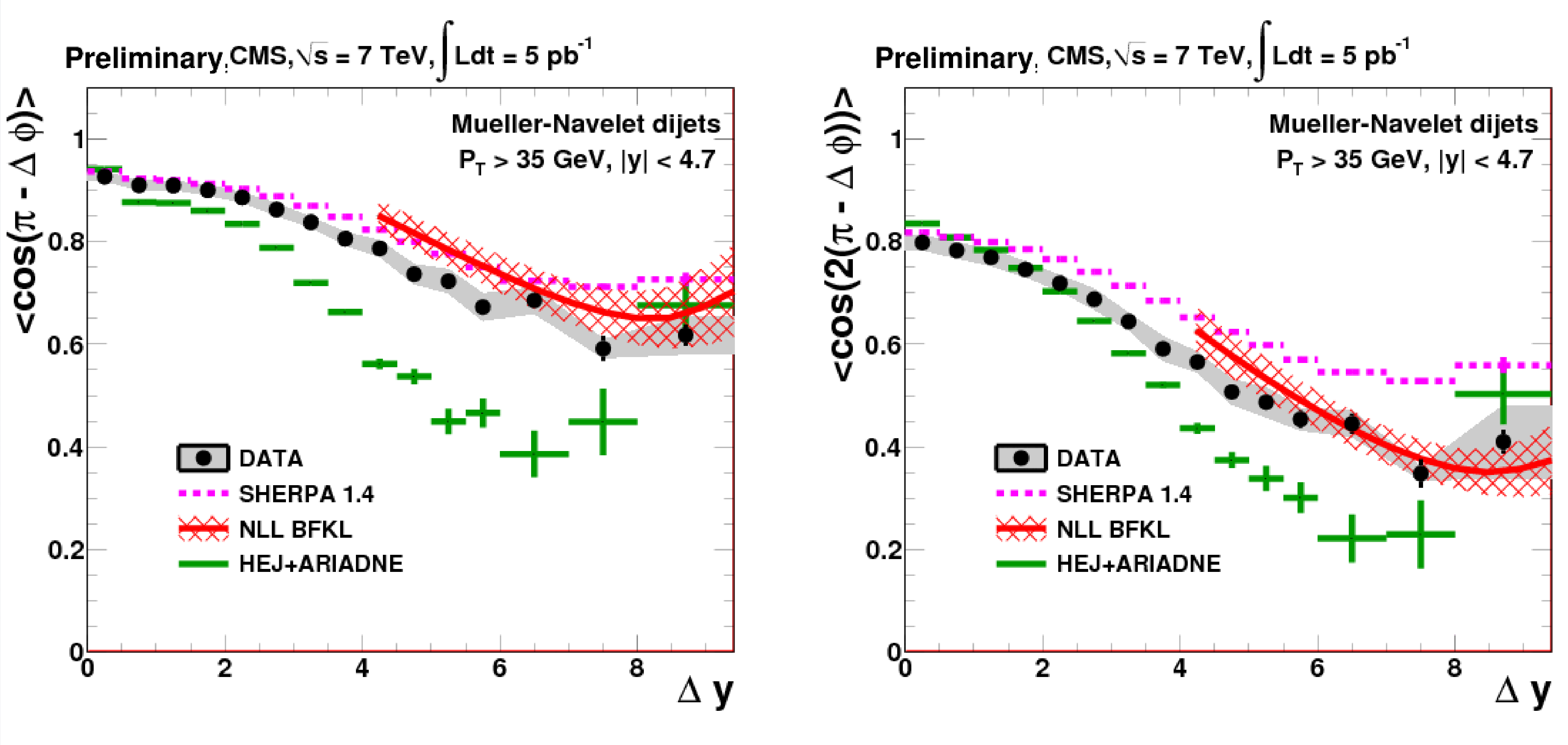


GLAPD

EPJ C 72 (2012) 2216
7 TeV, pT_min = 35 GeV
Δy = | | < 9.4

MC generators: contain terms beyond GLAPD

