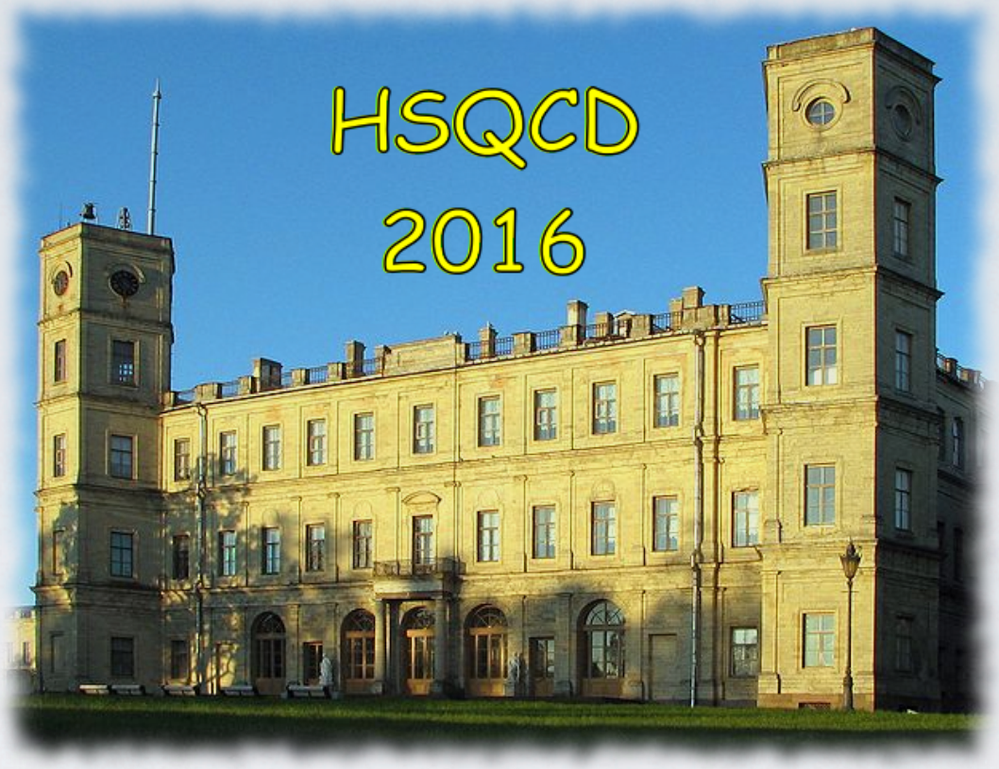

Manifestations of BFKL-evolution effects at collider energies

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St. Petersburg Polytechnic University

Outline:

- Motivation: high energy asymptotics
- BFKLP: NLA BFKL within generalized BLM
- γ*γ*- collisions
- Dijets from QCD 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)**

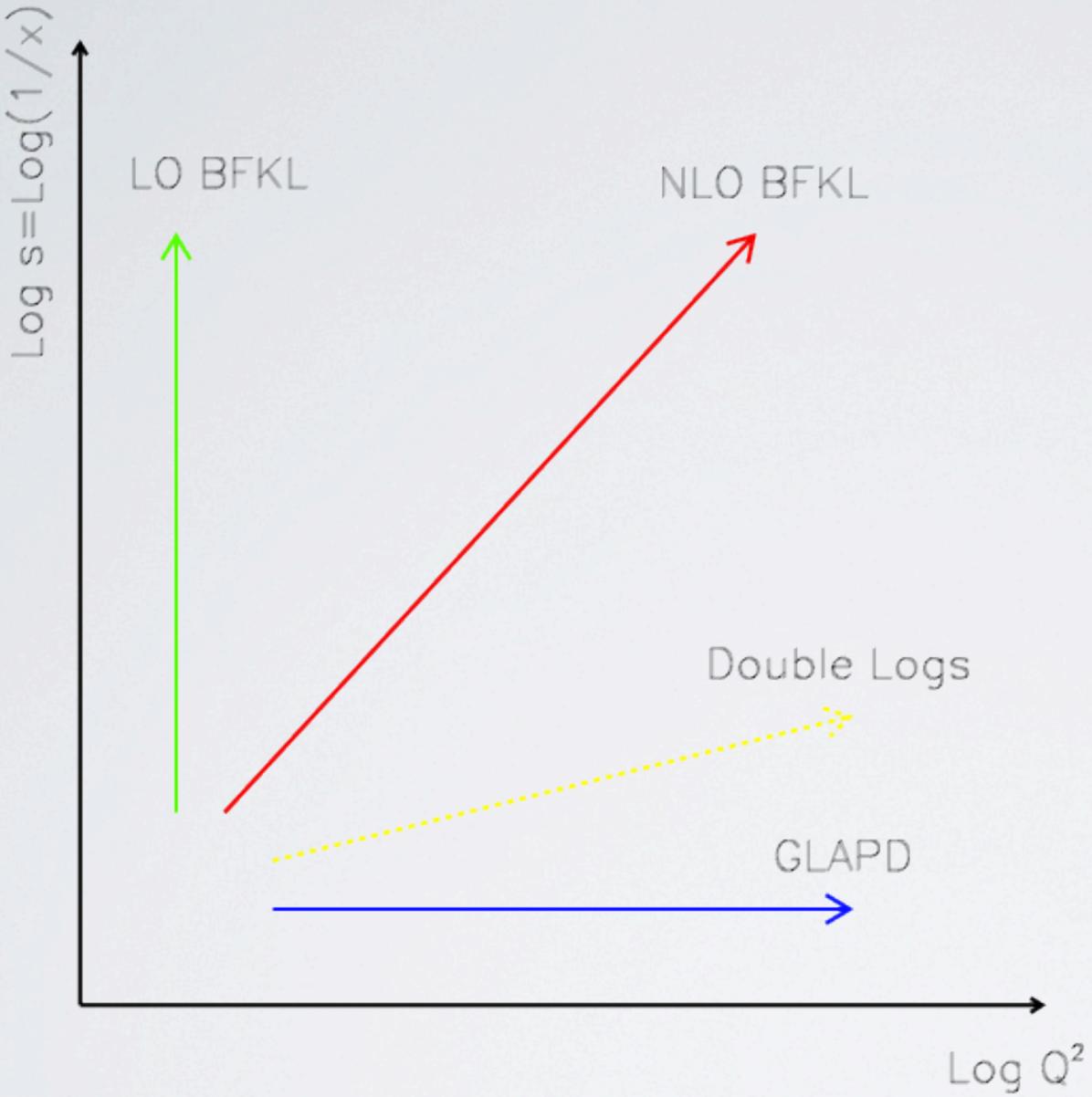
High-energy QCD asymptotics: GLAPD and BFKL

