Search for BFKL-evolution effects at high energies

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Outline:

- **Motivation: high energy asymptotics**
- **BFKLP: NLA BFKL within generalized BLM**
- **$\gamma^*\gamma^*$- 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)

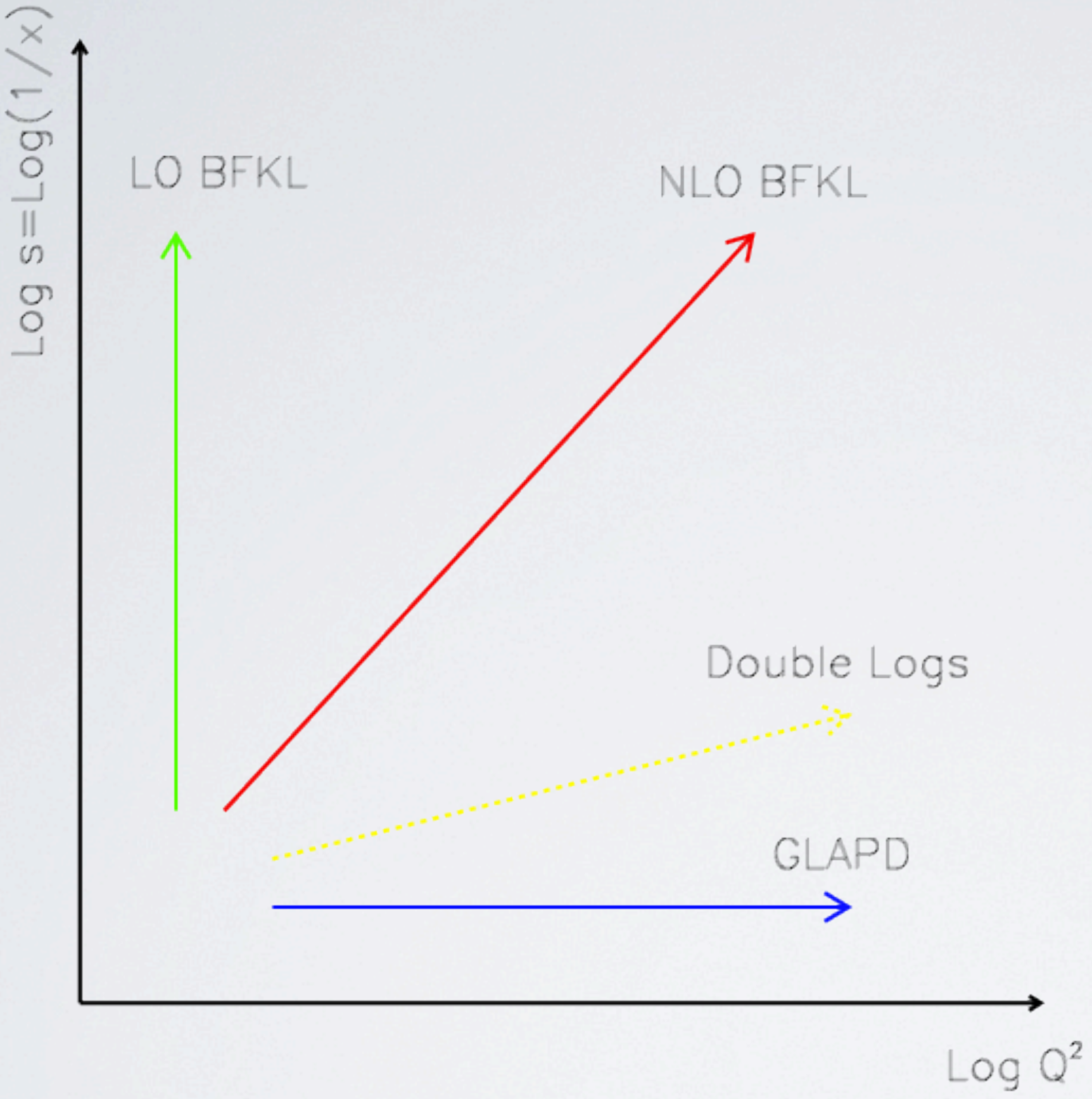
High-energy QCD asymptotics: GLAPD and BFKL

$s=(p_1+p_2)^2$
$t=(p_1-p_3)^2$ $Q^2=-t$
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:** $a_P = 1.1$

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):
$s>>Q^2 >> m^2$
$Q^2/s = x \rightarrow 0$
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:

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

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

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

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

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

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

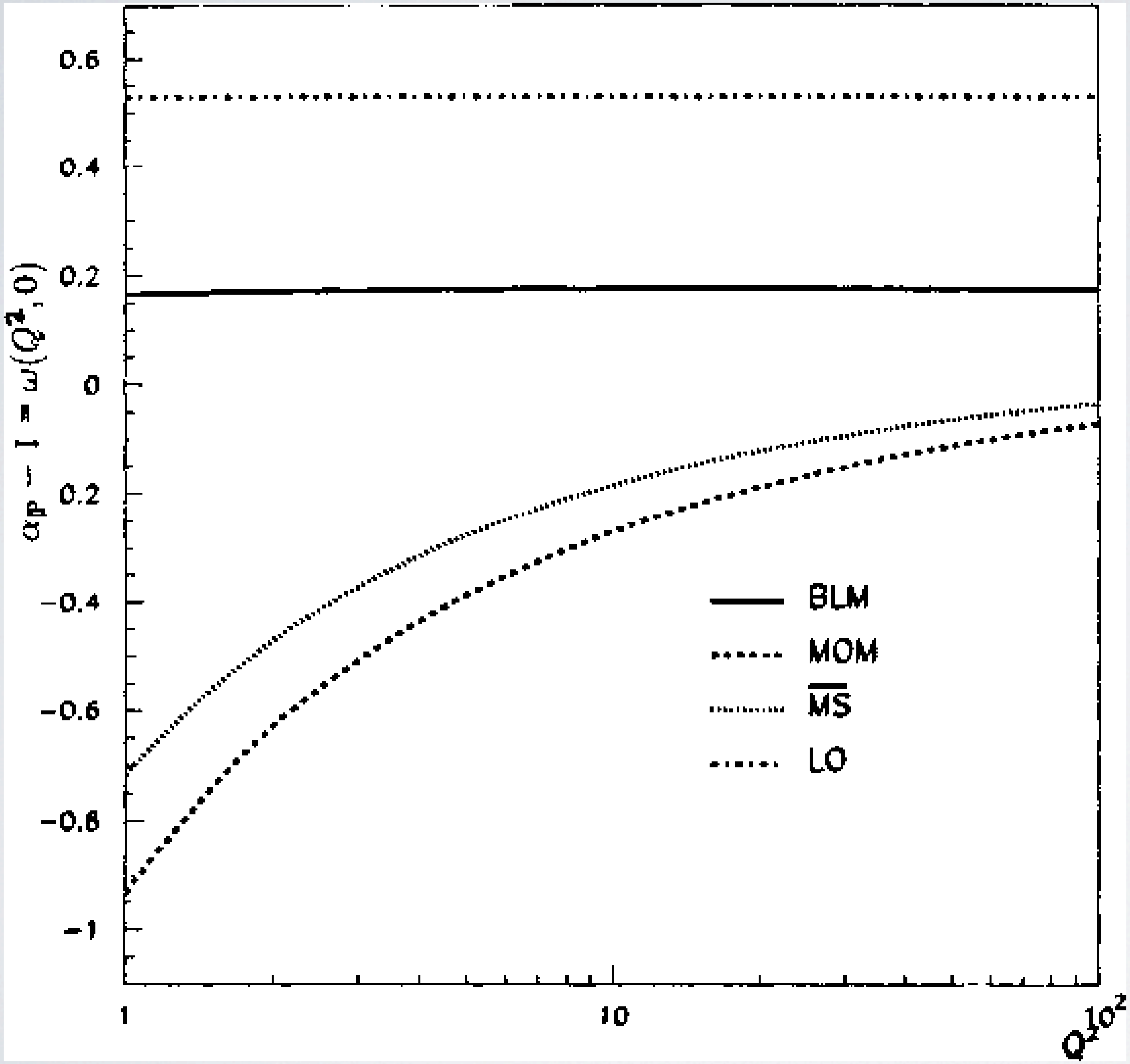
$$r_{\overline{MS}}(\nu) = r^{\beta}_{\overline{MS}}(\nu) + r^{\text{conf}}_{\overline{MS}}(\nu)$$