Dijets: <cos> vs NLL BFKL+BFKLP



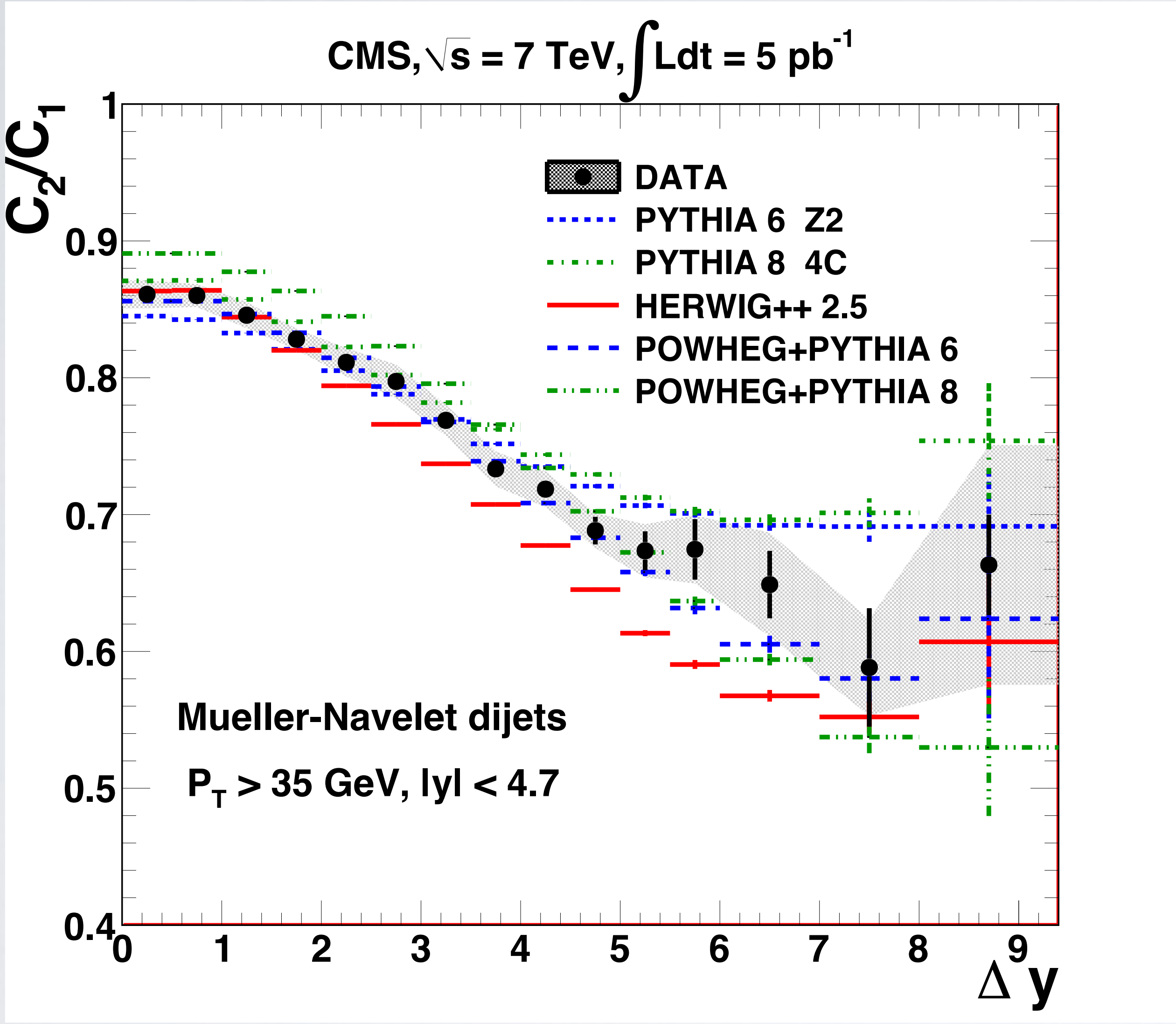
CMS (2016)
7 TeV, pT_min = 35 GeV
Δy = | | < 9.4