$s=(p_1+p_2)^2$
$t=(p_1-p_3)^2$ $\quad Q^2=-t$
Scattering in the Standard Model (QCD) at high energies:
Large logarithms: as log(s), as 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):
(as 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):
(as log(s))^n resummation
Total cross section ~ $s^{(a_P-1)}$
a_P – Pomeron intercept **soft scattering data: $a_P = 1.1$**

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

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

(Brodsky, Lepage & Mackenzie - 83) BLM approach

NLL BFKL: 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 wihinn generalized BLM

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

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

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

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

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

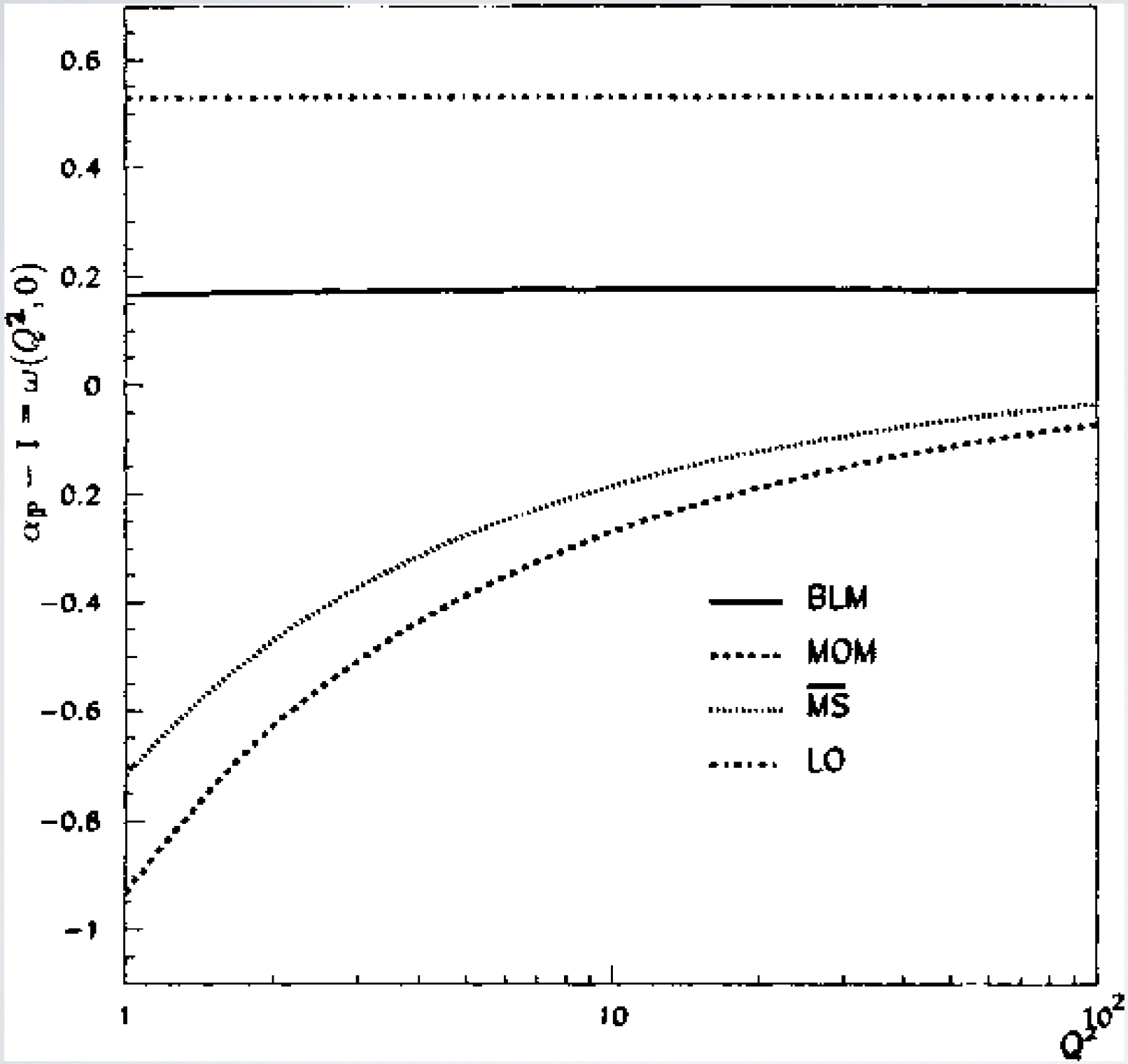
$$r_{\overline{MS}}(\nu)=r^{\beta}_{\overline{MS}}(\nu)+r^{\rm conf}_{\overline{MS}}(\nu)$$