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

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

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

BFKLP: NLL BFKL within generalized BLM



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

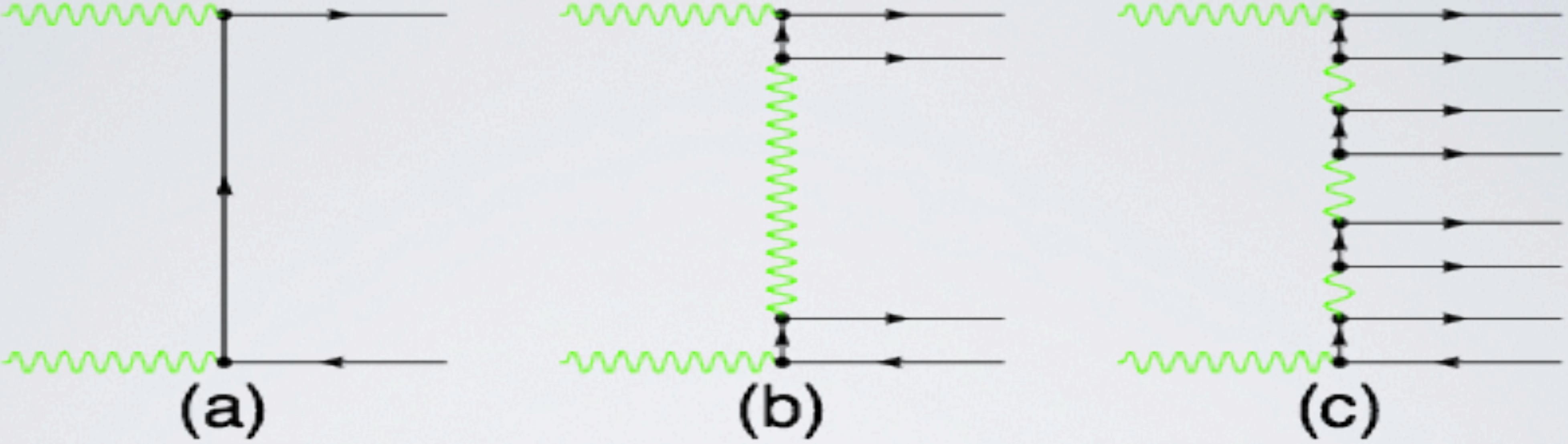
BFKLP: NLL BFKL within generalized BLM

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
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-conjecture

Asymptotics of QED cross sections



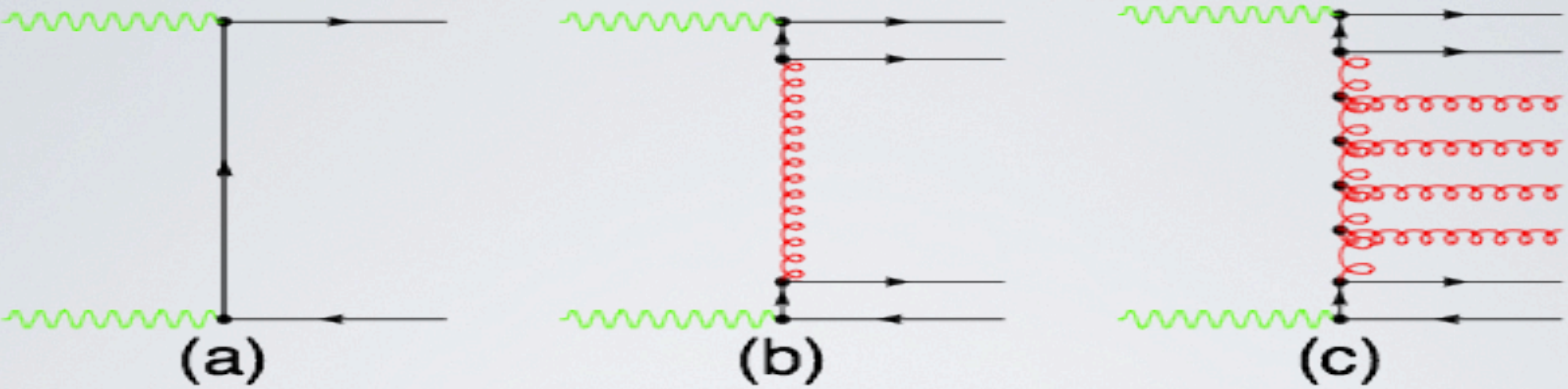
$\sigma \sim (a_{QED})^2 \log(s)/s$ $\sigma \sim (a_{QED})^4 \, \mathrm{const}(s)$

