BFKL evolution manifestation in jet production at colliders

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Outline:

- High energy asymptotics of pQCD
- BFKLP: NLL BFKL within generalized BLM
- $\gamma^*\gamma^*$- collisions at LEP2
- Dijets from pQCD dynamics: GLAPD vs. BFKL
- Summary

Lev N. Lipatov:

- **High-energy asymptotics in QED**
  V. Gribov, V. Gorshkov, L. Lipatov, G. Frolov (1969-70)

- **High-energy Bjorken asymptotics in QCD: GLAPD**
  V. Gribov, L. Lipatov (1971-72) L. Lipatov (1974)
  G. Altarelli, G. Parisi (1977) Yu. Dokshitzer (1977)

- **High-energy asymptotics in QCD: LL BFKL**
  V. Fadin, E. Kuraev, L. Lipatov (1975-77)
  I. Balitsky, L. Lipatov (1978) L. Lipatov (1986)

1940 - 2017

- **High-energy asymptotics in QCD: NLL BFKL**
  V.Fadin, L.Lipatov (1989-98)
  S. Brodsky, V. Fadin, V. K., L. Lipatov, G. Pivovarov (1999-02)

- **High-energy asymptotics in quantum gravity**
  L. Lipatov (1989)
- **High-energy QCD as an integrable theory**
  L. Lipatov (1993) L. Faddeev, G. Korchemsky (1994)
- **AdS/CFT (N=4 SUSY)**
  A. Kotikov, L. Lipatov, A. Onischenko, V. Velizhanin

- **High-order estimate in QFT (1976)**
  L. Lipatov (1976)

Lev N. Lipatov: 3 BFKLs

- **BFKL**
  High-energy asymptotics in QCD: LL BFKL
  V. Fadin, E. Kuraev, L. Lipatov (1975-77)
  I. Balitsky, L. Lipatov (1978) L. Lipatov (1986)

- **BFKL**
  High-energy asymptotics in QCD: spin-dependent evolution, GPDF
  A. Bukhvostov, G. Frolov, E. Kuraev, L .Lipatov (1982-86)

- **BFKLP**
  High-energy asymptotics in QCD: NLL BFKL
  S. Brodsky, V. Fadin, V. K., L. Lipatov, G. Pivovarov (1999-02)

High-energy asymptotics of pQCD: 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: $\alpha_s \log(s)$, $\alpha_s \log(Q^2)$

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

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

High energy asymptotics

- Large-angle scattering:

QED and 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:

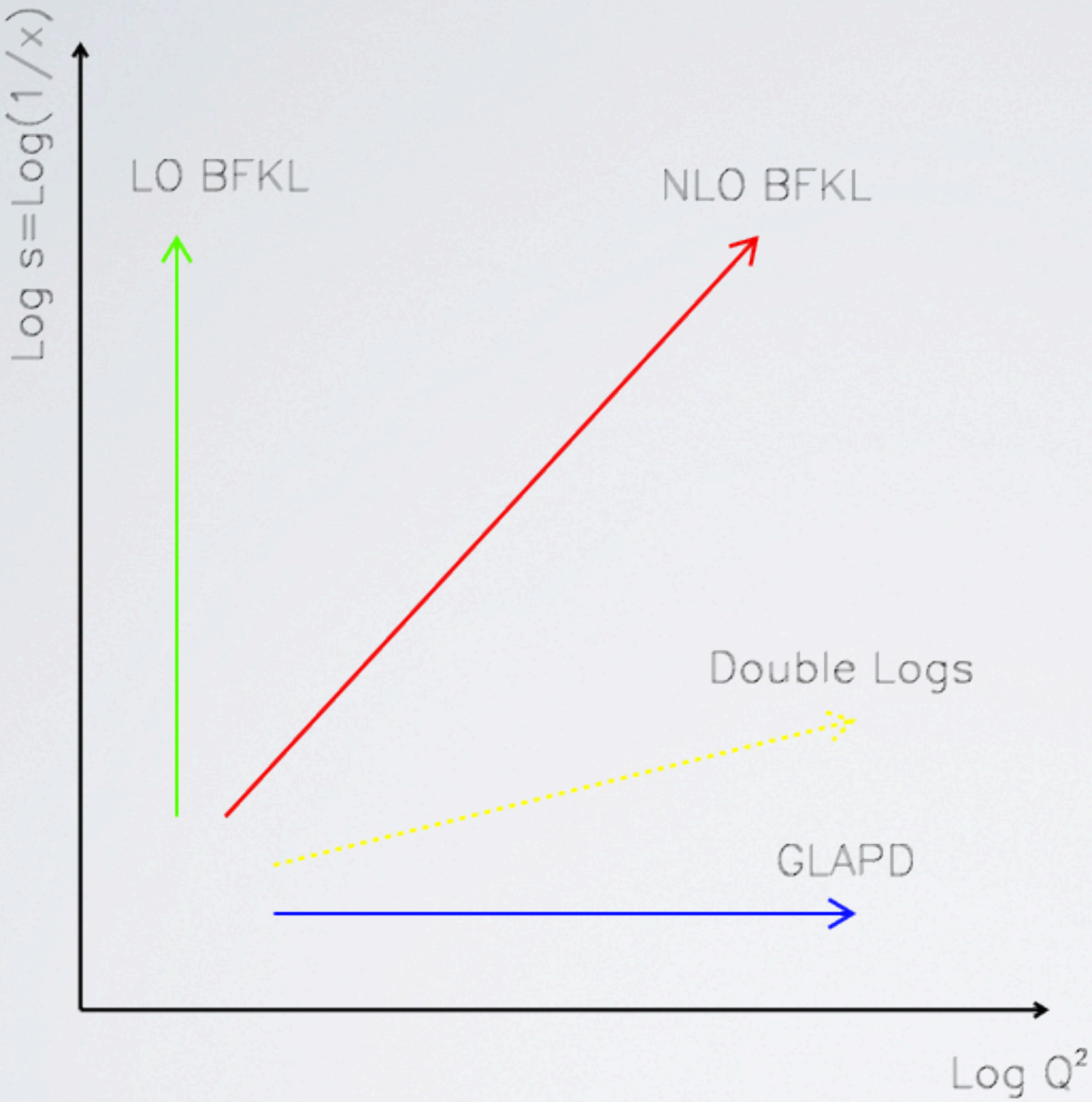
QED in Gribov-Regge limit

- 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)

Asymptotics of pQCD: x-section



Bjorken limit (GLAPD):

