Jets with large rapidity separation at CMS: dijet "K-factor" and azimuthal angle decorrelations

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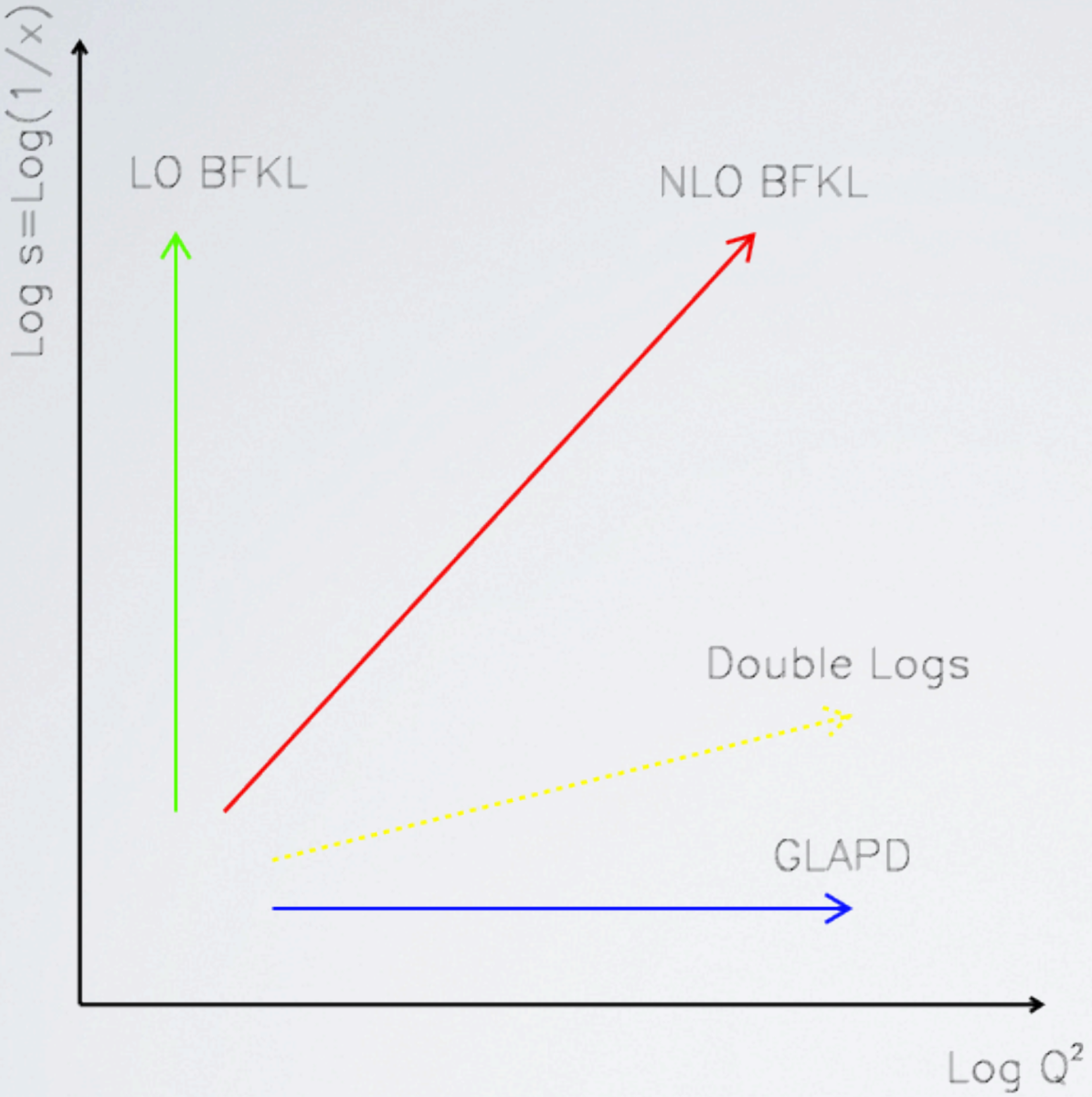
Outline:

- **Motivation: why BFKL?**
- **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**

x-section asymptotics



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

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

High-energy QCD asymptotics: GLAPD and BFKL

$s=(p_1+p_2)^2$
$t=(p_1-p_3)^2$ $\quad\quad$ $Q^2=-t$
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 ~ $1/Q^4$

Regge-Gribov 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 $\quad\quad$ **soft scattering data: $a_P = 1.1$**

LL BFKL: problems

LL BFKL: designed for infinite collision energies

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

Total cross section in LL BFKL:

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

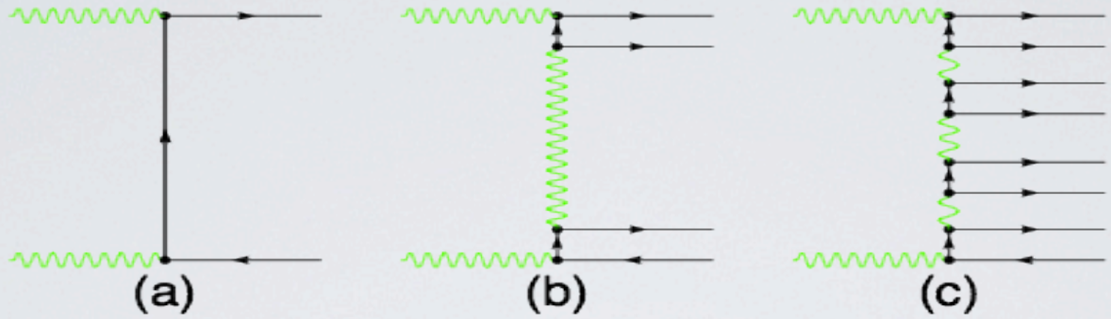
Chronicles of BFKL: next-to-leading logs (NLL)