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

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

Asymptotics of QCD cross sections: γγ



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

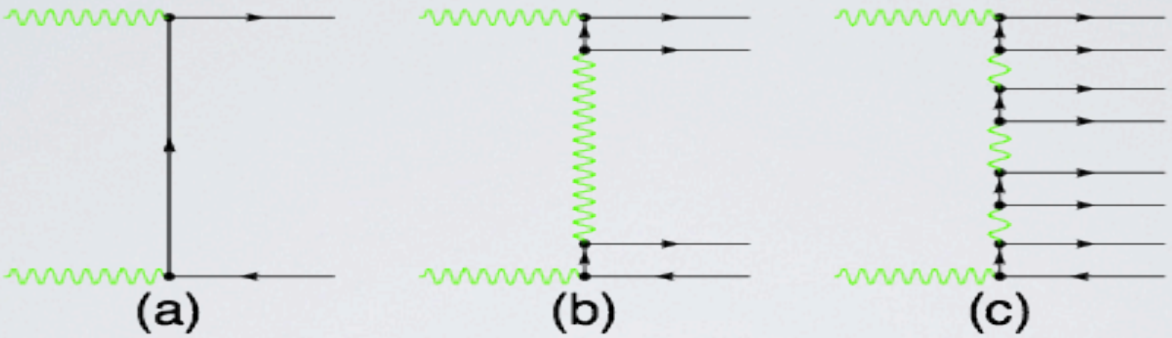
All orders: **LL BFKL**

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

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

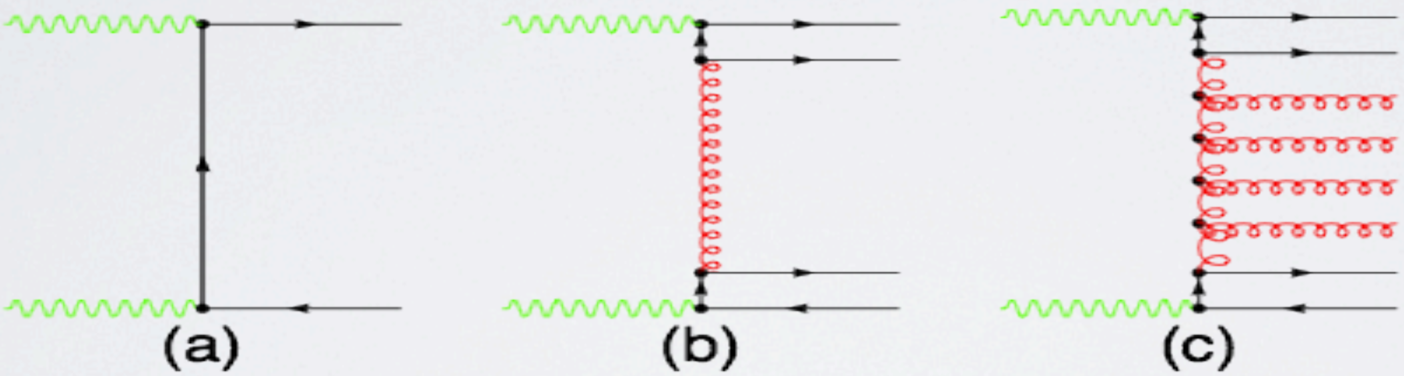
$a_P = 1 + C\,(a_S) \approx 1.2$ **NLL BFKL** **S.Brodsky, V Fadin, VK,**
L. Lipatov, G. Pivovarov (2001-02)

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

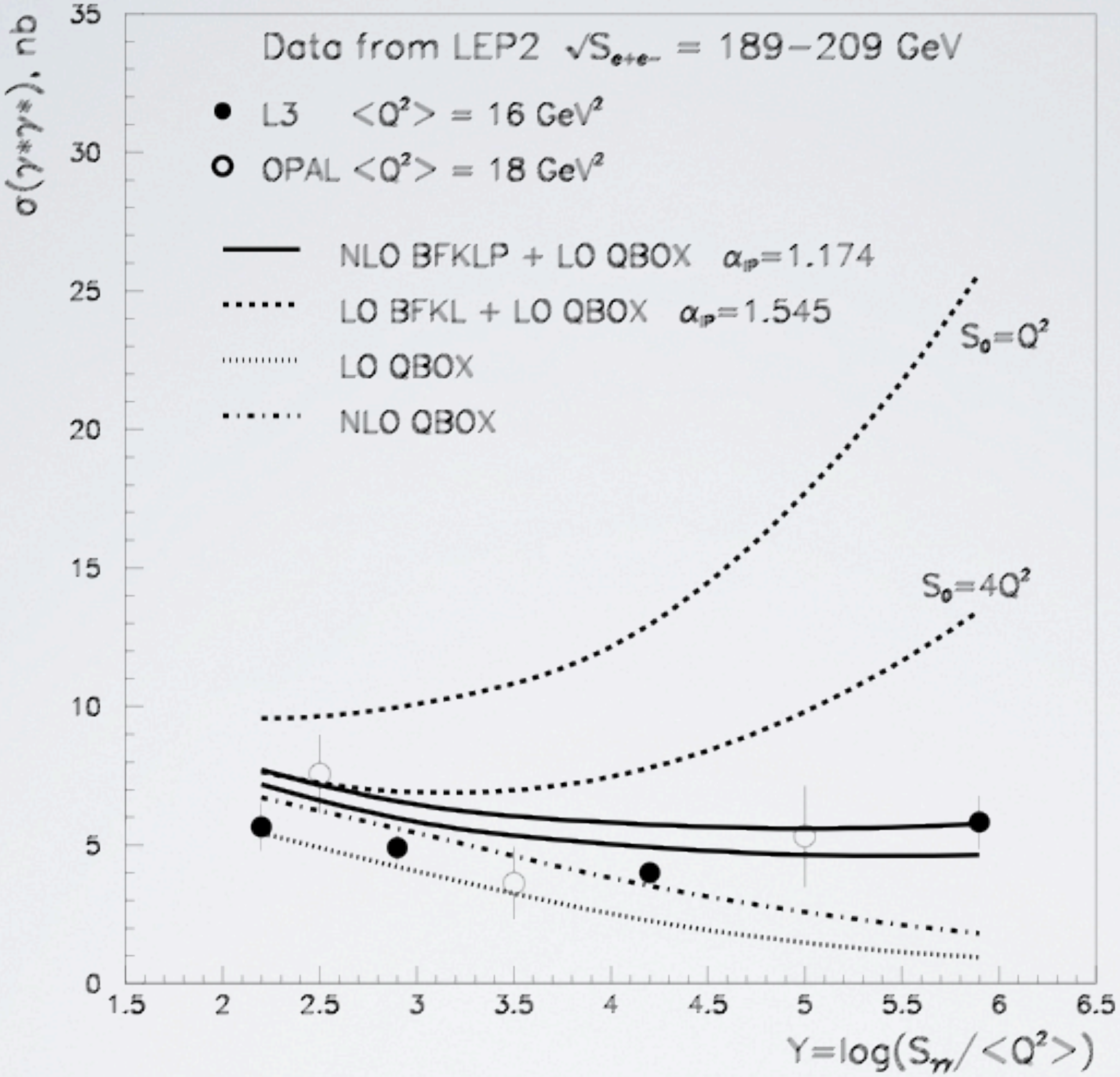


LL BFKL
J. Bartels et al (96), S.J. Brodsky & Hautmann (97)