$s \sim Q^2 >> m^2$

$Q^2/s = x \sim 1$

Large-angle (large-x) scattering

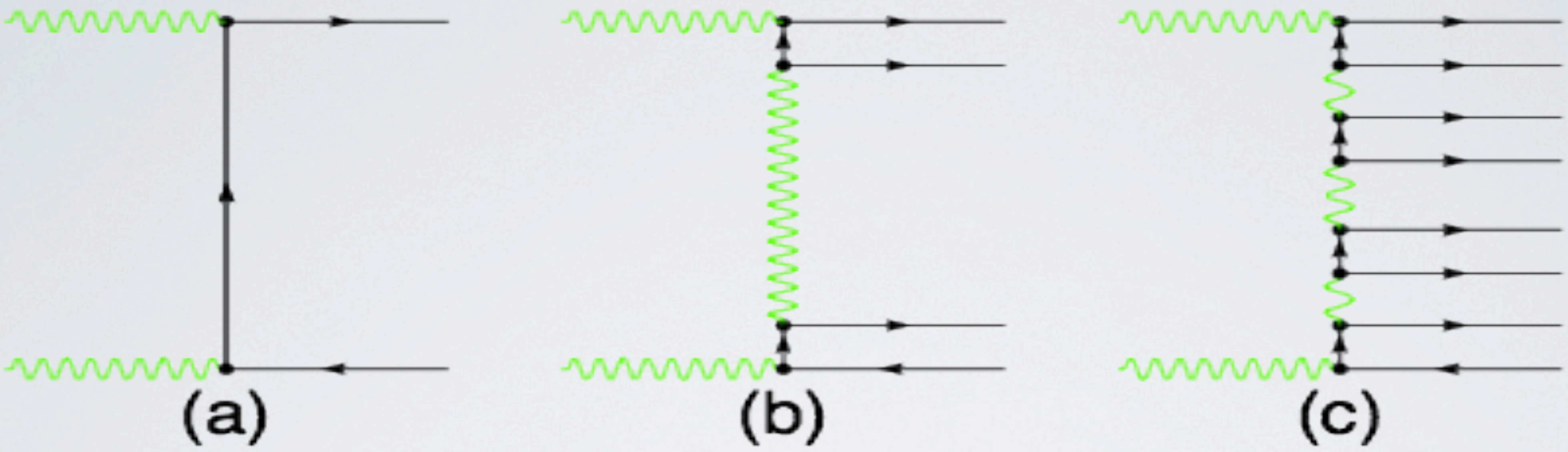
Gribov-Regge limit (BFKL):

$s >> Q^2 >> m^2$

$Q^2/s = x \to 0$

Small-angle (small-x) scattering

Asymptotics of QED cross sections



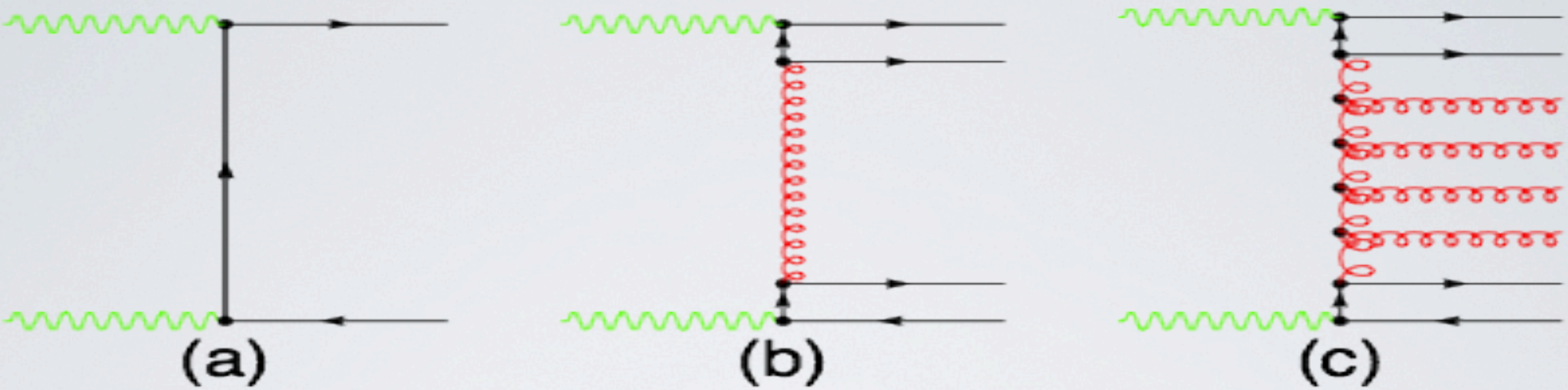
$\sigma \sim (a_{QED})^2 \log(s)/s$ $\sigma \sim (a_{QED})^4$ const(s)

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 -> ∞: $\sim (a_{QED})^4 (S/S_0)^{(aP-1)}$

$a_P = 1 + C\,(a_{QED})^2 \approx 1.002$

Asymptotics of QCD cross sections: γγ



$\sigma \sim (a_{QED})^2 \log(s)/s$ $\sigma \sim (a_{QED})^2 (a_s)^2 \, \mathrm{const}(s)$

All orders: LL BFKL

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

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

$a_P = 1 + C\,(a_s) \approx 1.2$ **NLL BFKL** S.Brodsky, V Fadin, VK, L. Lipatov, G. Pivovarov (2001-02)

Ultrahigh energies: all particles behave as hadrons!

Leading Log (LL) BFKL: problems

LL BFKL: designed for infinite collision energies

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

Cross section in LL BFKL:

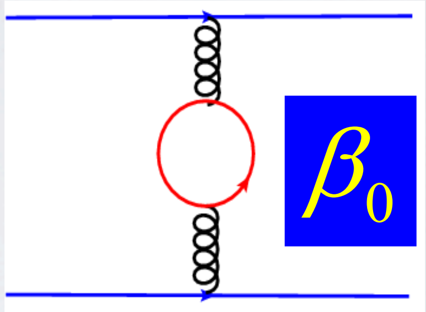
$$\sigma = \sigma_0 (S/S_0)^{(a_P - 1)} \qquad a_P = 1 + C\, a_s \approx 1.5\text{-}1.6$$

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

BFKL: next-to-leading logs (NLL)

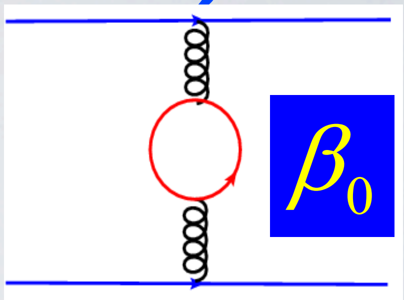
V.S. Fadin & L.N. Lipatov (89-98)
C.Camici & M. Ciafaloni (96-98)
next-to-leading log approximation (NLL) BFKL
MSbar-renormalization scheme: large corrections