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

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

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

BFKLP: NLL BFKL within generalized BLM



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

BFKLP: NLL BFKL within generalized BLM

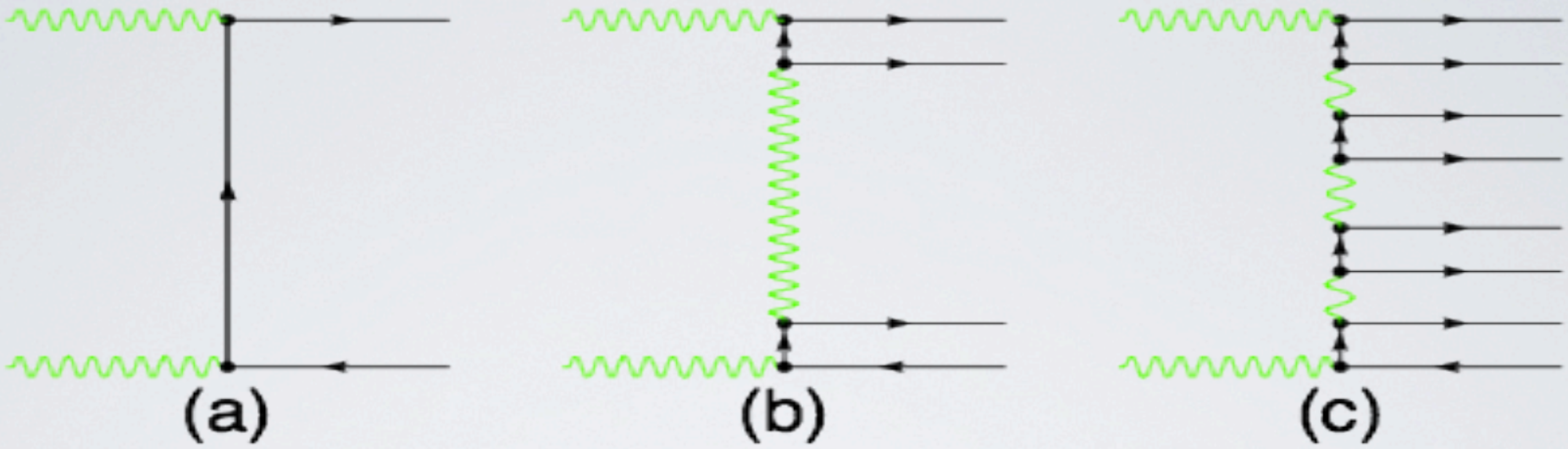
V.S. Fadin & L.N. Lipatov (89-98)
C.Camici & M. Ciafaloni (96-98)
next-to-leading log approximation (NLL) BFKL
MSbar-renormalization scheme: large corrections

S.J. Brodsky, V.S. Fadin, VK, L.N. Lipatov, G.B. Pivovarov(98-99) BFKLP
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: $\sigma_0 (S/S_0)^{(aP-1)}$ $a_P = 1 + C\, a_s$

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



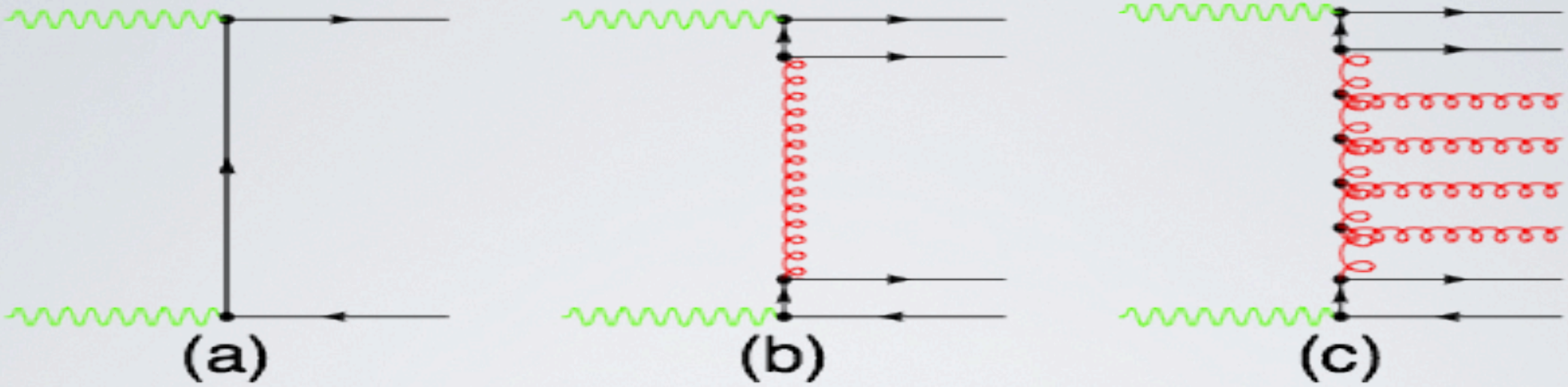
$\sigma \sim (a_{QED})^2 \log(s)/s \quad \sigma \sim (a_{QED})^4 \text{ const}(s)$