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

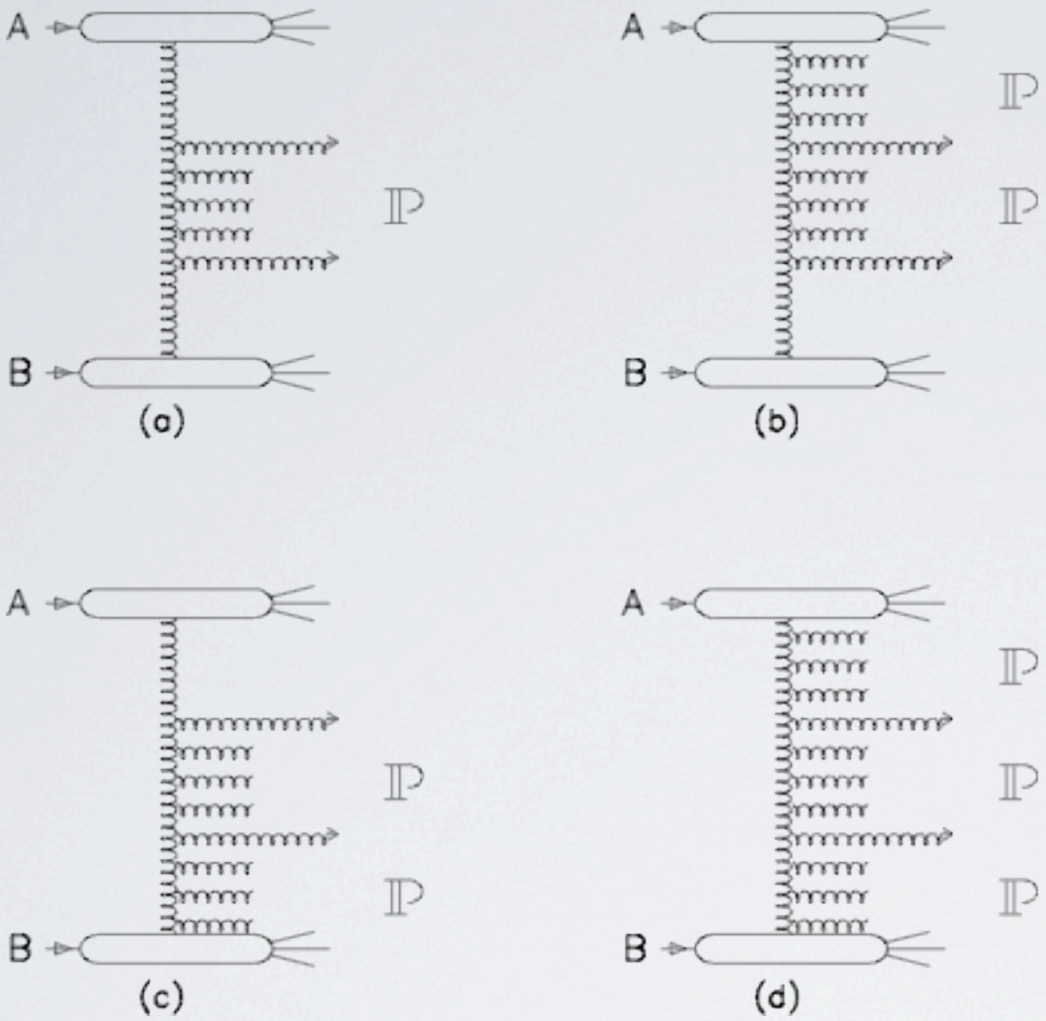


S.J Brodsky, VK, L.N. Lipatov, V.S. Fadin & G.B. Pivovarov (2002)

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

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

Mueller-Navelet (87):

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

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

$$\Delta y = |y_1 - y_2|$$

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

Dijet observables:

“K-factor” = inclusive dijet /”exclusive” dijet
“K-factor” = MN dijet /”exclusive” dijet
as a function of rapidity separation between jets

Inclusive dijet: $N_{jets} \geq 2$ $p_T \geq p_{Tmin}$
all jet pairs

Mueller-Navelet dijet: $N_{jets} \geq 2$ $p_T \geq p_{Tmin}$
most forward & most backward jets

“exclusive” dijet (2-jet events) with extra jet veto:
$N_{jets} = 2$, $p_T \geq p_{Tmin}$
veto for extra jets $p_T \geq p_{Tveto}$
$p_{Tveto} \leq p_{Tmin}$

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)

