Search for asymptotic QCD effects at colliders

Victor Kim

Petersburg Nuclear Physics Institute NRC KI, Gatchina
St. Petersburg Polytechnic University

Outline:

- Motivation: high energy asymptotics of pQCD
- BFKLP: NLL BFKL within generalized BLM
- γ*γ*- collisions at LEP2
- Dijets from pQCD dynamics: GLAPD vs. BFKL
- Forward dijets at LHC: dijet "K-factor" vs |y|
- Forward dijets at LHC: azimuthal decorrelations vs |y|
- Summary

High energy asymptotics

- Large-angle scattering:

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)

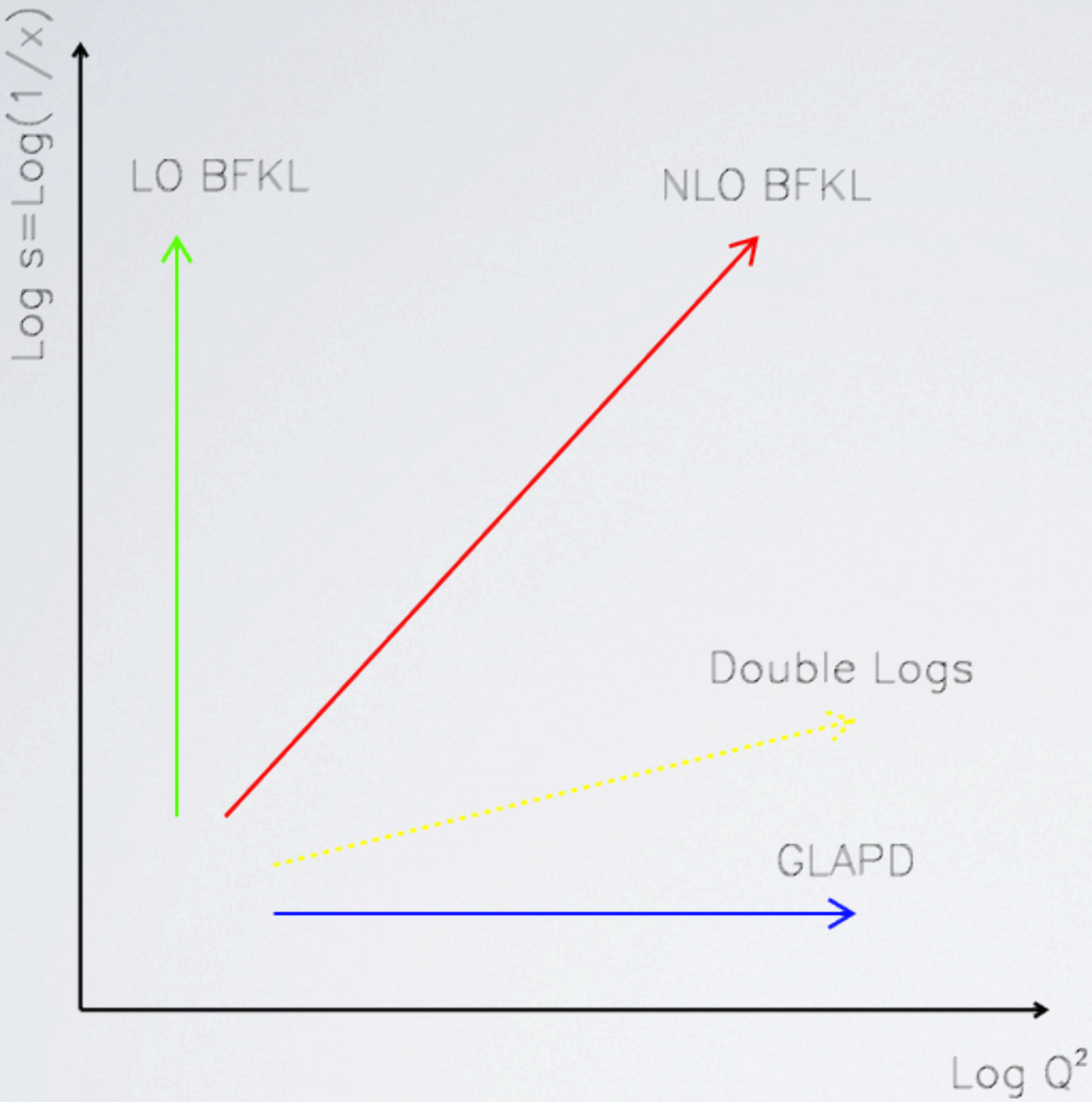
High-energy asymptotics of pQCD: GLAPD and BFKL

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

Bjorken limit (large-angle scattering):
$s \sim Q^2 >> m^2$
$Q^2/s = x \sim 1$
Gribov-Lipatov-Altarelli-Parisi-Dokshitzer (GLAPD) <–> 1-scale RG:
$(a_s \log(Q^2))^n$ 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: $a_P = 1.1$

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

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:

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

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.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 generalized for non-Abelian
(Brodsky, Lepage & Mackenzie - 83) BLM approach

NLL BFKL: standard 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

BLM in high orders: S. Mikhailov & A. Kataev (2015),
PMC - S. Brodsky et al. (2012-15)

Naïve BLM application at NLO does not work (!):
- NLL BFKL in MSbar scheme
- Upsilon ->ggg decay in NLO in Msbar scheme