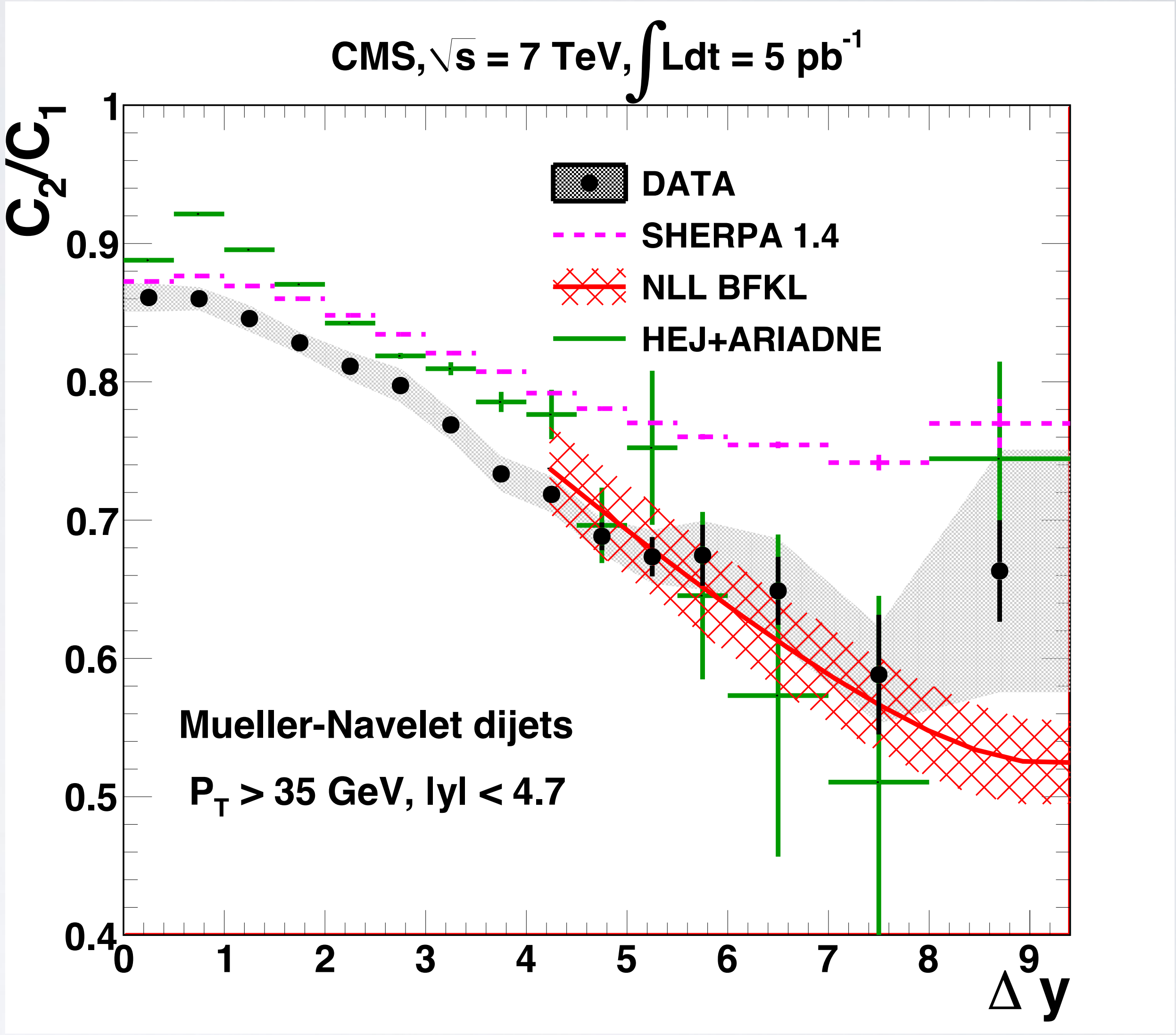
NLL BFKL + BFKLP (2014)
B. Ducloue, L. Szymanowski & S. Wallon