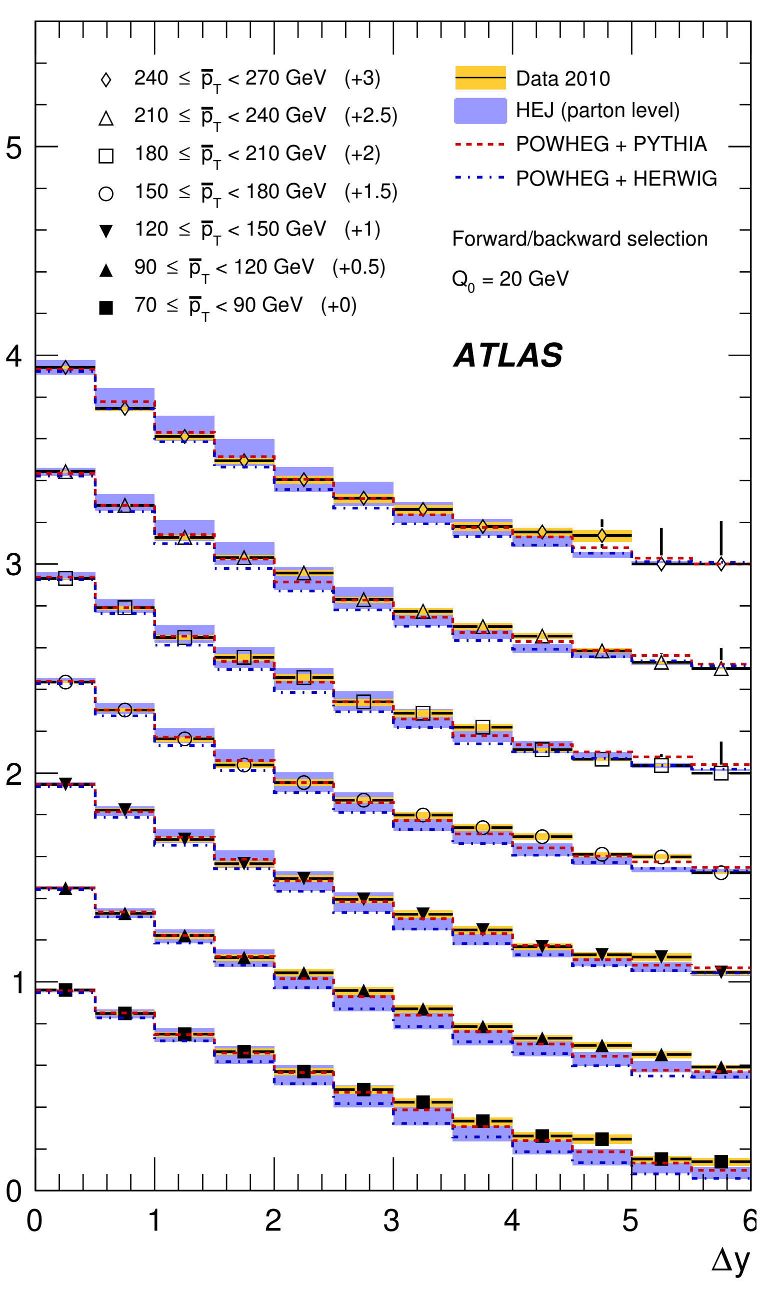
LHC: ATLAS -> $|\Delta y| < 6$ $70 \text{ GeV} < p_T < 90 \text{ GeV}$

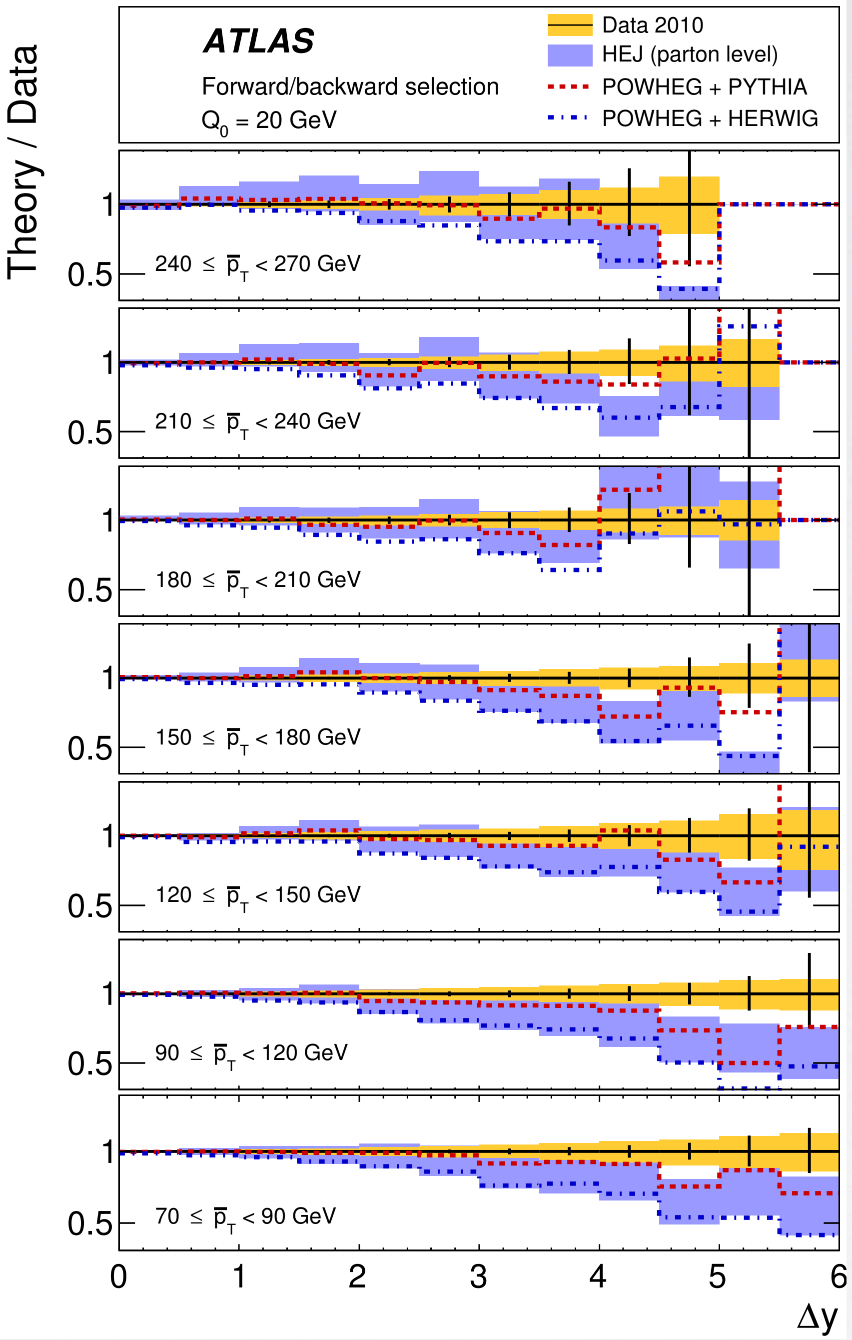
- (inverse) “K-factor” (2011)

LHC: CMS -> $|\Delta y| < 9.4$ $p_{Tmin} = 35$ GeV

- “K-factor” (2012)
- azimuthal angle decorr. (prel. 2013)