S.Brodsky, P.Lepage & P.Mackenzie - BLM (1983)
Resummation of running coupling within
the standard BLM is not possible for NLL BFKL:
BLM approach valid only for Abelian case

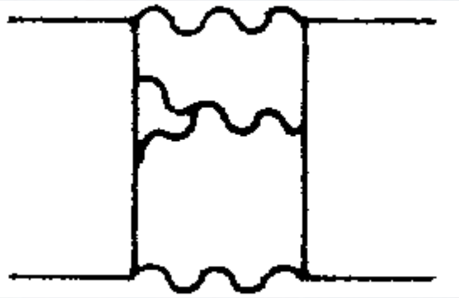


NLL BFKL in BFKLP: generalized BLM

S.Brodsky, P.Lepage & P.Mackenzie (83) BLM approach for NLO
- QCD – asymptotically conformal
- non-conformal corrections (running coupling corrections) are resummed into optimal scale



Standard BLM approach for does not work (!) for:
- NLL BFKL in MSbar scheme
- Upsilon ->ggg decay in NLO in Msbar scheme



BLM resummation depends on non-Abelian structure in LO

BLM generalized on non-Abelian case:
S.J. Brodsky, V.S. Fadin, VK, L.N. Lipatov, G.B. Pivovarov(98-99) BFKLP

BFKLP: NLL BFKL within generalized BLM - 1

Direct BLM application does not work in non-Abelian case(!):

- **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 (guage dependent)

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

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

BLM generazlized on 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 a_s

BLM resummation depends on non-Abelian structure in LO

BFKLP: NLL BFKL within generalized BLM - 2

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

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

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

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

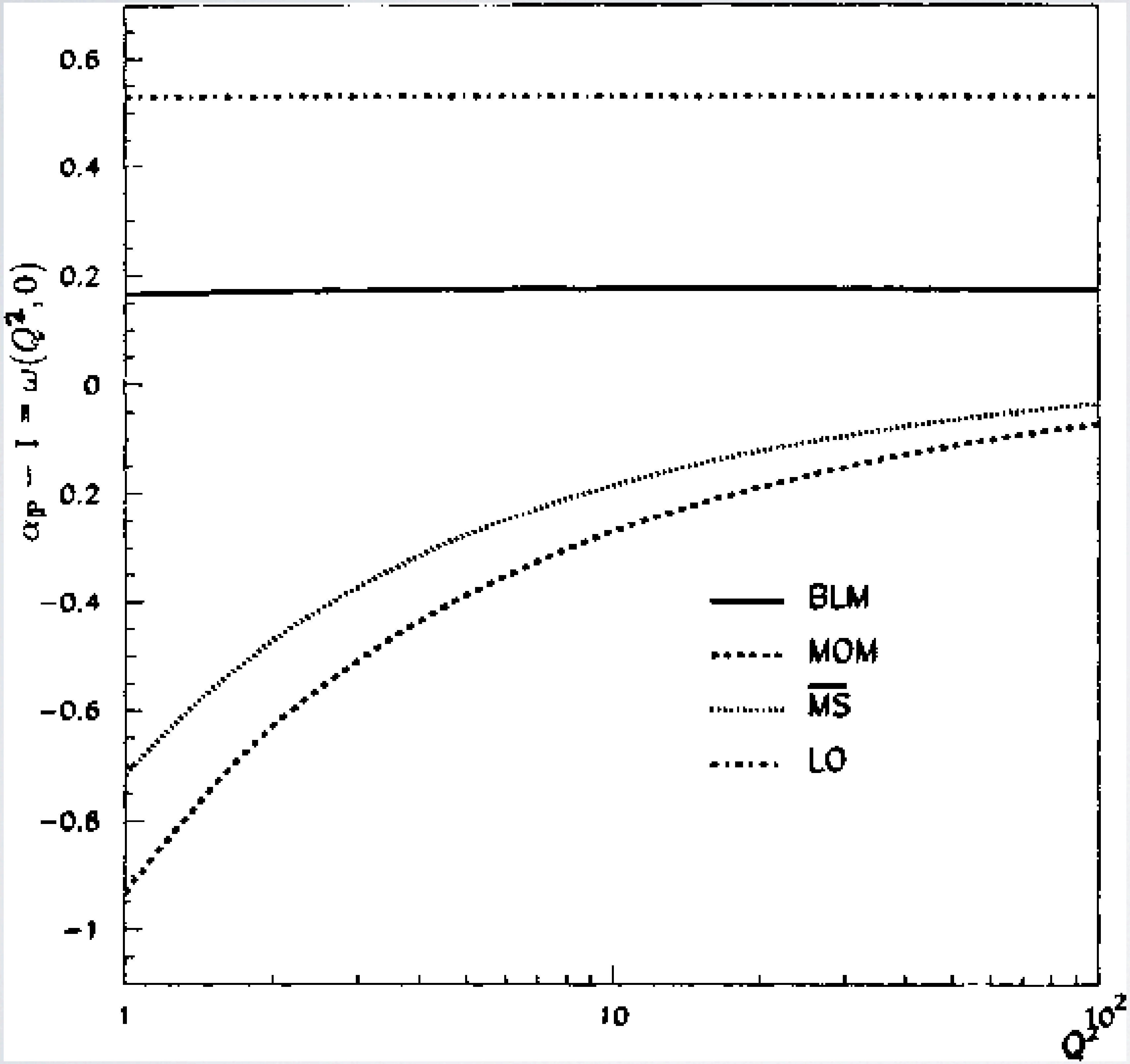
$$r_{\overline{MS}}(\nu) = r^{\beta}_{\overline{MS}}(\nu) + r^{\mathrm{conf}}_{\overline{MS}}(\nu)$$

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

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

$$\left. - \chi_L''(\nu) + \frac{\pi^2-4}{3}\chi_L(\nu) - \frac{\pi^3}{\cosh(\pi\nu)} - 6\zeta(3) + 4\varphi(\nu)\right]$$