MSbar-renormalization scheme: nonphysical RG scheme (!)
S.Brodsky, Rathmann et al (1997)

BFKLP: NLL BFKL within generalized BLM - 1

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 (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

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

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

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

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

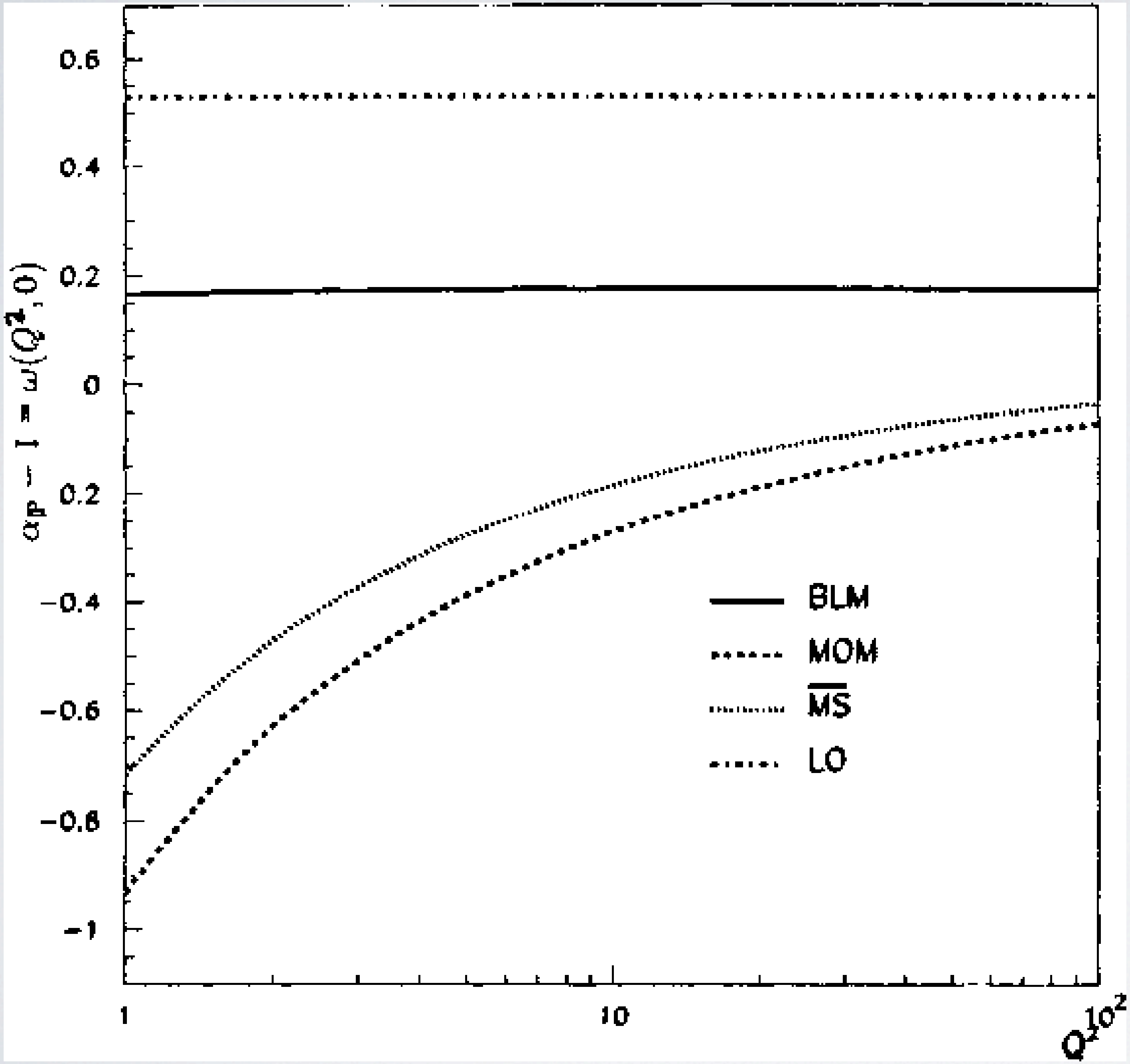
$$r_{\overline{MS}}(\nu) = r^{\beta}_{\overline{MS}}(\nu) + r^{\mathrm{conf}}_{\overline{MS}}(\nu)$$