Dijet “K-factor” at 7 TeV



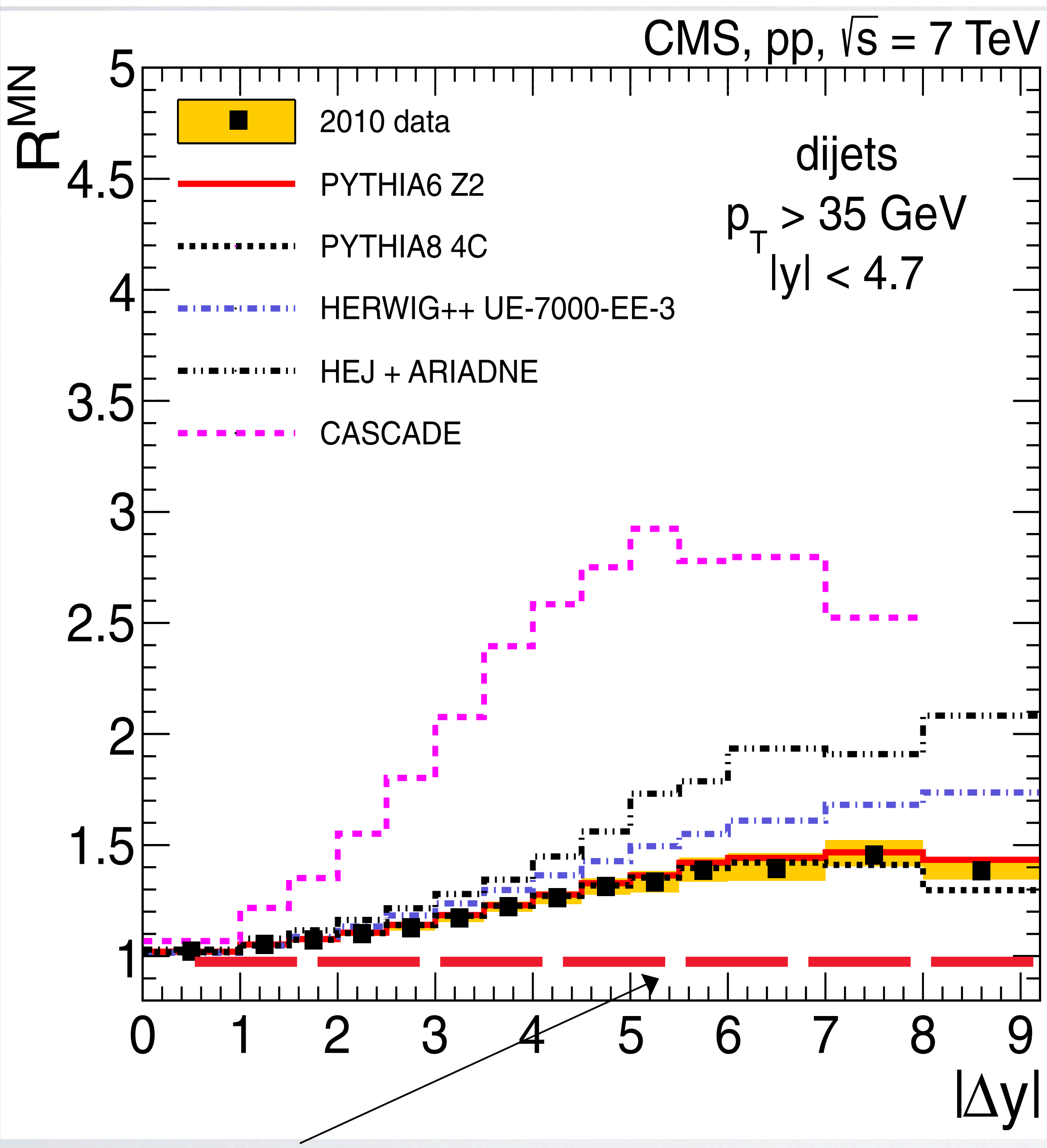


1/ (MN dijet K-factor) = “exclusive” dijet/ MN dijet

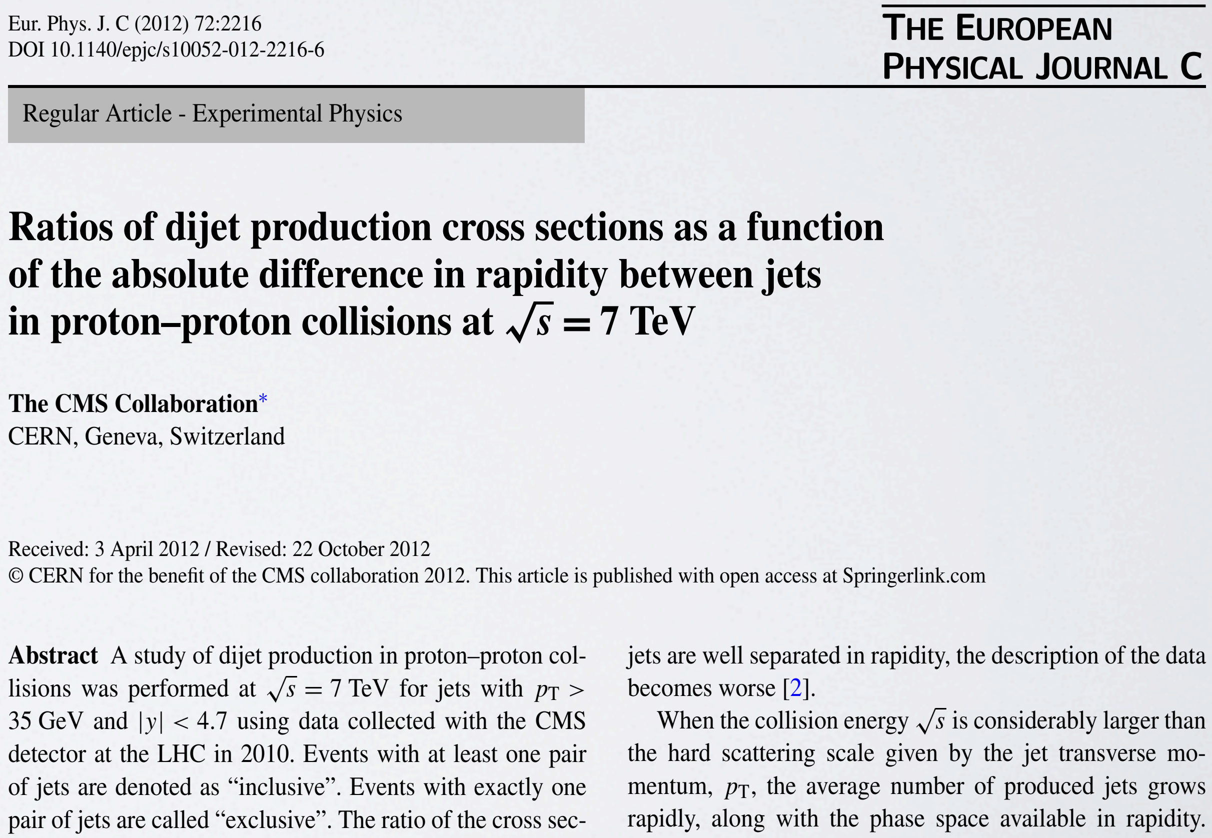
ATLAS, JHEP (2011)
arXiv: 1107.1641
7 TeV

70 < pT < 90 GeV
|Δy| < 6

CMS: dijet “K-factor”



GLAPD


Eur. Phys. J. C (2012) 72:2216
DOI 10.1140/epjc/s10052-012-2216-6

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PHYSICAL JOURNAL C

Regular Article - Experimental Physics

Ratios of dijet production cross sections as a function of the absolute difference in rapidity between jets in proton–proton collisions at $\sqrt{s} = 7$ TeV

The CMS Collaboration*
CERN, Geneva, Switzerland

Received: 3 April 2012 / Revised: 22 October 2012

Abstract A study of dijet production in proton–proton collisions was performed at $\sqrt{s} = 7$ TeV for jets with $p_T >$ 35 GeV and $|y| < 4.7$ using data collected with the CMS detector at the LHC in 2010. Events with at least one pair of jets are denoted as “inclusive”. Events with exactly one pair of jets are called “exclusive”. The ratio of the cross sec-

jets are well separated in rapidity, the description of the data becomes worse [2].