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

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

Asymptotics of QCD cross sections: γγ



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

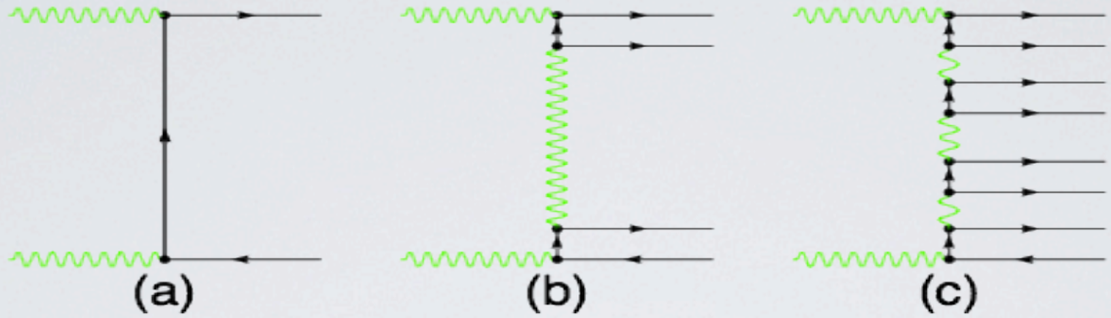
All orders: LL BFKL

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)**

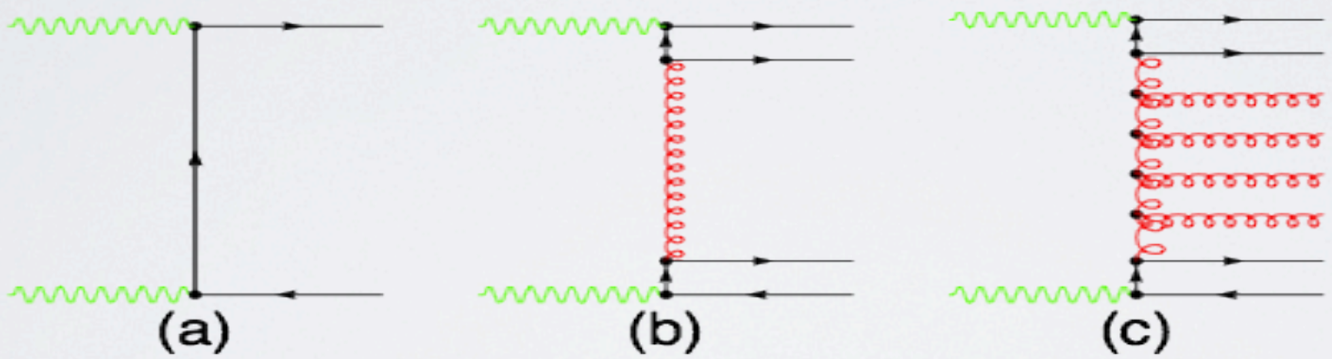
$a_P = 1 + C (a_S) \approx 1.2$ **NLL BFKL S.Brodsky, V Fadin, VK, L. Lipatov, G. Pivovarov (2001-02)**

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

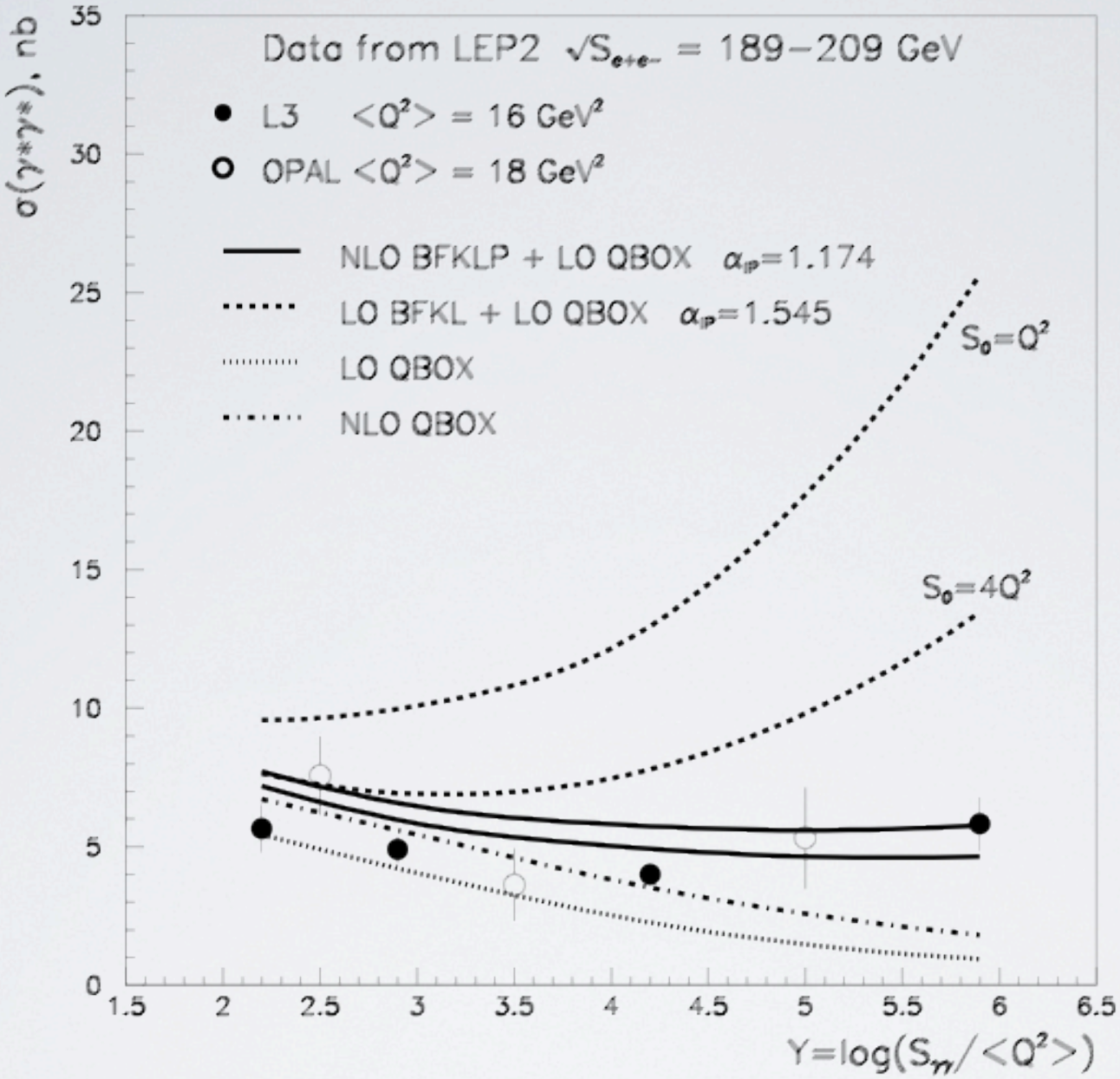


LL BFKL
J. Bartels et al (96), S.J. Brodsky & Hautmann (97)

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:
I. Balitsky, J.Chirilli, J. Bartels et al.