Dijets: <cos2/>/<cos>) vs NLL BFKL + BFKLP

BFKL conformal feature: cosine ratio

A. Sabio Vera et al (2007)





CMS (2016)
7 TeV, pT_min = 35 GeV
Δy < 9.4

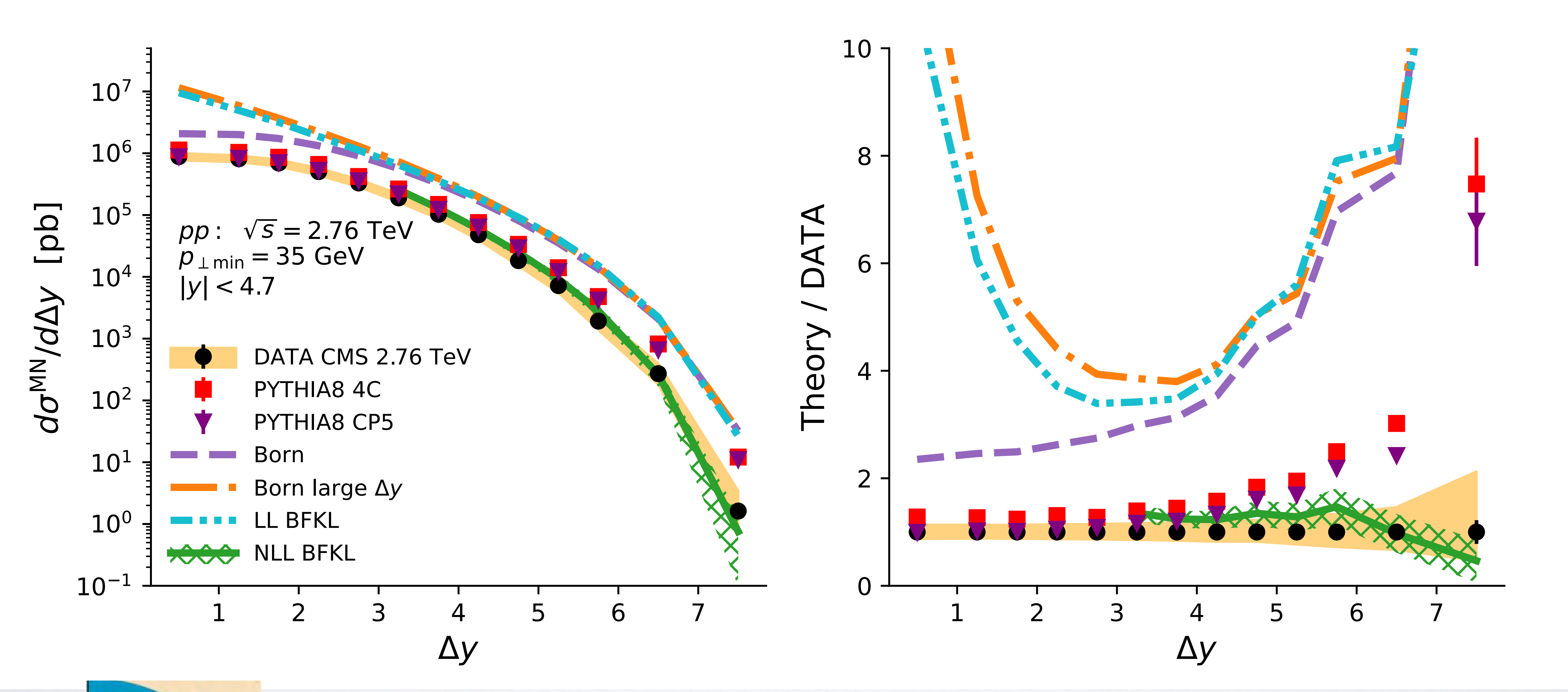
NLL BFKL + BFKLP (2014)
B. Ducloue, L. Szymanowski & S. Wallon

MN dijets within NLL BFKL improved by BFKLP

BFKL with BFKLP F. Caporale, D.Yu. Ivanov, B. Murdaca, A. Papa,
. Rev. (2015)