BFKLP: NLL BFKL within generalized BLM - 3



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

BFKLP: NLL BFKL within generalized BLM - 4

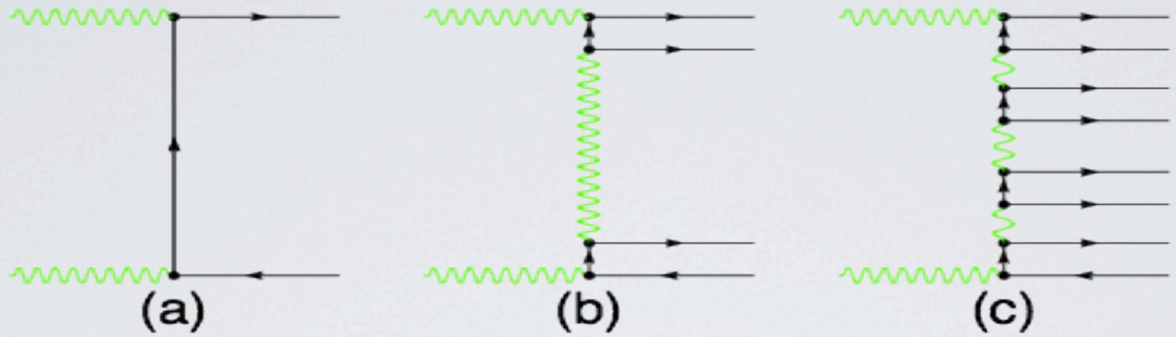
V.S. Fadin & L.N. Lipatov (89-98)
C.Camici & M. Ciafaloni (96-98)
next-to-leading log approximation (NLL) BFKL
MSbar-renormalization scheme: large corrections

S.J. Brodsky, V.S. Fadin, VK, L.N. Lipatov, G.B. Pivovarov(98-99) BFKLP
D. Colferai, M. Ciafaloni & G. Salam (99) ...
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: $\sigma_0 (S/S_0)^{(a_P-1)}$ $a_P = 1 + C\, a_S$

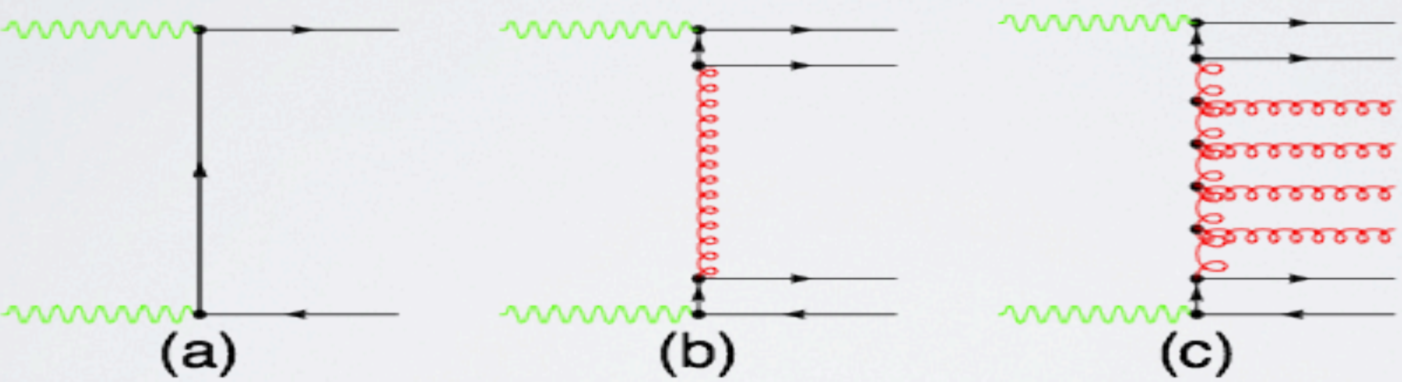
L.N. Lipatov, A.V. Kotikov et al. (2000-06)
SUSY N=4 BFKL-Pomeron
Anomalous dimensions: test of AdS/CFT

Asymptotics of QED cross sections



V.N. Gribov, L.N. Lipatov, G.V. Frolov & V.G. Gorshkov (69-71)
Cheng & T.T. Wu (69-71)

Asymptotics of QCD cross sections

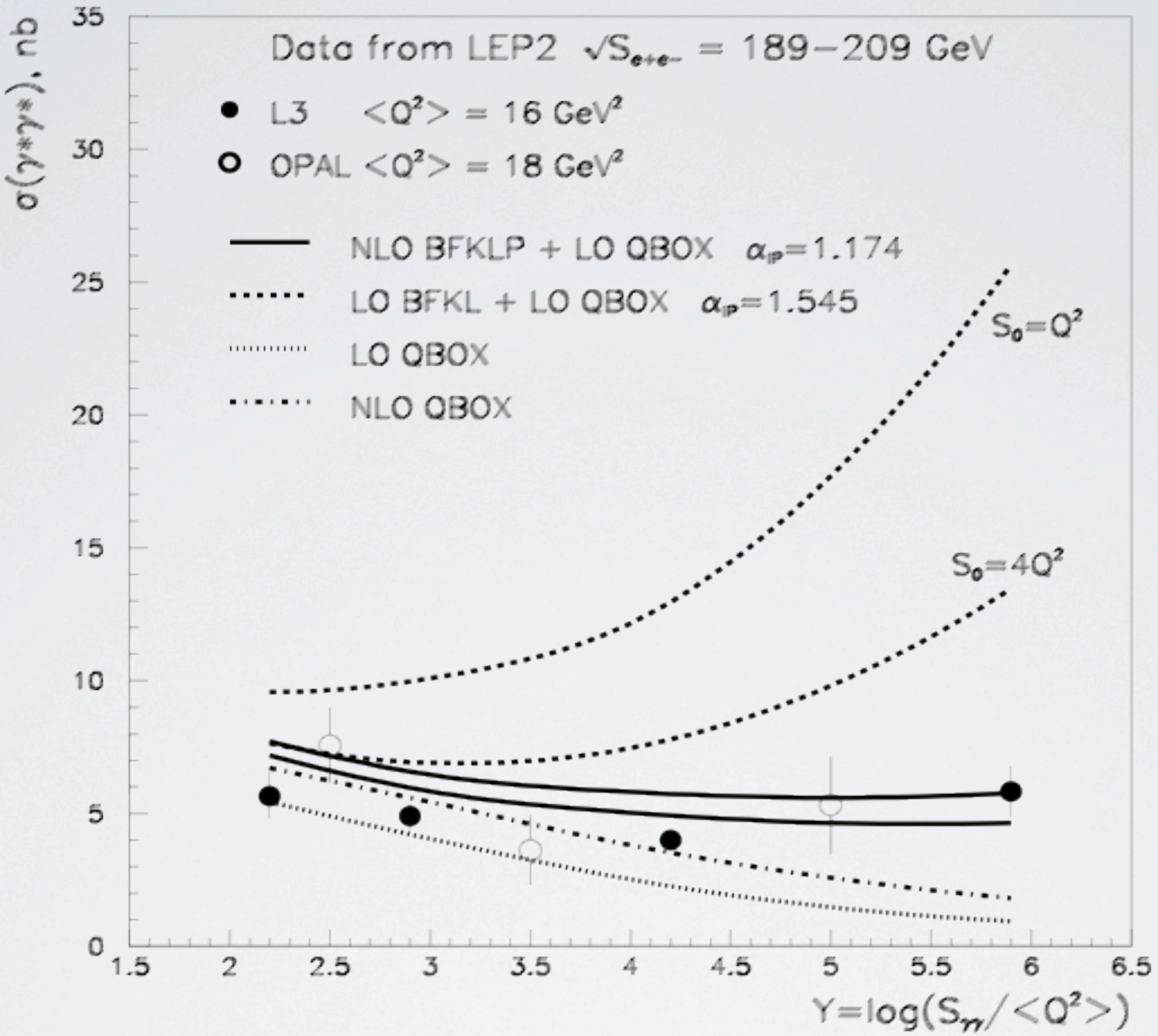


LL BFKL
J. Bartels et al (96), S.J. Brodsky & Hautmann (97)