Highly virtual photon scattering at LEP-2

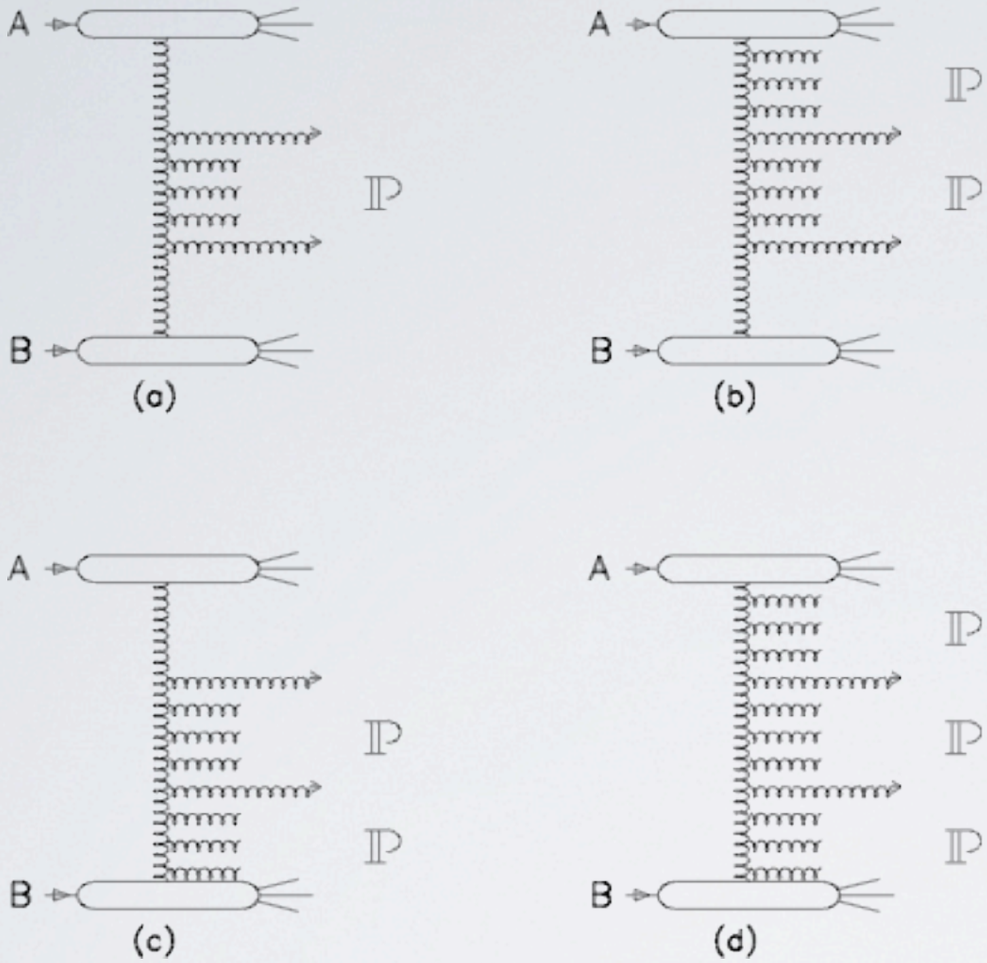


S.J Brodsky, VK, L.N. Lipatov, V.S. Fadin & G.B. Pivovarov (2002)

BFKLP: NLL BFKL + generalized BLM

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

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

GLAPD: x-section → $C_1 \alpha_s^2 + C_2 \alpha_s^3 + \ldots$
Born x-section → $C_1 \alpha_s^2$

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

Mueller-Navelet (87):