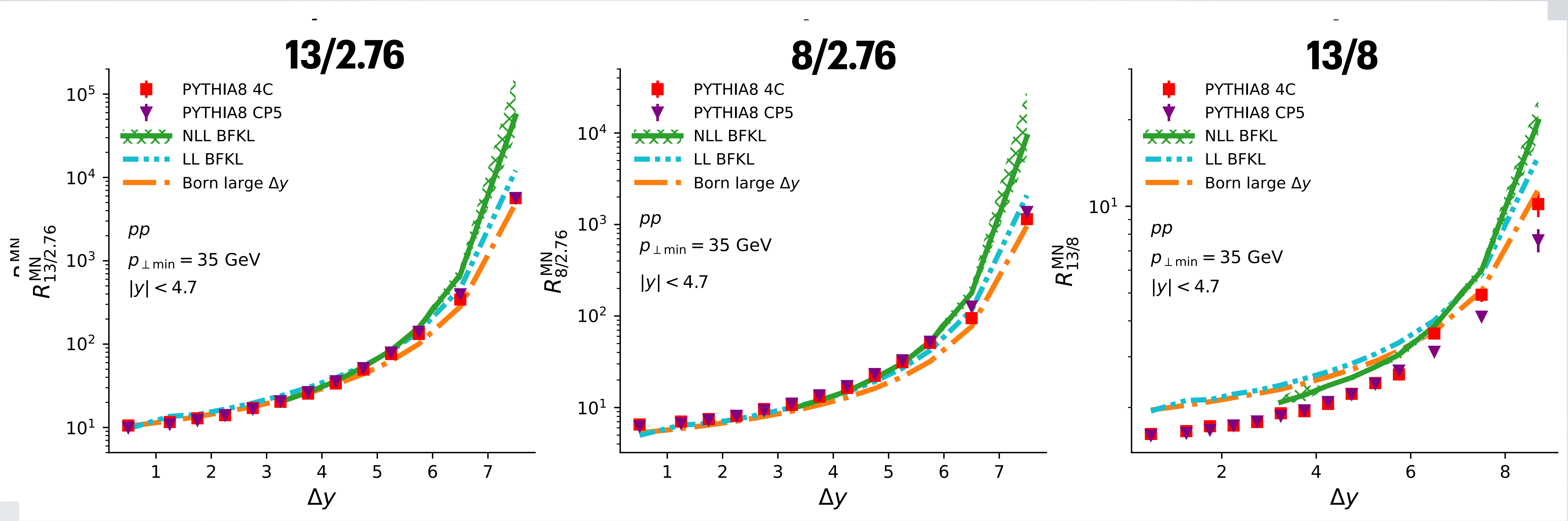
BFKL with BFKLP: 2.76 TeV dijet x-section A. Egorov & VK
Phys. Rev. (2023)

A



CMS (2022)
2.76 TeV, pT_min = 35 GeV

MN dijet x-section ratio within NLL BFKL with BFKLP: collision energy dependence at LHC



A. Egorov & VK, Phys. Rev. D (2023)

NLL BFKL with BFKLP prediction: strong energy dependence

Direct NLL BFKL manifestation

CMS dijet production with large rapidity separation between jets

A. Egorov & VK, Phys. Rev. D (2023)

-> Some indication on BFKL in exclusive dijets production

- at LHC 13 TeV at CMS:
- Mueller-Tang (MT) dijets

➔ Some indication with NLL BFKL (BFKLP improved) in Mueller-Navelet (MN) and inclusive dijet in x-section ratios and azimuthal décorrelations at LHC 7 TeV

- MN and inclusive dijet

-> The new observation of NLL BFKL (BFKLP improved) in dijets

- in at LHC 2.26 TeV
- MN dijet x-sections

- Prediction for dijet observables:
- - MN dijet x-section energy ratios 8/2.76, 13/2.76 13/8
- - K-factor with extra jet veto, number of extra jets, ... ?
- LHC Run 3 at 13.6 TeV ?!

Pomeron in pQCD: established NLL BFKL in dijets

New Physics:

- new particles and interactions beyond SM
- new dynamics within SM

New dynamics within SM:

- phase transitions at dense baryon matter
-

NB. New Physics beyond SM should manifest above new high energy SM dynamics!

LL BFKL remarkable properties

2D-conformal properties
BFKL(Schredinger eq) as ”quantization”of RG-DGLAP (Euler-Lagrange eq)
L.N. Lipatov (1986)

Effective action for reggeized gluons
L.N. Lipatov (1995)

LL BFKL 2D-conformal block symmetry:
Feynman-like rules for inclusive x-sections
VK, G.B. Pivovarov (1997)

LL BFKL 2D-conformal block symmetry
H. Navelet, R. Peschanski (1998-1999)

Effective Regge QCD: gluon intercept as RG constant
VK, G.B. Pivovarov (1997)

Feynman rules for Reggeized gluons
E.N. Antonov, E.A. Kuraev, L.N. Lipatov, I. Cherednikov (2005)

LL BFKL motivated approaches

LL BFKL Pomeron
2D conformal symmetry and 1/N expansion
➥ factorization into integrable theory

high-energy QCD -> integrable system!