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

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

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

BFKLP: NLL BFKL within generalized BLM - 3



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

BFKLP: NLL BFKL within generalized BLM - 4

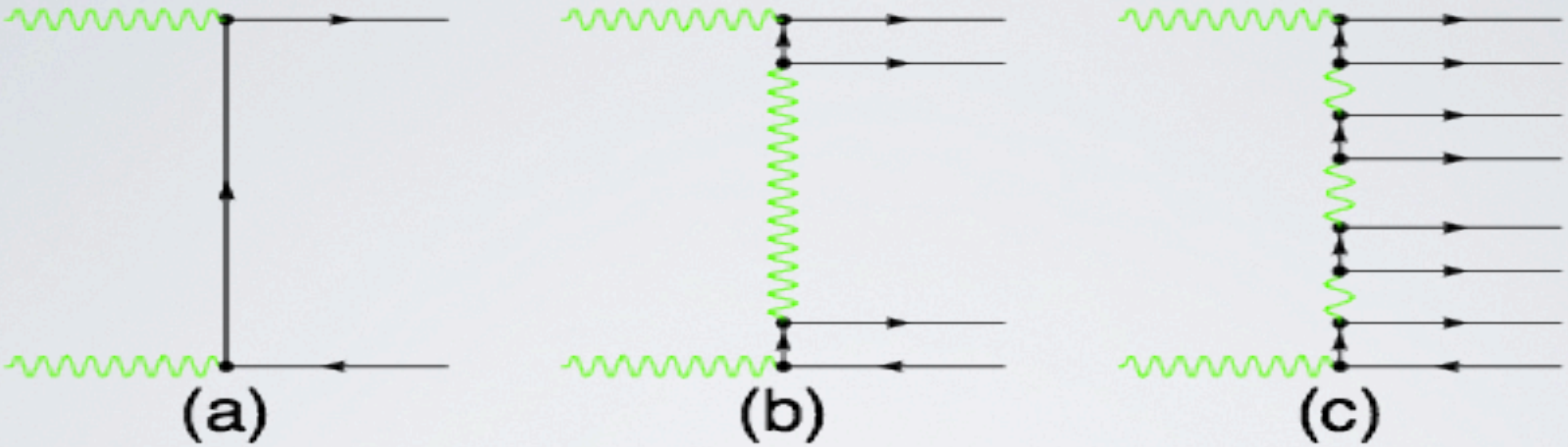
V.S. Fadin & L.N. Lipatov (89-98)
C.Camici & M. Ciafaloni (96-98)
next-to-leading log approximation (NLL) BFKL
MSbar-renormalization scheme: large corrections

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: $\sigma_0 \, (S/S_0)^{(a_P-1)}$ $\quad a_P = 1 + C\, a_S$

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



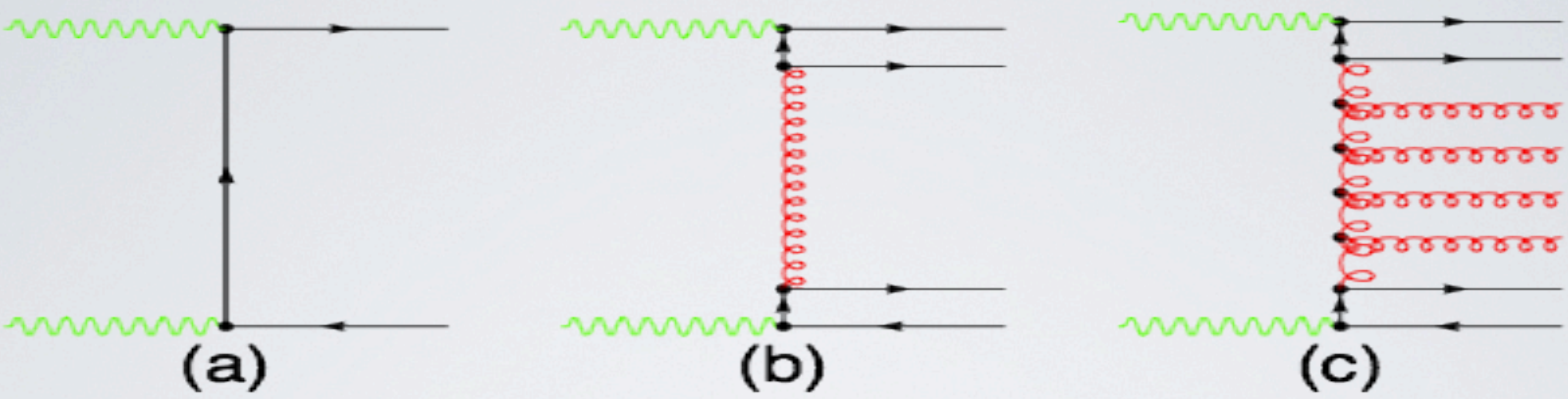
$\sigma \sim (a_{QED})^2 \log(s)/s$ $\sigma \sim (a_{QED})^4 \,\mathrm{const}(s)$