NLL BFKL (with LO impact factors)
S.J. Brodsky, V.S. Fadin, VK, L.N. Lipatov & G.B. Pivovarov (2001-02)

NLO impact factors and full NLL BFKL (in progess):
I. Balitsky, J.Chirilli, J. Bartels et al., A. Papa, D. Ivanov et al.

Highly virtual photon scattering at LEP-2

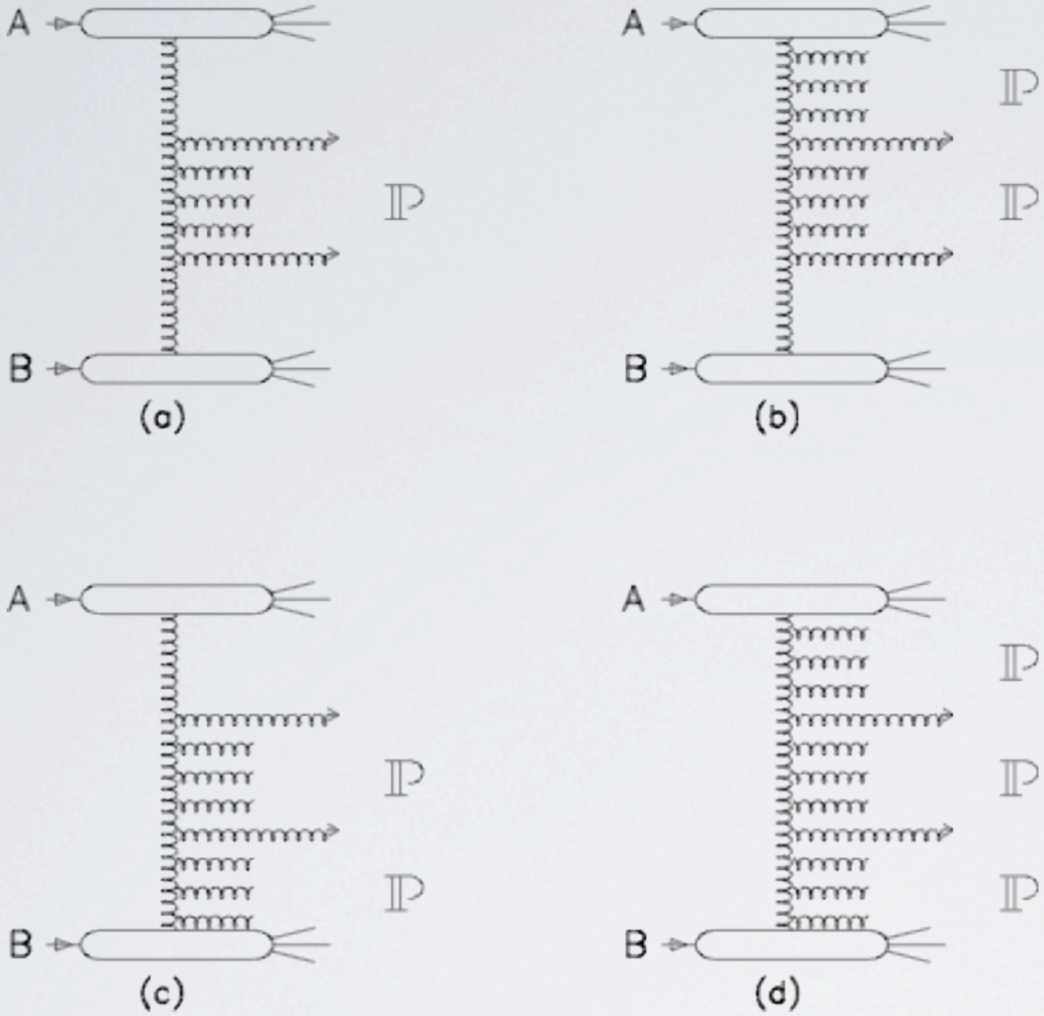


S.J Brodsky, VK, L.N. Lipatov, V.S. Fadin & G.B. Pivovarov (2002)

BFKLP: NLL BFKL + generalized BLM (LO impact factors)

LL BFKL: ruled out

BFKL: dijet processes



Jet production

GLAPD: ordering on κT
y – no ordering

BFKL: ordering on y
κT – no ordering

A. Mueller & H. Navelet, Nucl. Phys. (87)
Most forward/backward (Mueller-Navelet) dijets: x-section ~ exp(|Δ|y)

V.T. Kim & G.B. Pivovarov, Phys. Rev. (96)
Inclusive dijets

J.C. Collins, R.K. Ellis (91), S. Catani et al (91)
E.M.Levin, M.G.Ryskin, Yu.M.Shabelsky, A.G.Shuvaev (91)
kT-factorization

Dijet K-factor: 2-parton scattering

K-factor = x-section / Born x-section

GLAPD: x-section $\rightarrow C_1\,\alpha_s^{\,2} + C_2\,\alpha_s^{\,3} + \ldots$
Born x-section $\rightarrow C_1\,\alpha_s^{\,2}$

K-factor = $(1 + C_2/C_1\,\alpha_s + C_3/C_1\,\alpha_s^{\,2} + \ldots)$

Mueller-Navelet (87):

BFKL $\rightarrow$ enhanced $(\alpha_s\,\Delta y)$-terms
x-section $\rightarrow B_1\,\alpha_s^{\,2}\,\Delta y + B_2\,\alpha_s^{\,3}\,\Delta y^2 + \ldots$
Born x-section $\rightarrow B_1\,\alpha_s^{\,2}\,\Delta y$

K-factor_MN $\rightarrow \exp(\alpha_s \Delta y)$

$\Delta y = |y_1 - y_2| \sim \log(1/x)$

Dijet K-factor: not measurable

K-factor = x-section / Born x-section
Born x-section: no real and no virtual corrections

only a theoretical quantity - > not measurable (!)
Experiment: one cannot forbid virtual corrections by kinematical conditions