L.N. Lipatov (1994)
L.D. Faddeev, G.P. Korchemsky (1994)

LL BFKL Pomeron with 1/N expansion
Dipole Pomeron

A.H. Mueller (1994)
N.N. Nikolaev, B.G. Zakharov (1994)

Reggeon field theory with BFKL Pomeron

E.M. Levin, A. Kovner, M. Lublinsky (2024)

LL BFKL motivated approaches

kT-factorization

S. Catani, M. Ciafaloni, F. Hautmann (1991)
J.C. Collins, R.K. Ellis (1991)
E.M. Levin, M.G. Ryskin, Yu. Shabelski, M.G. Shuvaev (1991)
G. Salam, H. Jung, N. Raicevic
S.P. Baranov, A.V. Lipatov, M.A. Malyshev, N.P. Zotov, G.I. Lykasov,
V.A. Saleev, A. Shipilova, A. Nefedov, …

CCFM evolution: interpolates with color coherence between LL BFKL and DGLAP

M. Ciafaloni (1988), S. Catani, F. Fiorani, G. Marchesini (1990)

KMR evolution: interpolates between LL BFKL and DGLAP

M.A. Kimber, A.D. Martin, M.G. Ryskin (1999)

Pomeron and Reggeon applications

LL BFKL Pomeron for diffractive physics:
double-Pomeron exchange for dijet, Higgs boson production
V.A. Khoze, M.G. Ryskin, A.D. Martin (1997-2006)

Pomeron and Reggeon calculus for various processes
V.A. Petrov, R.A. Ryutin, A.A. Godizov

NLL BFKL motivated approaches

SUSY N=2 NLL BFKL Pomeron

A.V. Kotikov, L.N. Lipatov (2000)

AdS/CFT-correspondence test with anomalous dimensions

A.V. Kotikov, L.N. Lipatov, A. Onischenko, V. Velizhanin (2002-2006)

Graviton-Pomeron duality

C.-I. Tan, C. Brower (2006)
L. Alvarez-Gaume et al. (2007)

Pomeron in nonpertubative QCD

Pomeron by quark and gluons condensates

P.V. Landshoff, O. Nachtmann (1987)

Non-planar Pomeron in QCD with 1/N expansion:

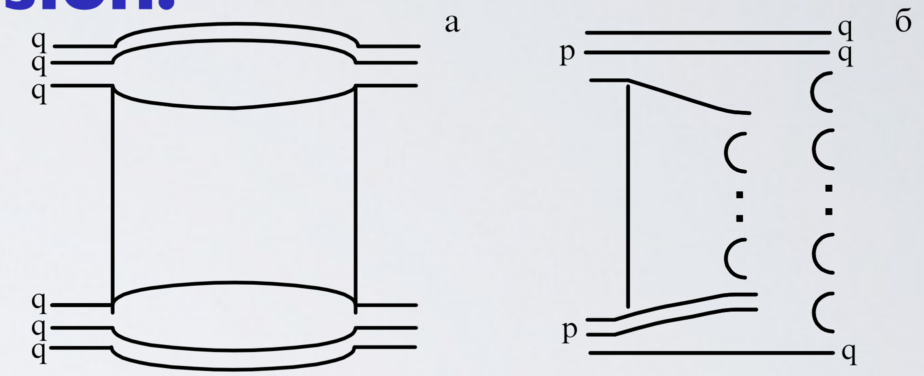
G.Veneziano (1977)

- dual parton model

A.Capella, J. Tran Tanh Van (1981)

- quark-gluon string model (QGSM)

A.B. Kaidalov, K.A. Ter-Martirosyan (1982)



Unitarity with 1/N expansion for saturation limit

Balitsky-Kovchegov equation **with $\alpha_s \to 0$: reproduces BFKL**

I.I. Balitslky (1996) Yu. Kovchegov (1999, 2000)

Color Glass Condensate evolution for saturation limit

with $\alpha_s \to 0$: reproduces BFKL

L. McLerran, R. Venugopalan (1994) H. Weigert, A. Kovner, A. Leonidov (2001)

F. Gelis, E. Iancu, J. Jalilian-Marian, R. Venugopalan (2010)

Summary

- **BFKL reproduces main classical Pomeron properties bringing new remarkable features: conformality, integrability, AdS/CFT duality, holographic properties …**

- **NLL BFKL manifests in dijet production with large rapidity separation in CMS data at LHC 2.76 TeV**

- **New Physics beyond SM should manifest within BFKL: the new high energy SM dynamics!**