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

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

Asymptotics of QCD cross sections: γγ



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

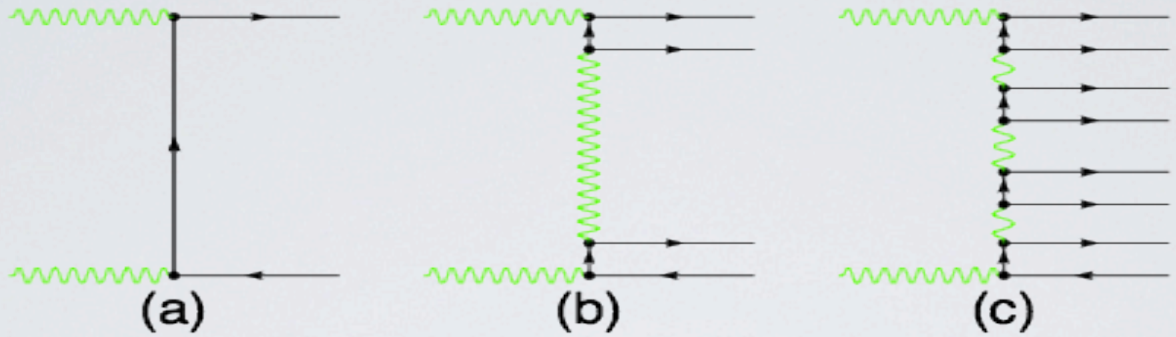
All orders: LL BFKL

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

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

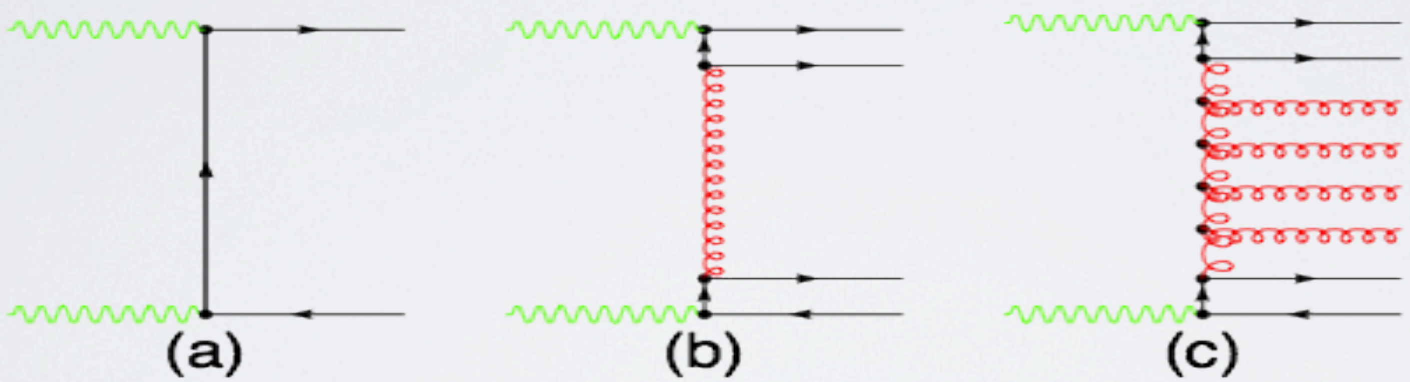
$a_P = 1 + C\,(a_S) \approx 1.2$ **NLL BFKL** S.Brodsky, V Fadin, VK, L. Lipatov, G. Pivovarov (2001-02)

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

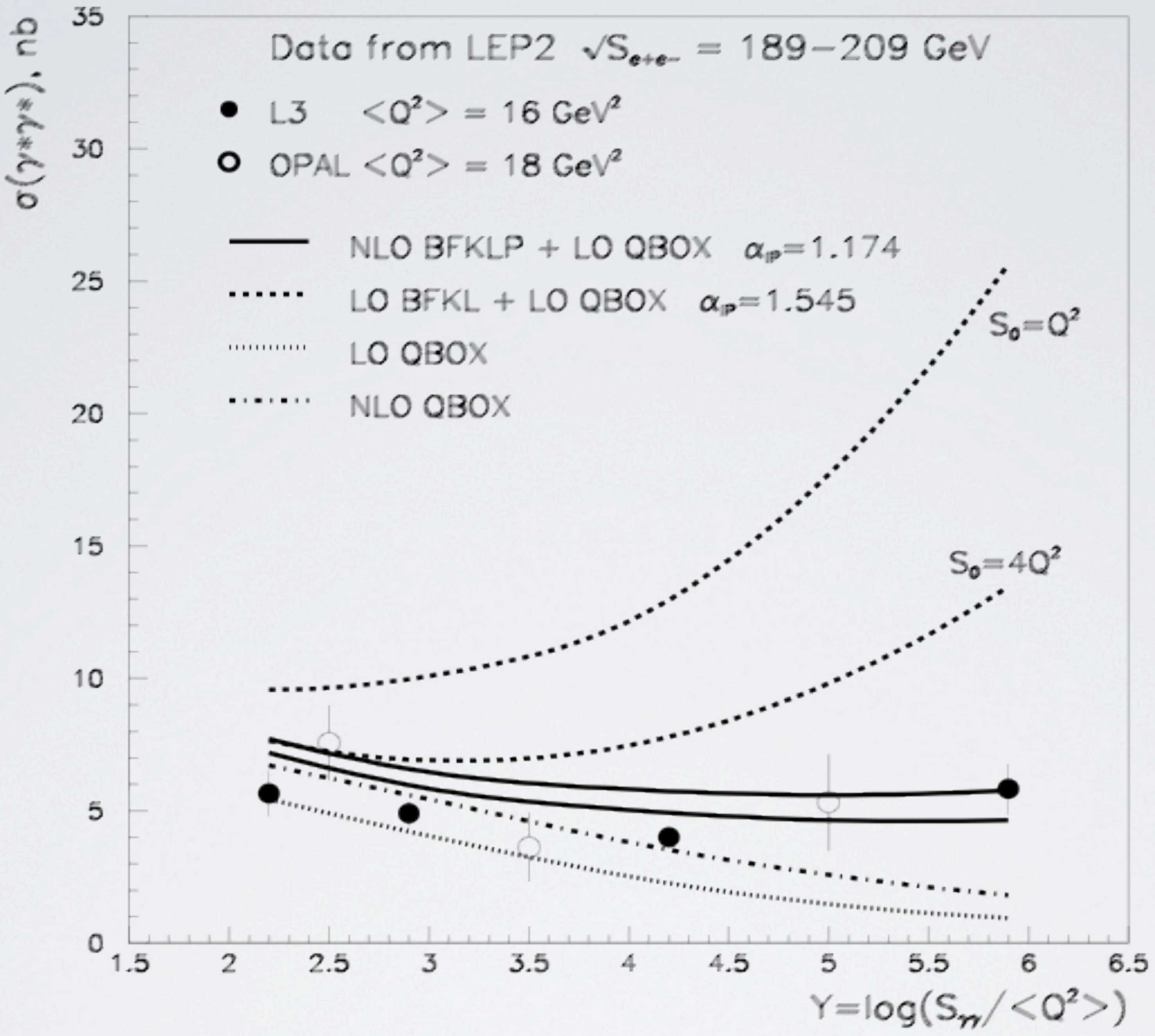


LL BFKL
J. Bartels et al (96), S.J. Brodsky & Hautmann (97)