When the collision energy $\sqrt{s}$ is considerably larger than the hard scattering scale given by the jet transverse momentum, p_T, the average number of produced jets grows rapidly, along with the phase space available in rapidity.

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 –> more sensitive to BFKL (!)
A. Sabio Vera et al (2011)

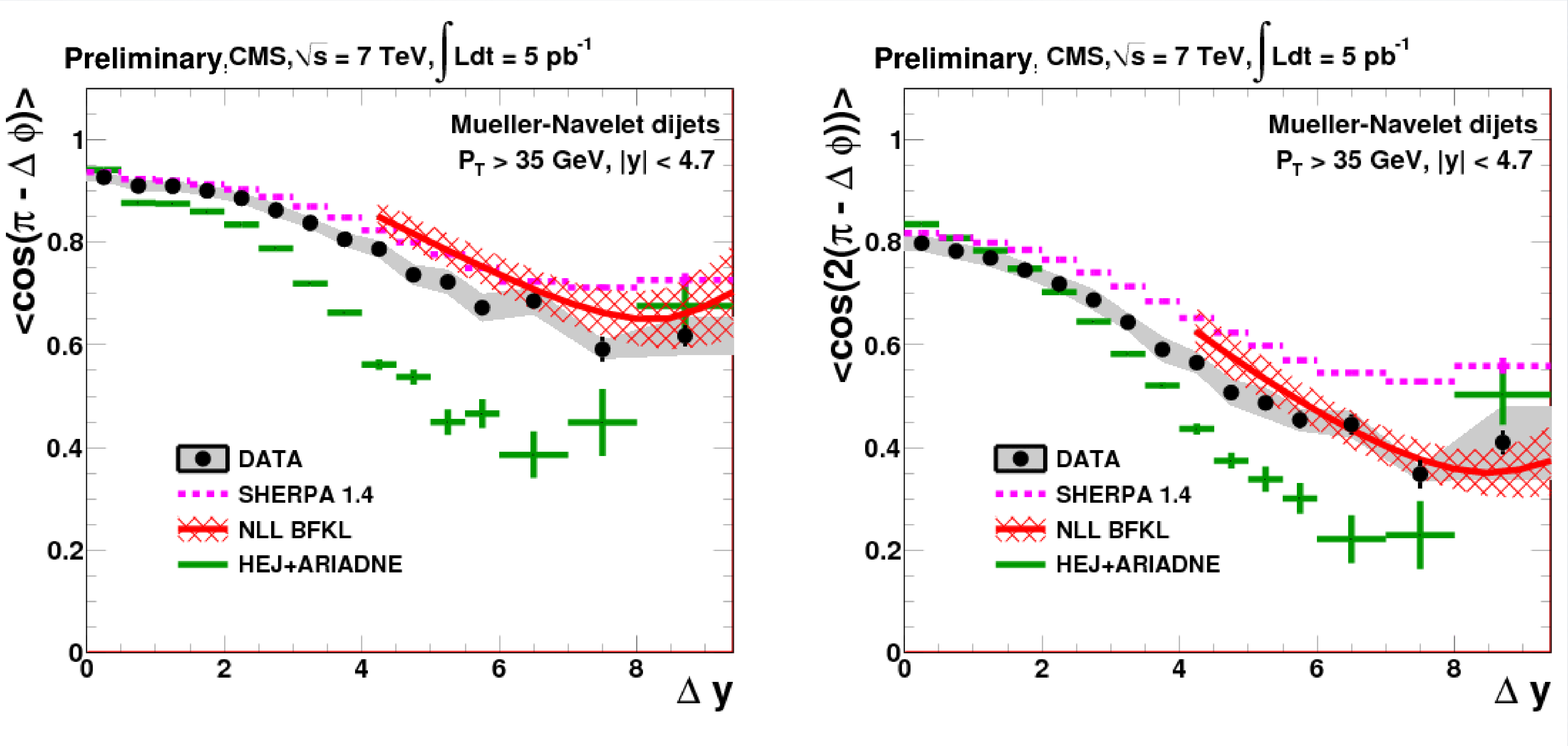
Forward dijets: azimuthal decorrelations