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

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

$\Delta y = |y_1 - y_2|$

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

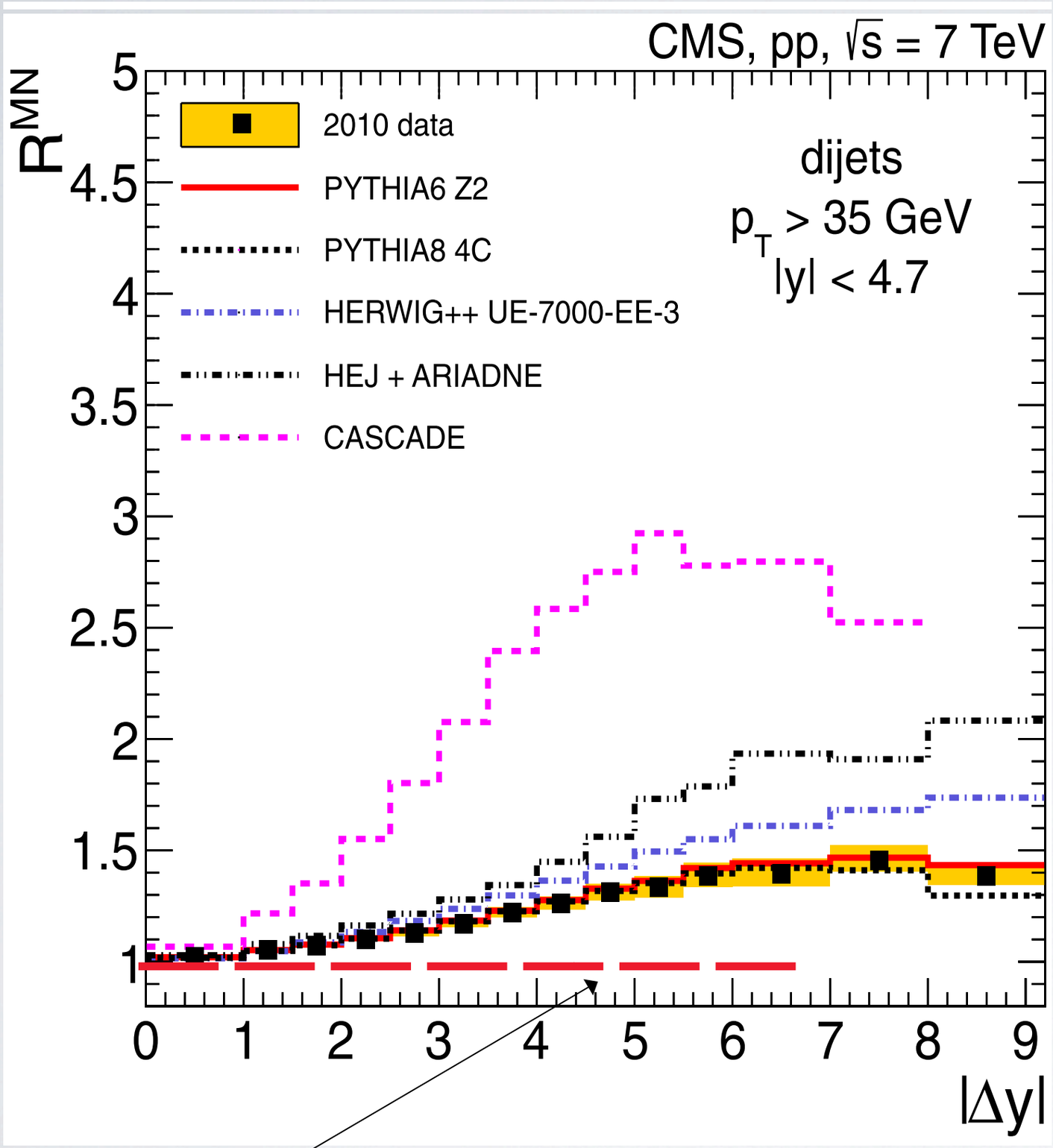
Forward dijets at Tevatron and LHC

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

LHC: ATLAS -> $|\Delta y| < 6$ $70 \text{ GeV} < p_T < 90 \text{ GeV}$
- (inverse) “K-factor” (2011)

LHC: CMS -> $|\Delta y| < 9.4$ $p_{Tmin} = 35$ GeV
- “K-factor” (2012)
- azimuthal angle decorr. (prel. 2013, LHCP2015)

CMS: dijet “K-factor”



GLAPD

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?
2) or BFKL effects cancels out in dijet ratio

in the latter case the "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)

Cosine ratios –> GLAPD cancellation

–> more sensitive to BFKL (!)

A. Sabio Vera et al (2011)

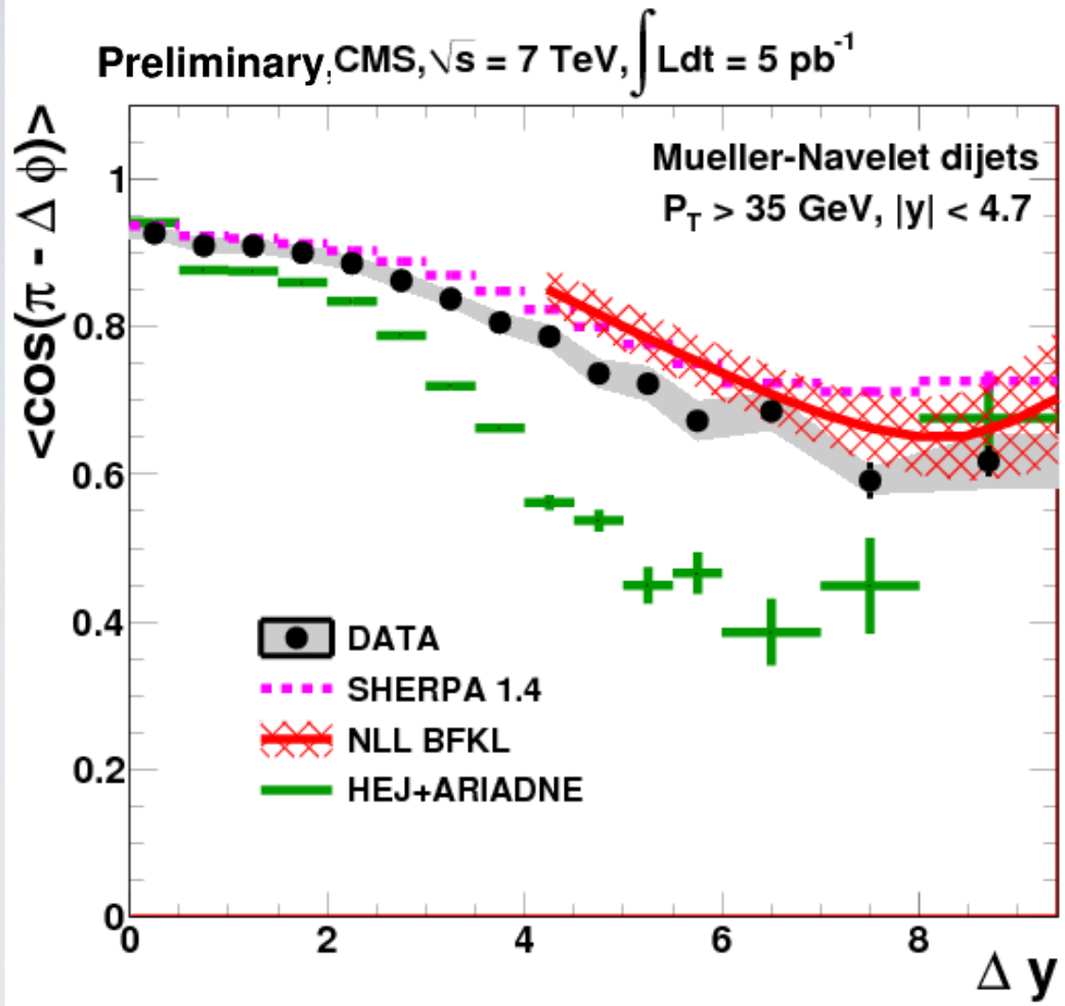
Forward dijets: azimuthal decorrelations