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

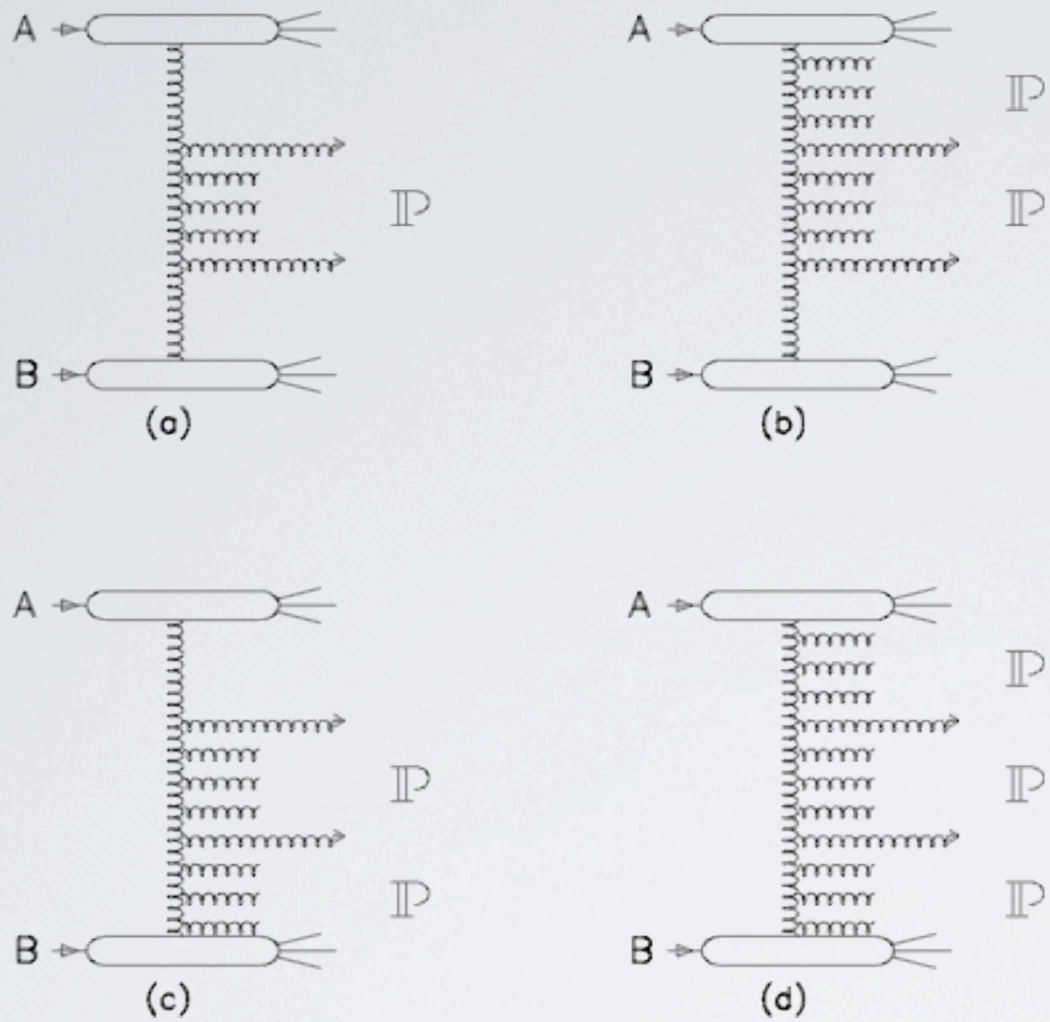


S.J Brodsky, VK, L.N. Lipatov, V.S. Fadin & G.B. Pivovarov (2002)