Exclusive dijet x-section: always contains virtual corrections

VK & G. Pivovarov:
Using dijets with extra jet veto instead of Born dijets

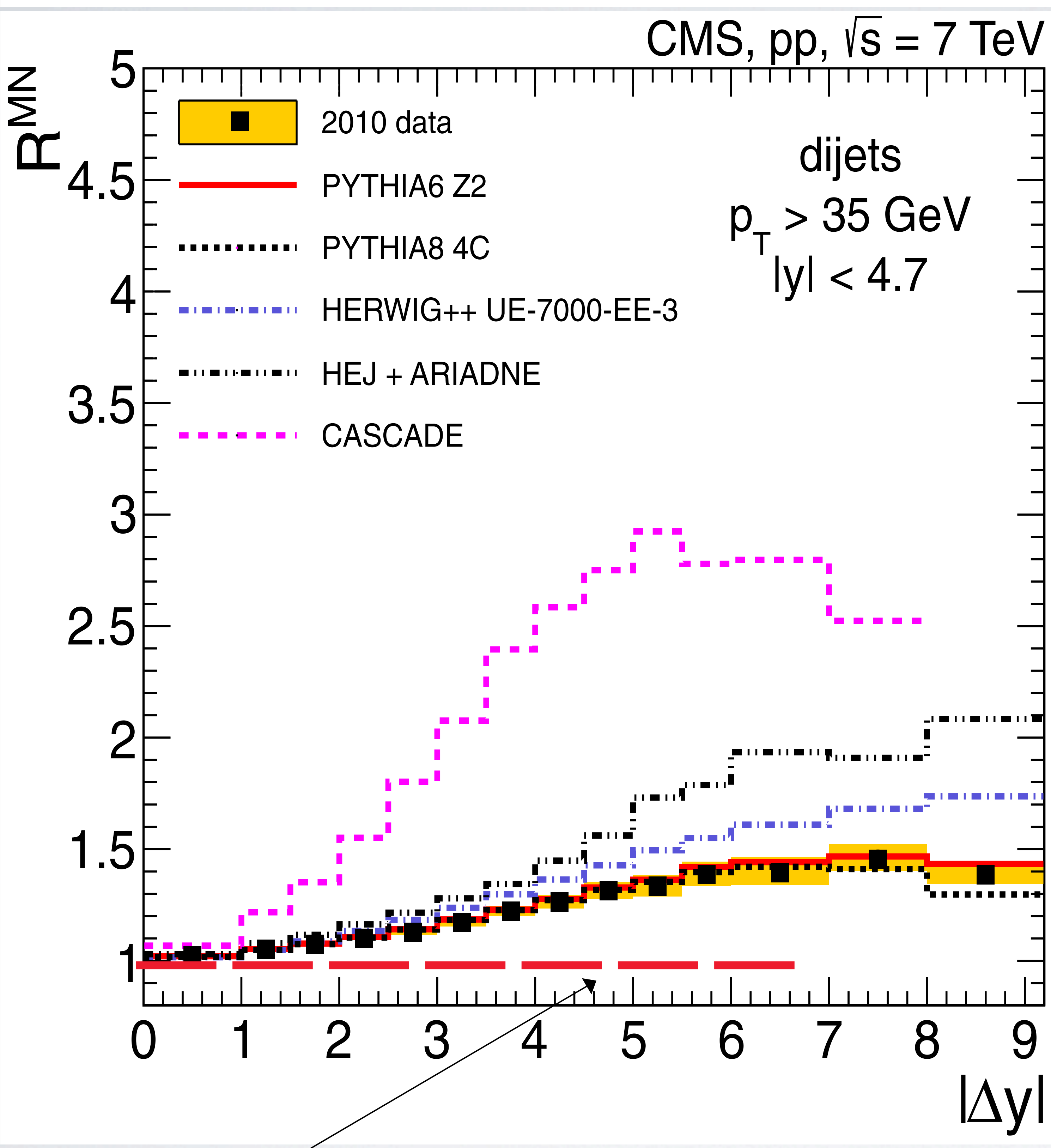
Forward dijets at Tevatron and LHC

Tevatron : D0 -> $|\Delta y| < 6$ $p_{Tmin} = 20$ GeV
- **azimuthal decorr. (1997)**
- **1800/630 GeV x-section ratio (2001)**

LHC: ATLAS -> $|\Delta y| < 6$ 70 GeV $< p_T <$ 90 GeV
- **(inverse) "K-factor" (2011)**

LHC: CMS -> $|\Delta y| < 9.4$ $p_{Tmin} = 35$ GeV
- **"K-factor" (2012)**
- **azimuthal angle decorr. EJP C (2016)**

CMS: dijet “K-factor”



GLAPD (no AO and CC)

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

Forward dijets at LHC:

Color coherence and AO effects

GLAPD: strong kT-ordering & no rapidity ordering
BFKL: strong rapidity ordering & no kT-ordering

Color coherence effects => rapidity ordering

Polar angle ordering (AO):
jet cone veto for larger cone angles => rapidity ordering

Pythia 6 and 8: GLAPD + AO (AO cannot be fully switched off!)
Herwig++: GLAPD + color coherence (CC cannot be swiched off)

No pure GLAPD MC generators (!) available
at present: Pythia and Herwig generators contain |Δy|-effects

small CC and AO |Δy|-effects in GLAPD-regime
can be large in BFKL-regime at large |Δy|

Forward dijets at LHC

GLAPD generators Pythia 6 and 8 (with AO) are consistent with CMS dijet "K-factor" data rather well:

1) no sizeable BFKL effects at present energies?
2) BFKL effects partially cancels out in dijet ratio?

in the latter case: "K-factor" with extra jet veto can be more sensitive BFKL effects
2-jet "exclusive" events: impose an extra jet veto $p_{Tveto} < p_{Tmin}$

Forward dijets:

azimuthal angle decorrelations

Cosines

V. Del Duca & C. Schmidt (94)

J. Stirling (94)

V. K. & G. Pivovarov (96)

Conformal properties of BFKL:

Cosine ratios –> GLAPD cancellation

–> more sensitive to BFKL (!)