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

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

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



CMS PAS-FSQ-12-002

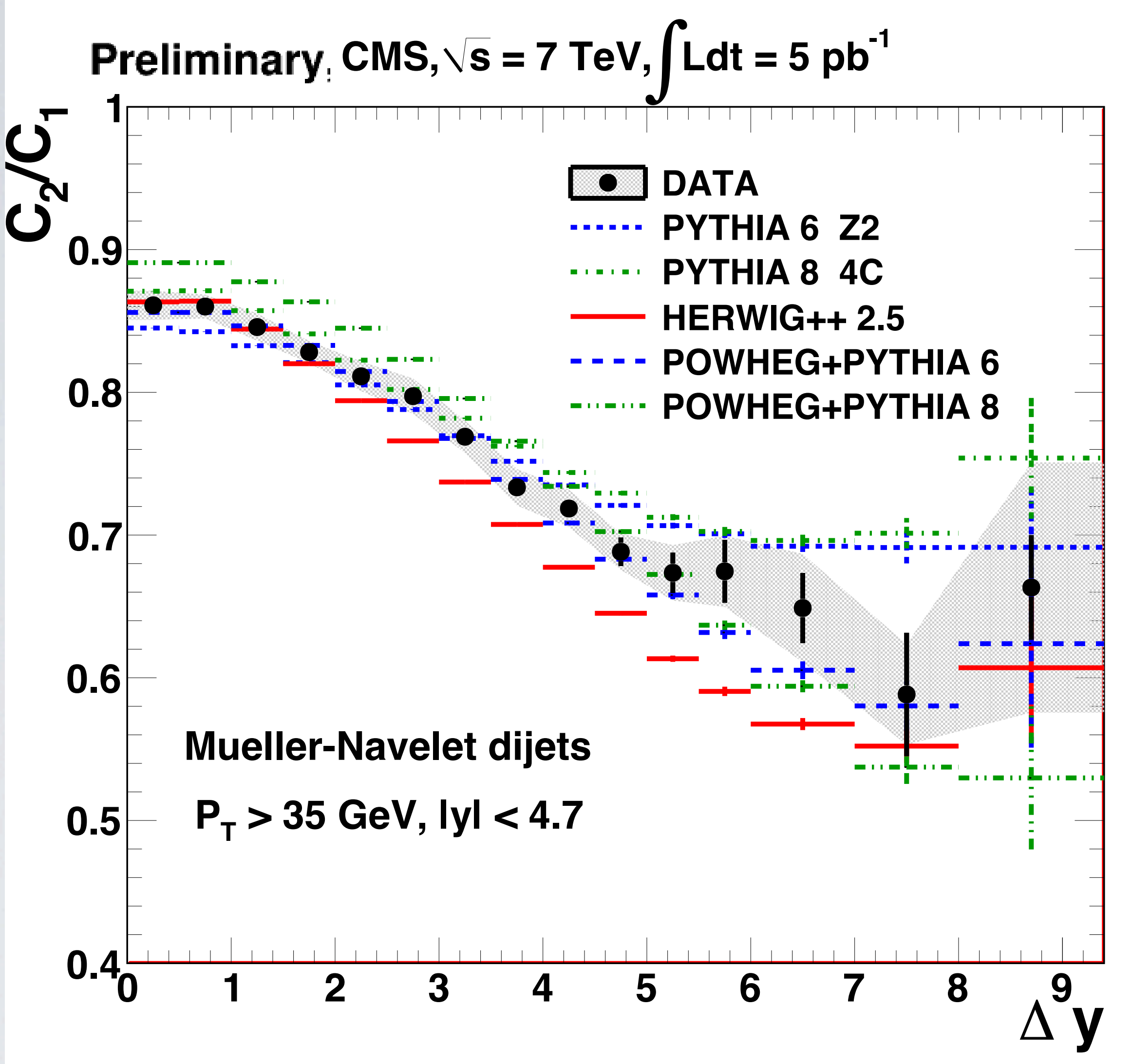
7 TeV, pT_min = 35 GeV

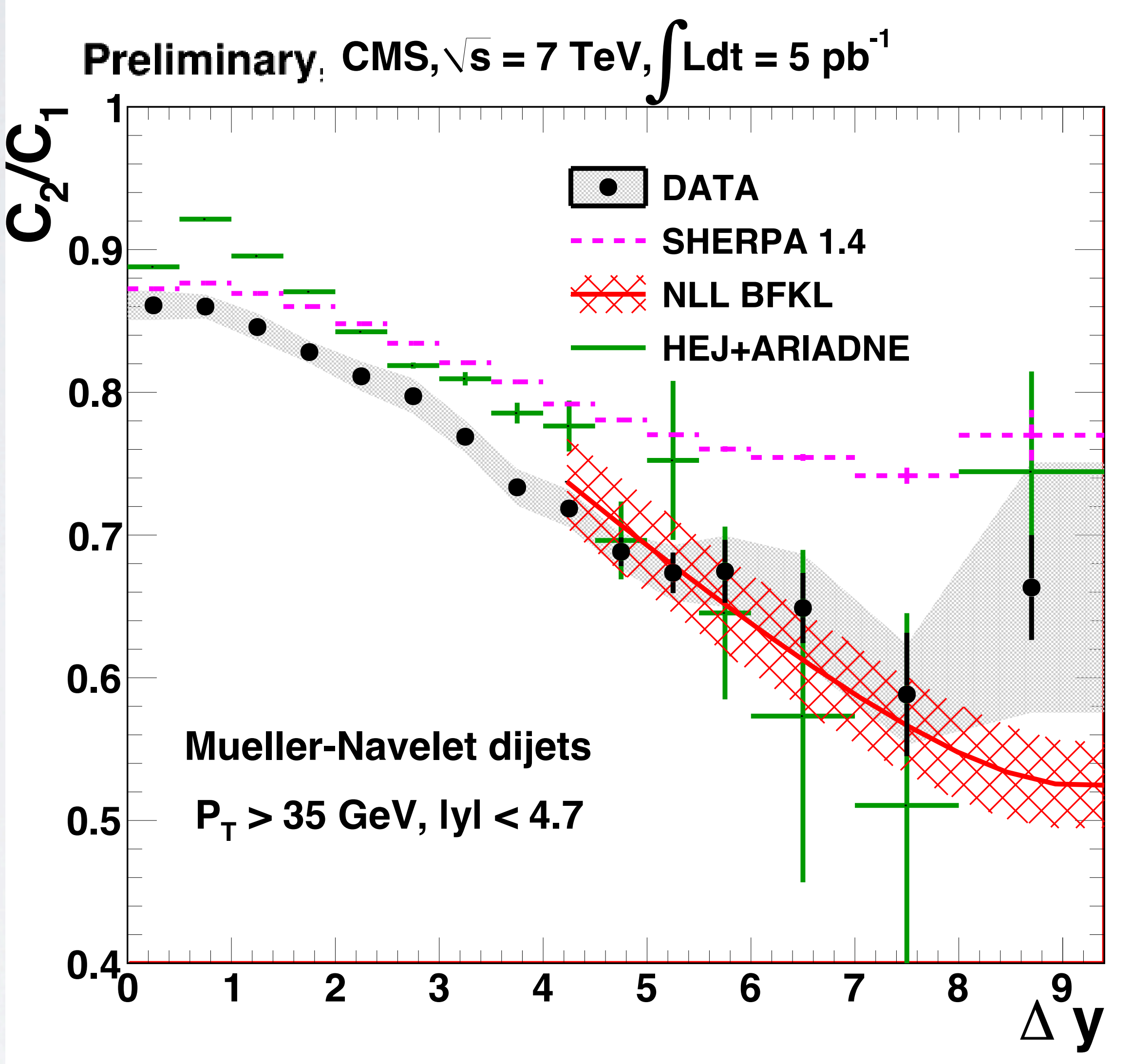
Δy = | | < 9.4

NLL BFKL + BFKLP (2014)

B. Ducloue, L. Szymanowski & S. Wallon

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





CMS PAS-FSQ-12-002
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 ?

- **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

-> the first indication on BFKL at LHC ?
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 ?!