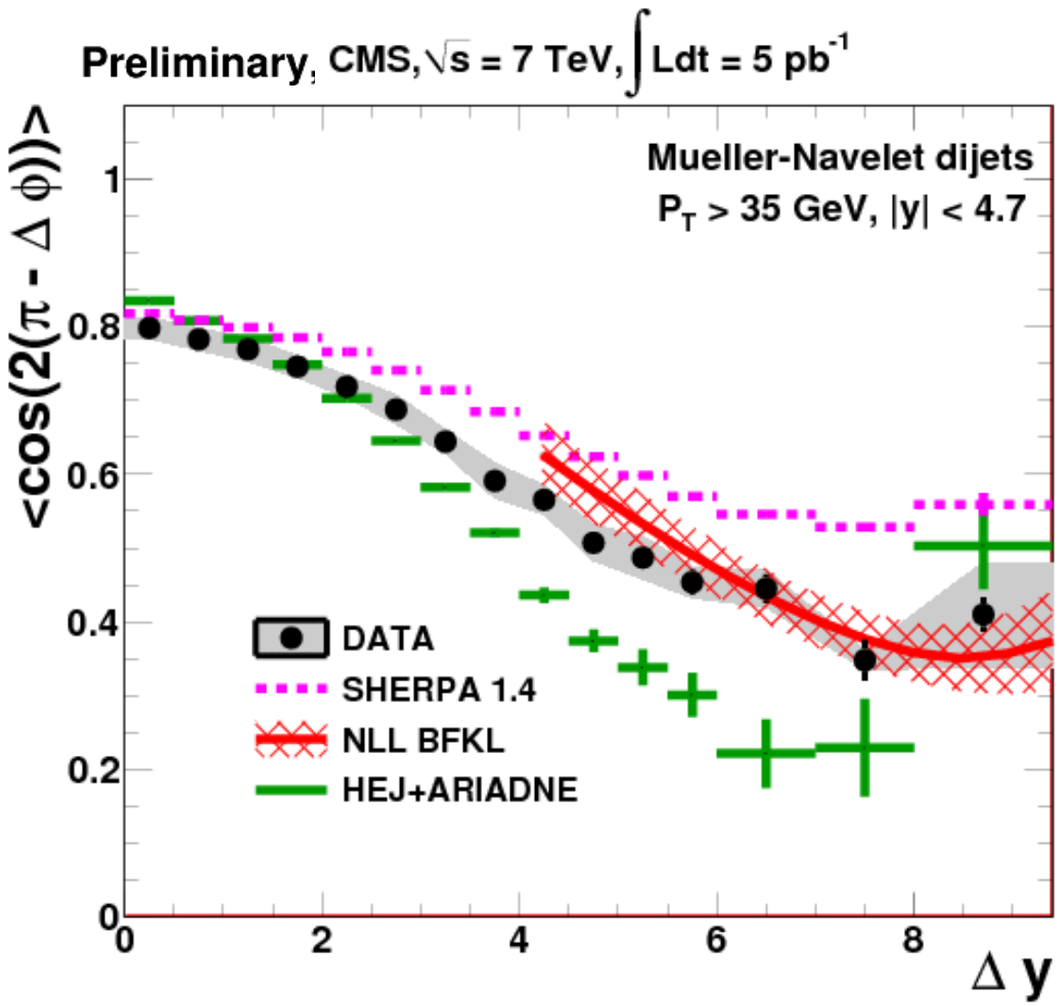
$$\frac{1}{\sigma}\frac{d\sigma}{d(\Delta\phi)}(\Delta y, p_{\mathrm{Tmin}}) = \frac{1}{2\pi}\left[1 + 2\sum_{n=1}^{\infty} C_n(\Delta y, p_{\mathrm{Tmin}}) \cdot cos(n(\pi - \Delta\phi))\right]$$