A. Sabio Vera et al (2011)

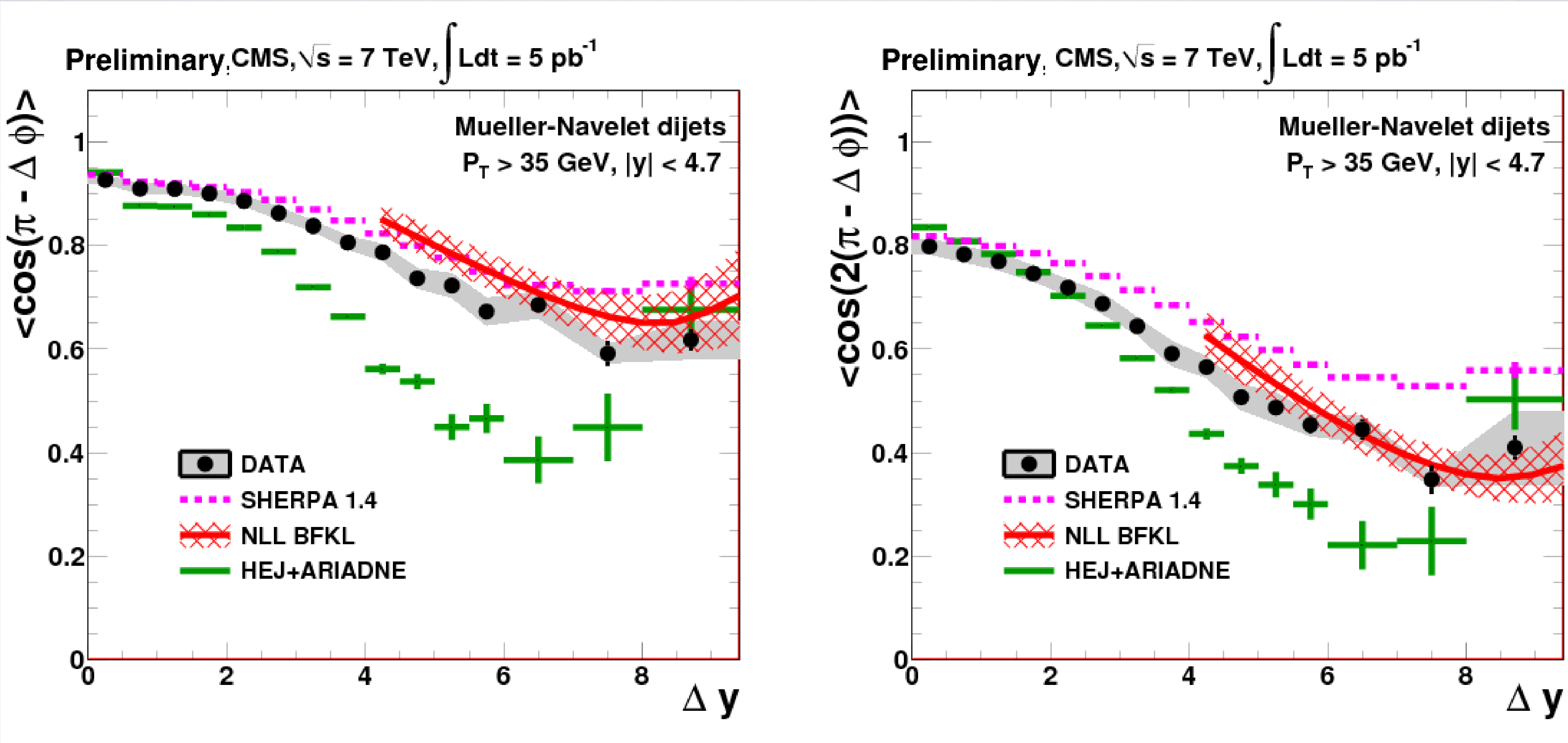
Forward dijets: azimuthal decorrelations

$$\frac{1}{\sigma}\frac{d\sigma}{d(\Delta\phi)}(\Delta y, p_{\mathrm{Tmin}}) = \frac{1}{2\pi}\left[1 + 2\sum_{n=1}^{\infty} C_n(\Delta y, p_{\mathrm{Tmin}}) \cdot cos(n(\pi - \Delta\phi))\right]$$

$$C_n(\Delta y, p_{\mathrm{Tmin}}) = \langle cos(n(\pi - \Delta\phi))\rangle, \text{ where } \Delta\phi = \phi_1 - \phi_2$$