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

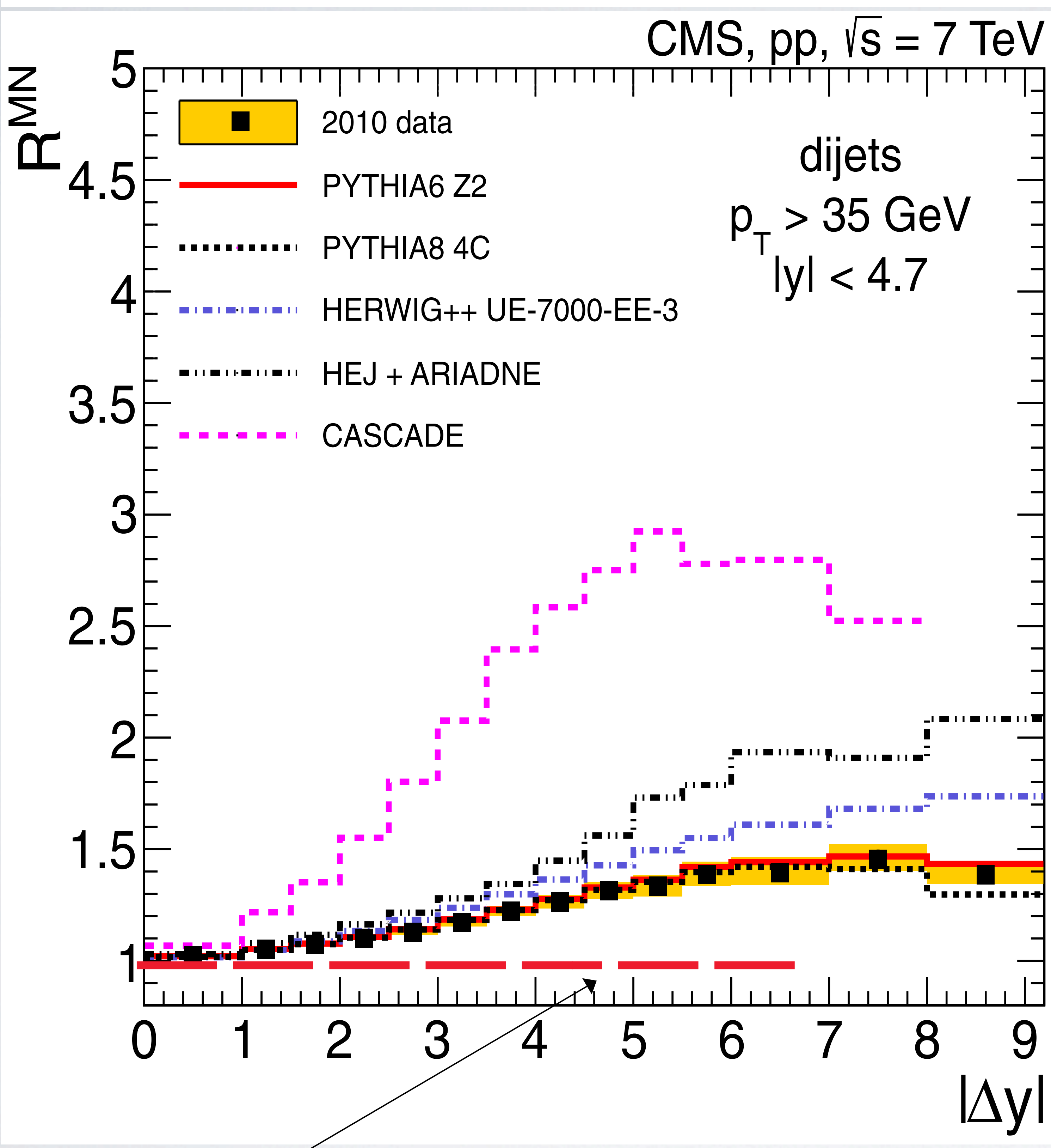
Forward dijets at Tevatron and LHC

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"



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

GLAPD (no AO and CC)

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)

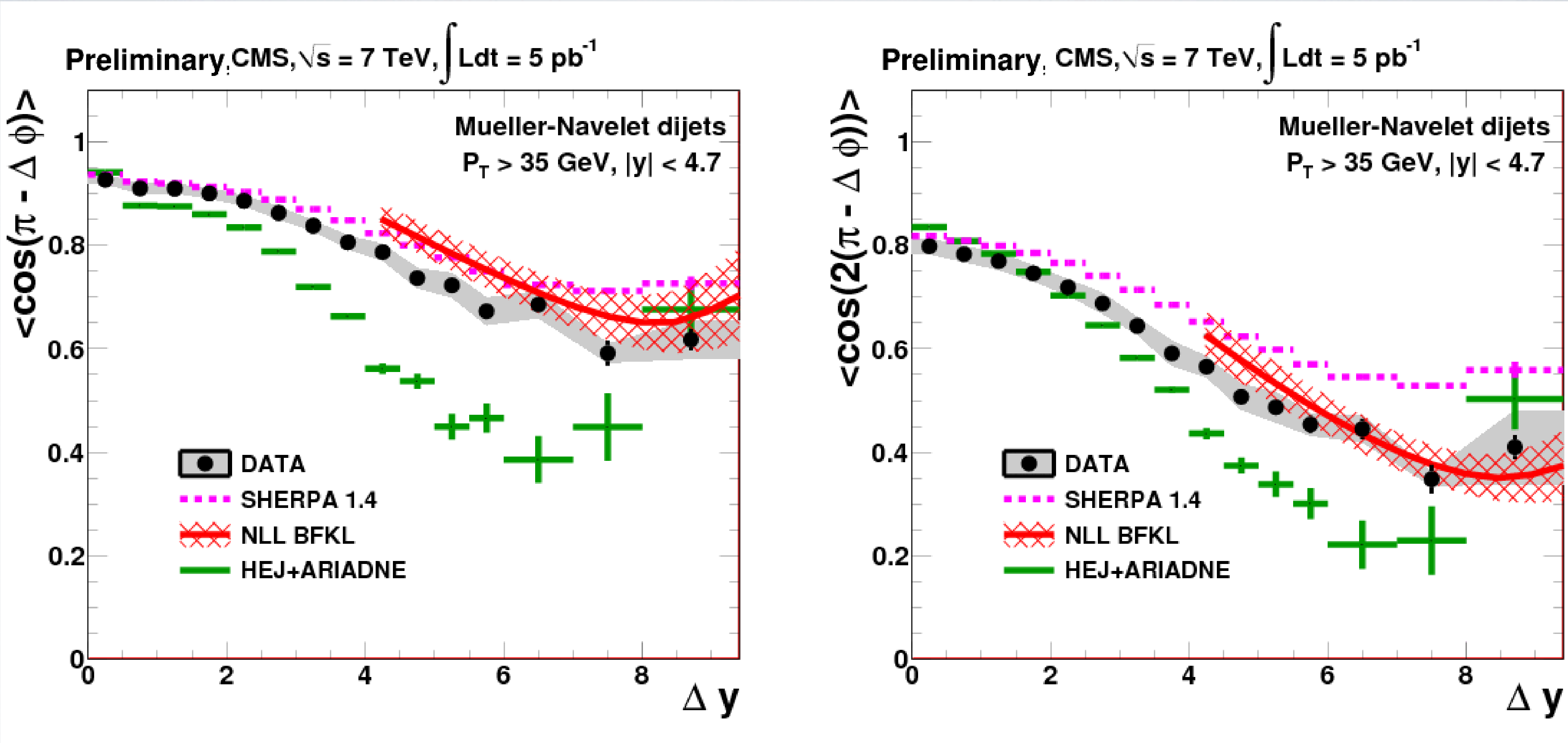
Forward dijets: azimuthal decorrelations