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

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

Dijets: <cos> vs NLL BFKL+BFKLP

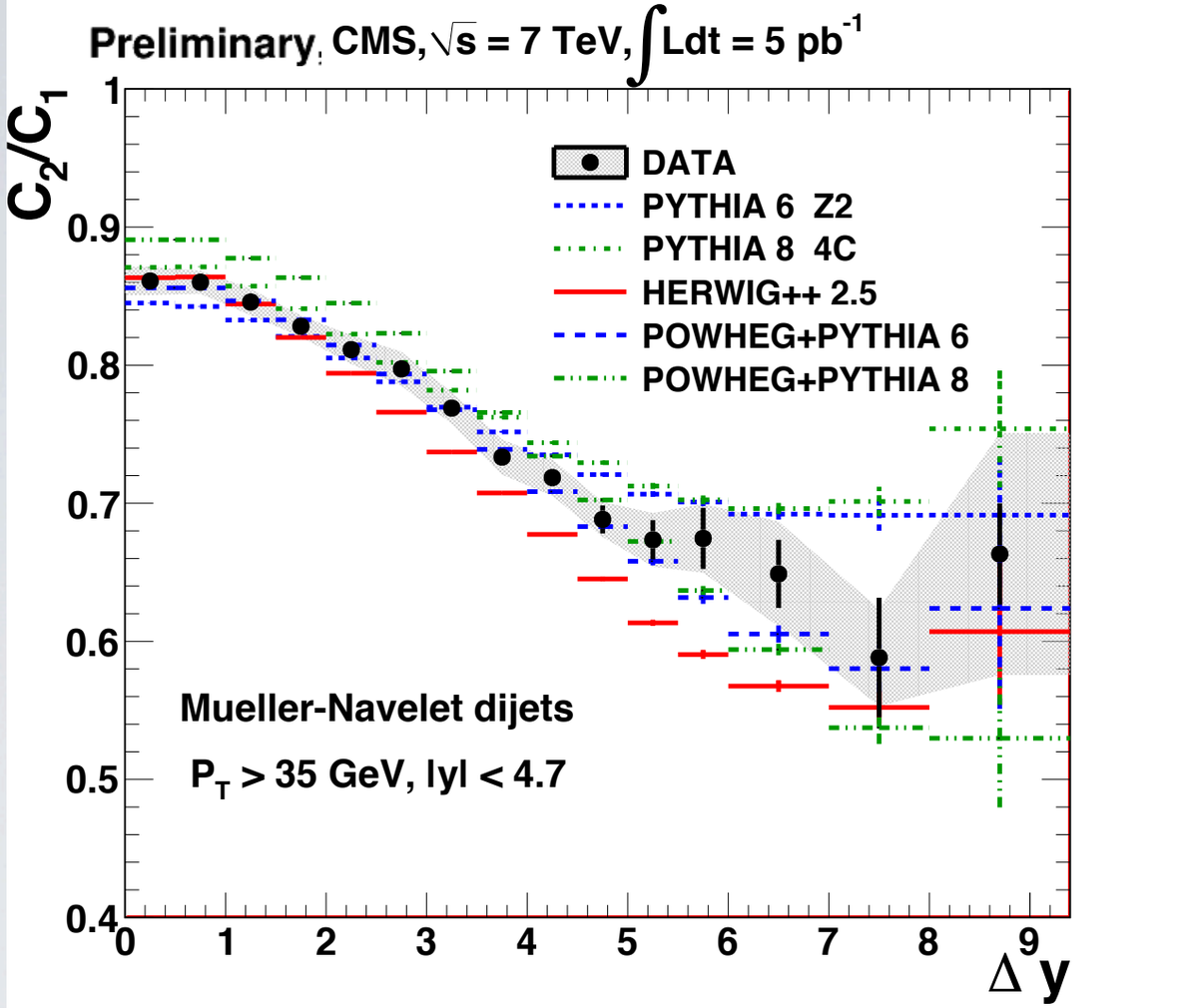


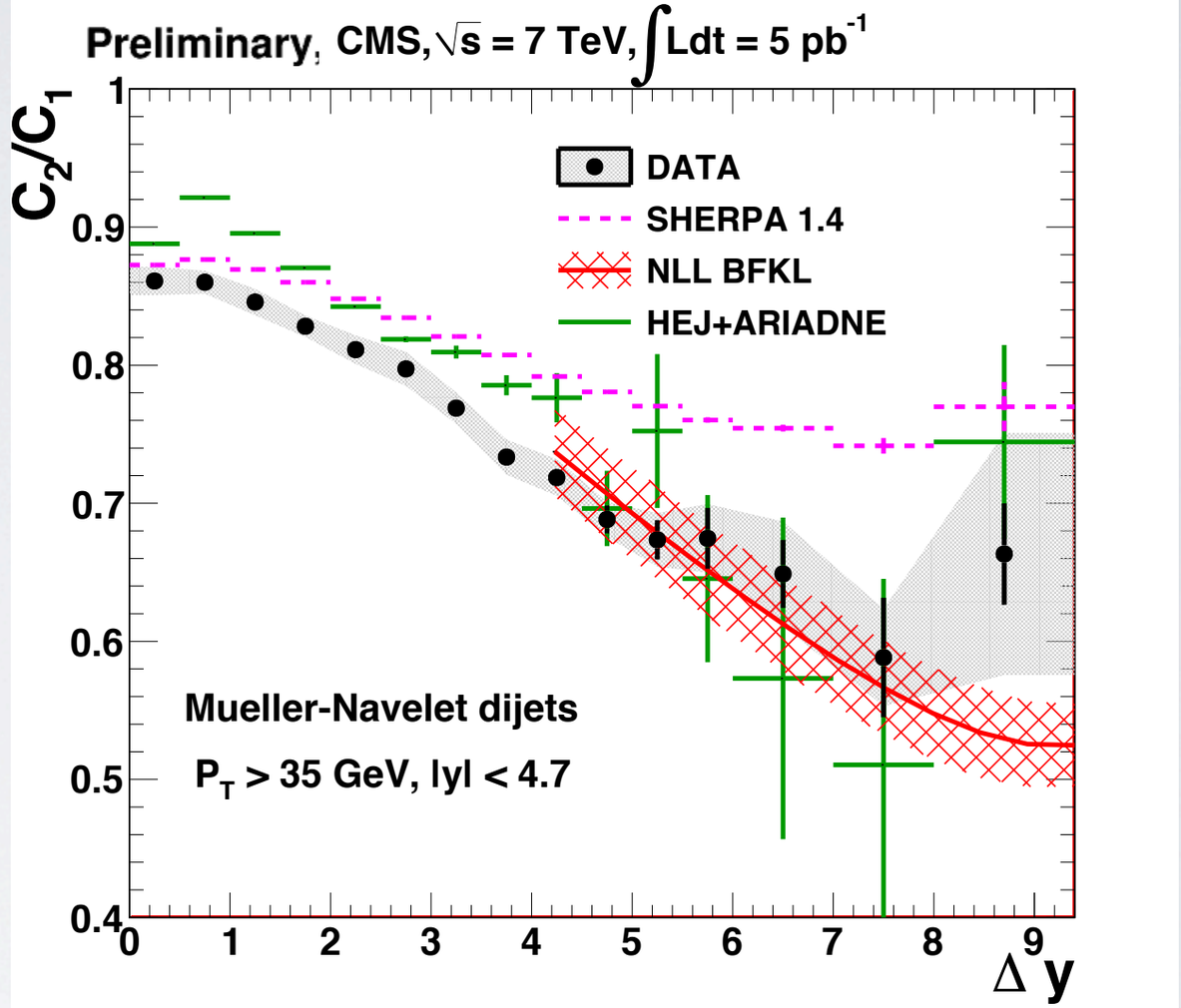


LHCP2015, St. Petersburg, Aug. 31- Sep. 5, 2015
CMS arXiv:1601.06713
7 TeV, pT_min = 35 GeV
Δy = | | < 9.4

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

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





LHCP2015, St. Petersburg, Aug. 31- Sep. 5, 2015
CMS arXiv:1601.06713
7 TeV, pT_min = 35 GeV
Δy < 9.4

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

Summary – 1

γ*γ*- 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 ?
Issues: No pure LL GLAPD predictions
(now only LL GLAPD with color coherence, angle ordering, ...)

Other observables:
- K-factor with extra jet veto, number of extra jets, ... ?
LHC Run 2 at 13 TeV ?!