V. del Duca & C. Schmidt (94-95)
Striling (94)
V. K. & G. Pivovarov (96-98)
A. Sabio Vera et al (2007-11)

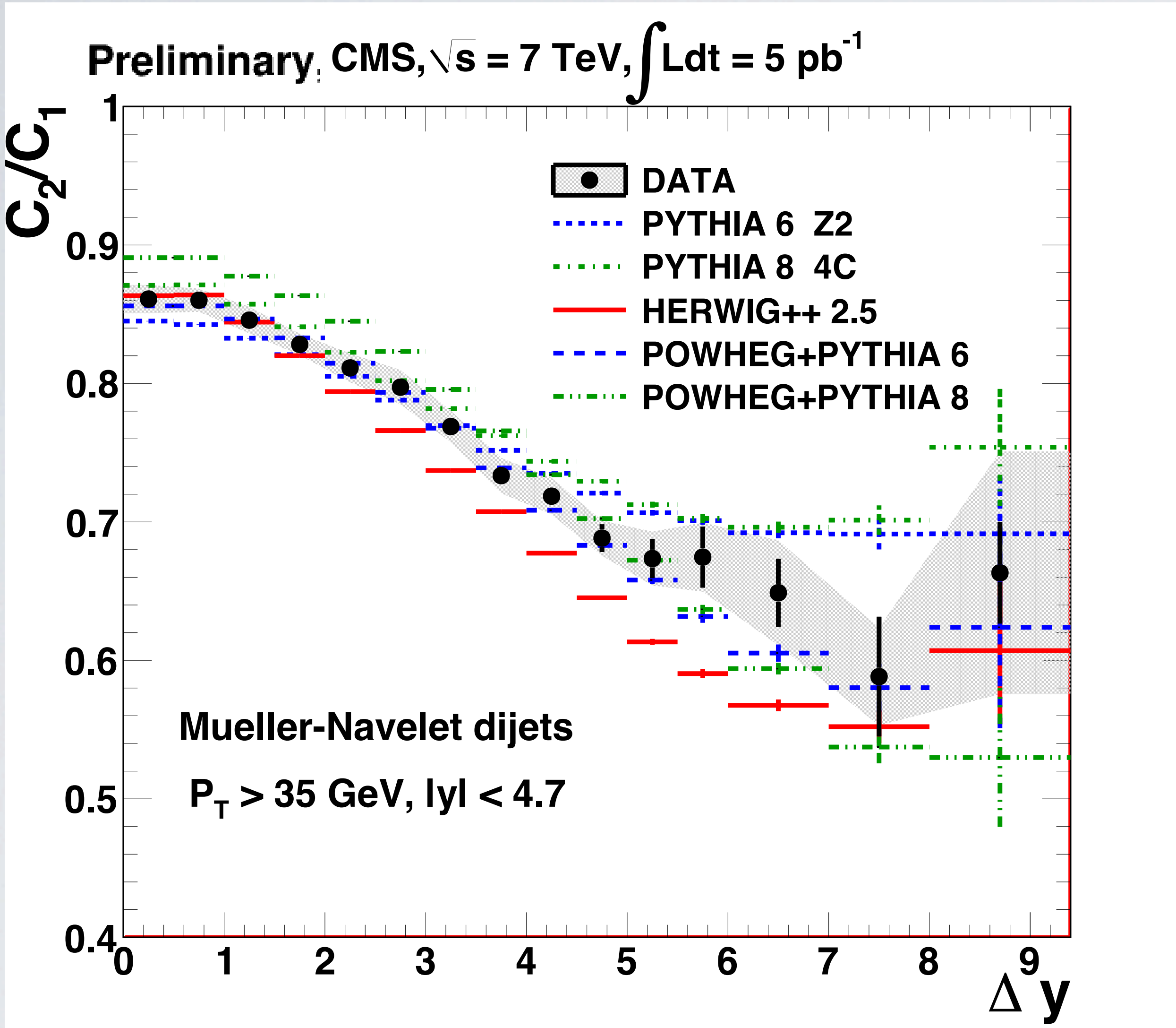
Dijets: <cos> vs NLL BFKL @BFKLP

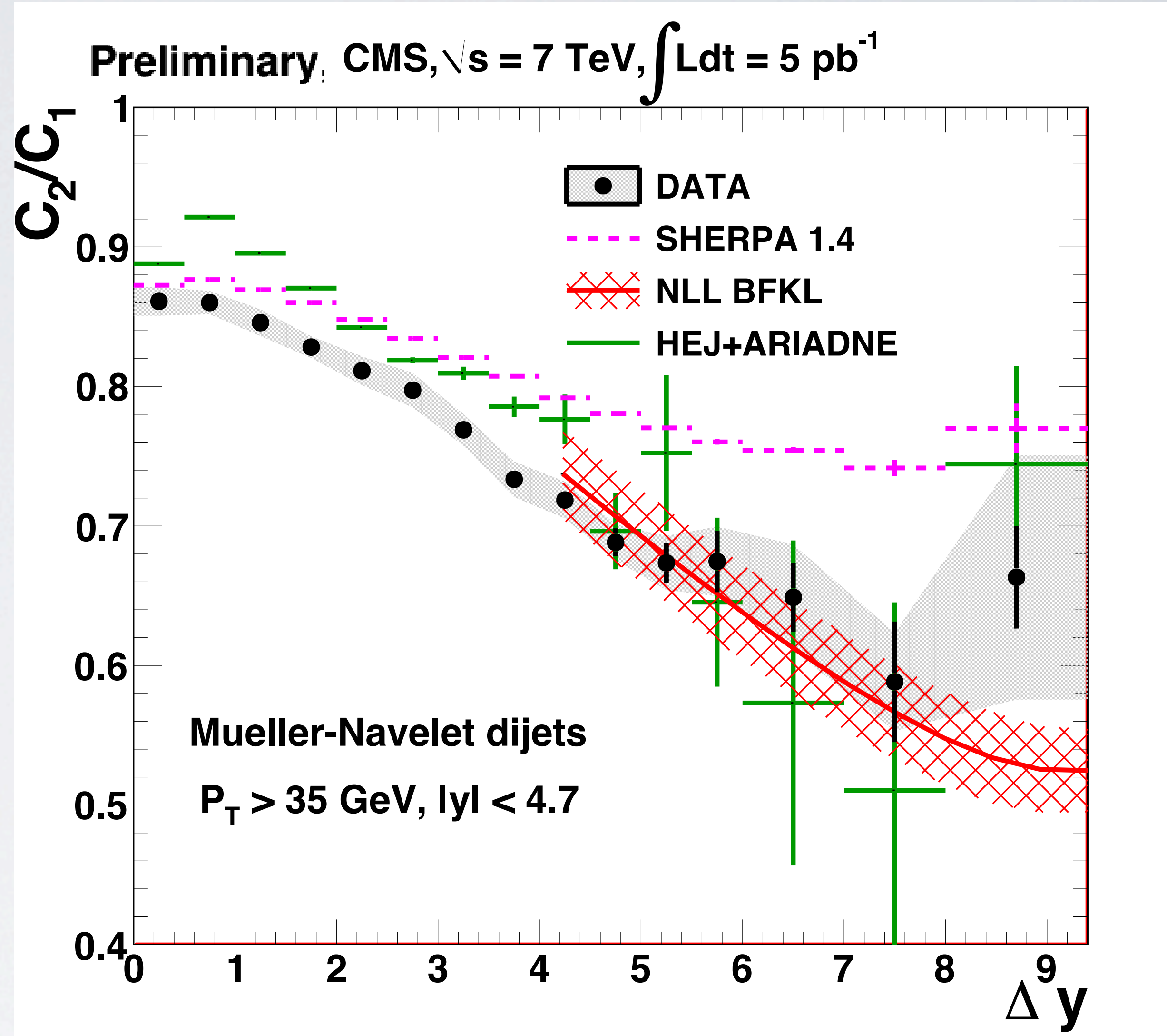


CMS: <cos> and <cos2>
JHEP 08 (2016) 139
7 TeV, pT_min = 35 GeV
Δy = | | < 9.4

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

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





CMS: <cos> ratio -> indication on BFKL?
JHEP 08 (2016) 139
7 TeV, pT_min = 35 GeV
Δy < 9.4

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

BFKL search:

other observables with jets

- **dijet "K-factor" with veto on extra jets**

  VK, G. Pivovarov et al. (2008)

- **number of produced jets**

  H. Jung et al. (2012)

- **dijets with rapidity gaps**

  A. Mueller & W.-K. Tang (1992)

  B. Peschanski, C. Royon et al. (2007-09)

Summary – 1

γ*γ*- collisions at LEP2

NLL BFKL improved by BFKLP (generalized BLM) with LO impact factors (2001-02):

Indication on BFKL evolution

Outlooks:

- Full NLL BFKL γ*γ*- collisions calculations
- γ*γ*- collisions at LHC(?)
- Future linear colliders

Summary - 2:

- **Forward dijet "K-factor" by CMS at 7 TeV :**
  moderate rise with increasing $|\Delta y|$

- however: pure GLAPD -> const?
Indication on BFKL evolution at LHC

- **Azimuthal angle decorrelations (AAD) of CMS dijets:**

- agreement with NLL BFKL improved by BFKLP (generalized BLM)
- partial agreement with GLAPD generators (Pythia, Herwig)
Indication on BFKL evolution at LHC

Other observables:

- dijet "K-factor" with extra jet veto, number of extra jets, …
- dijets with rapidity gaps, … ?

Upcoming LHC Run 2 data at 13 TeV ?!