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

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

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

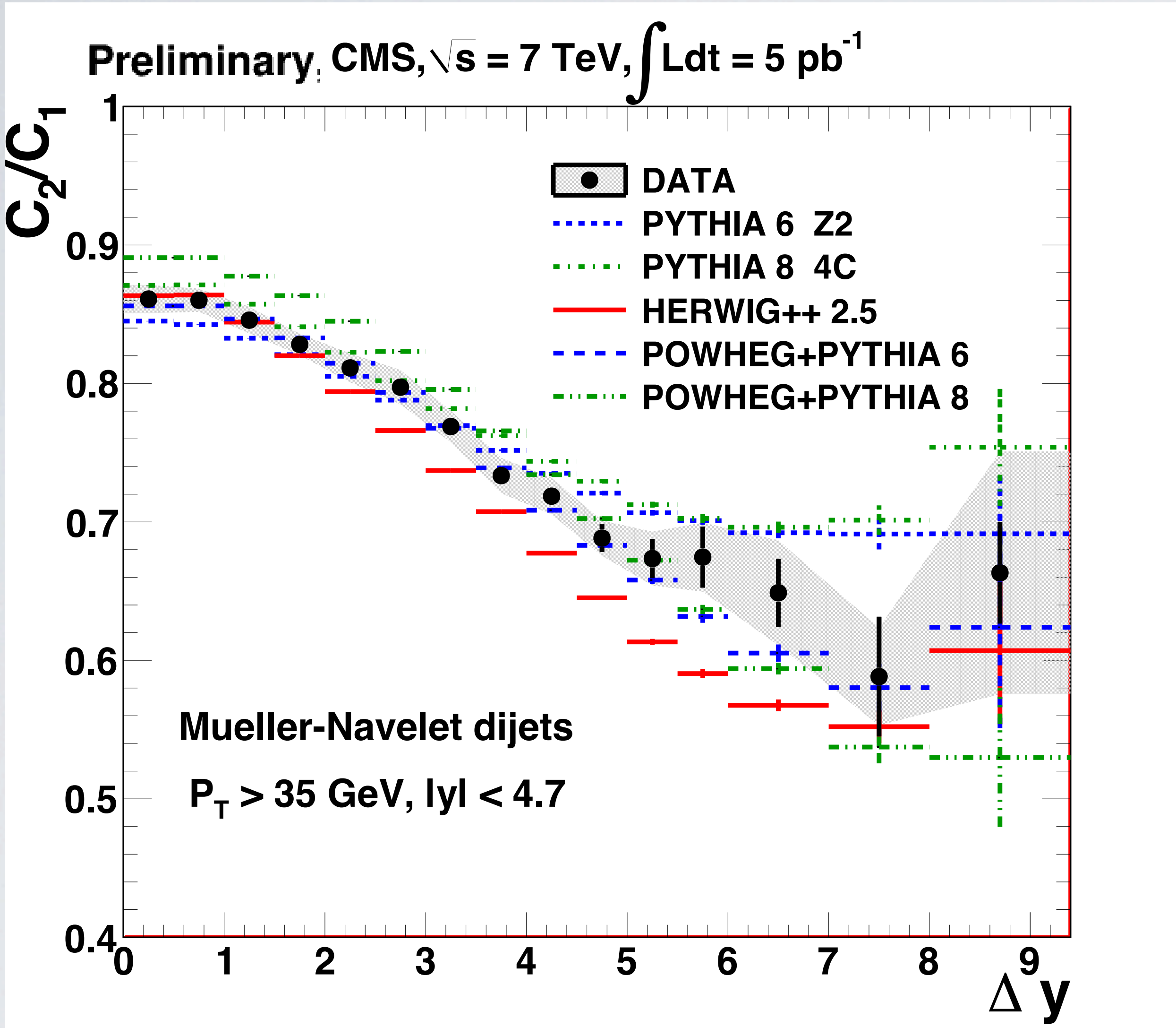
Dijets: <cos> vs NLL BFKL+BFKLP

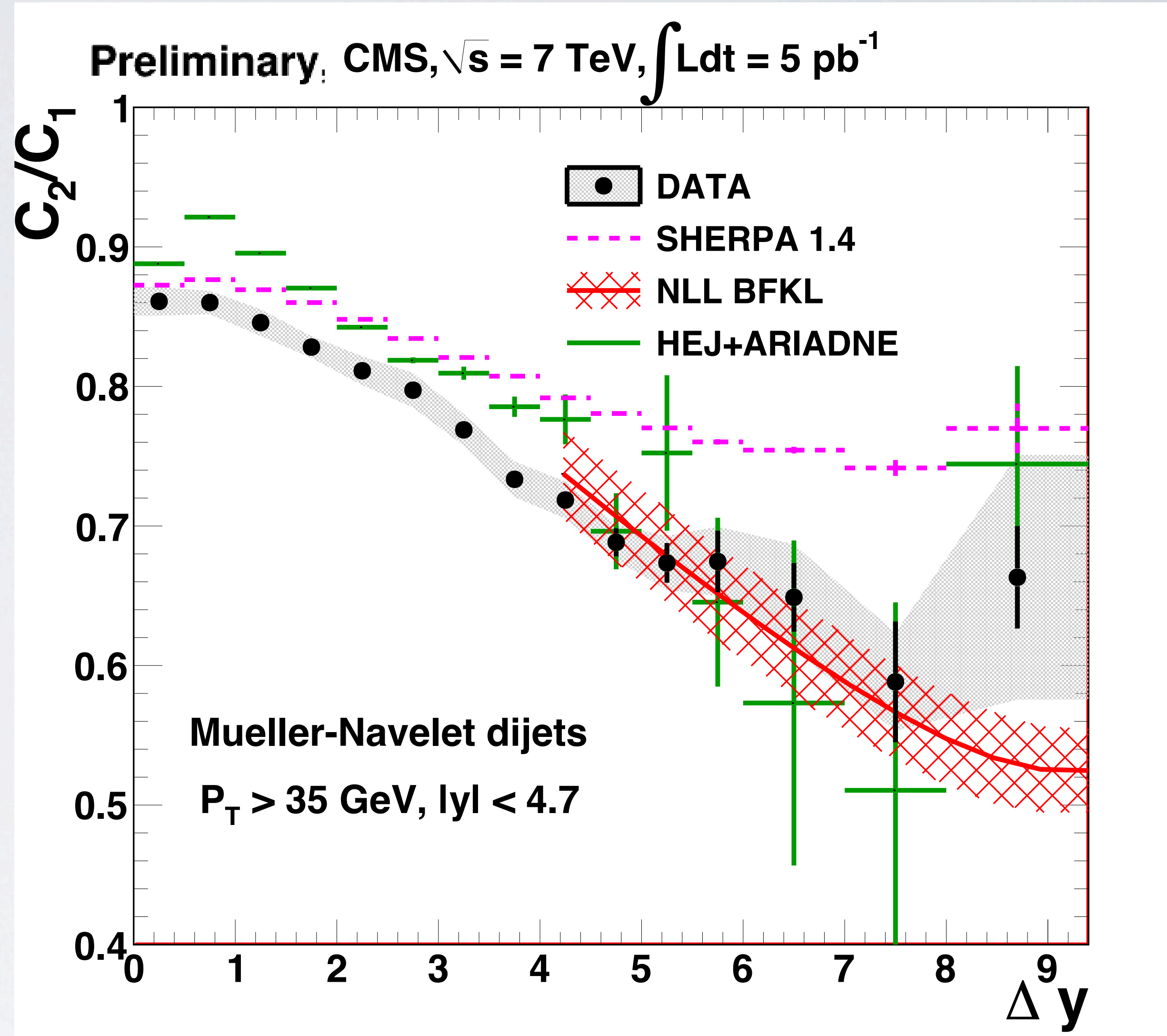


CMS: <cos> and <cos2>
JHEP 08 (2016) 139
7 TeV, pT_min = 35 GeV
Δy = | | < 9.4

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

$\gamma^*\gamma^*$- collisions at LEP2

NLL BFKL improved by BFKLP (generalized BLM) (2001-02):

Indication on BFKL evolution

Outlooks: Future linear colliders

Summary - 2:

- **Forward dijet "K-factor" by CMS at 7 TeV :**
  moderate rise with increasing |Δy|
  - Pythia describes the rise, Herwig overshoots the rise
  - however: pure GLAPD -> const ? Indication on BFKL evolution

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

- agreement with NLL BFKL improved by BFKLP (generalized BLM)
- GLAPD generators (Pythia, Herwig) describes AAD differently because different color coherence (CC) implementations Indication on BFKL evolution

-> The first indication on BFKL at LHC Run I?
Issues: No pure LL GLAPD predictions
(now only LL GLAPD with color coherence, angle ordering, ...)

Other observables:
- dijet "K-factor" with extra jet veto, number of extra jets, ...
- dijets with rapidity gaps, ... ?

LHC Run 2 at 13 TeV ?!