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

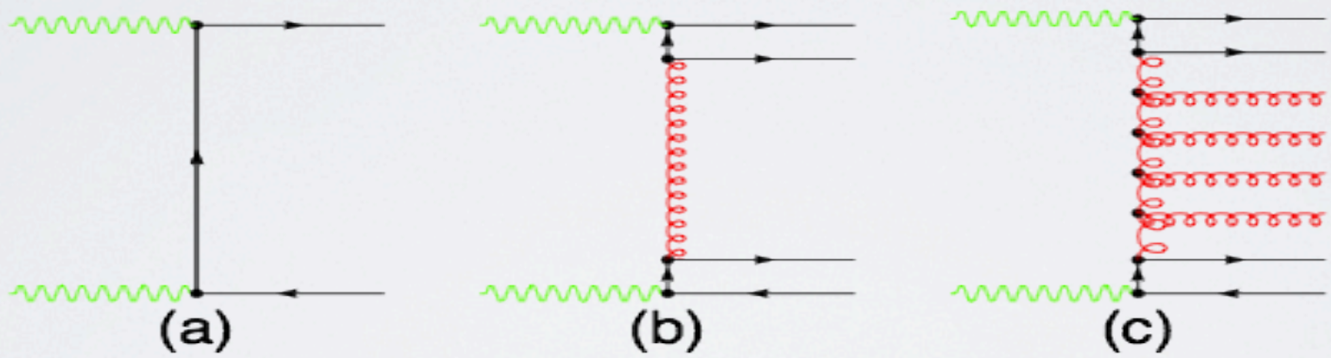
L.N. Lipatov, A.V. Kotikov et al. (2000-06)
SUSY N=4 BFKL-Pomeron
Anomalous dimensions: test of AdS/CFT-conjecture

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)

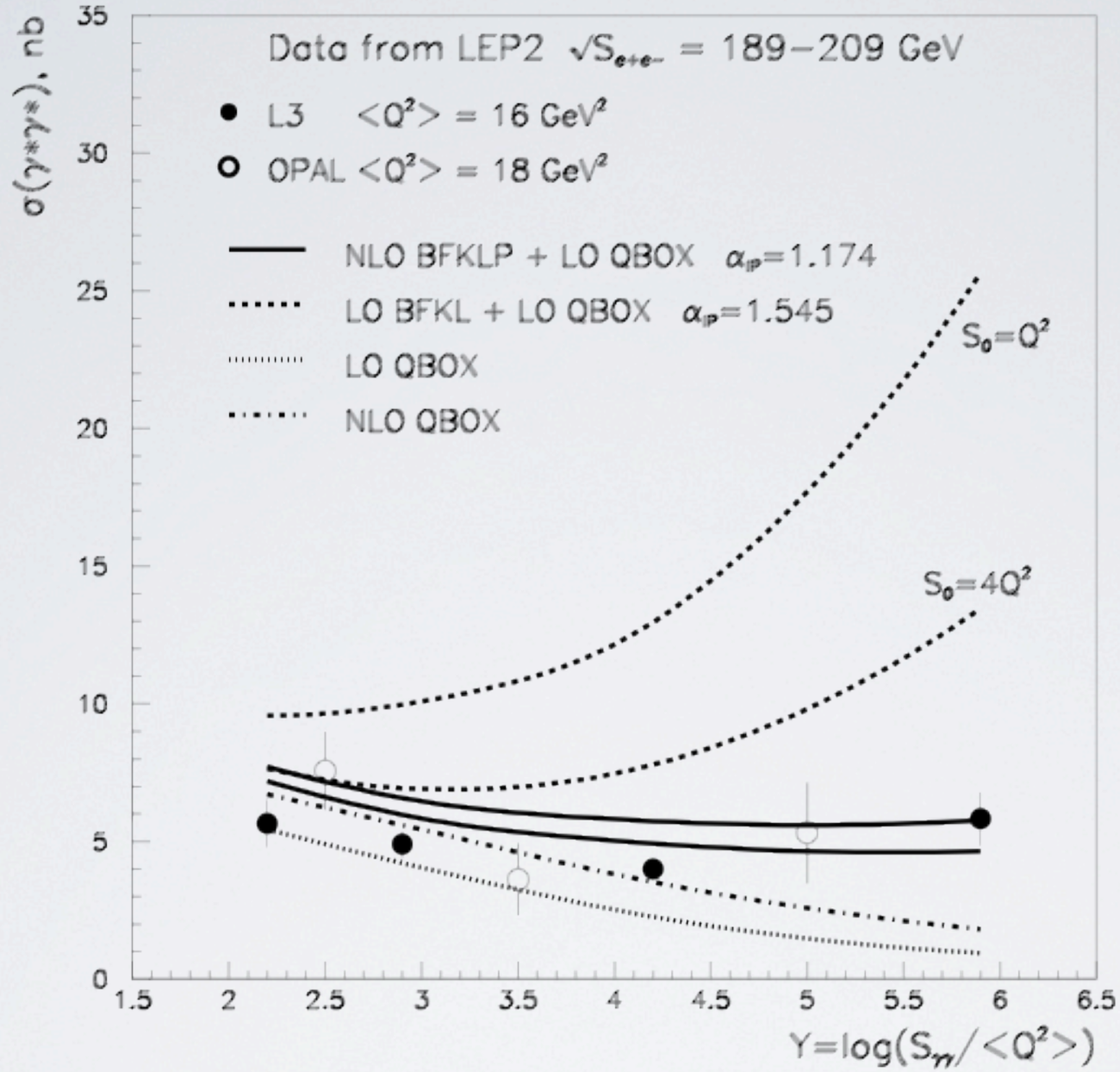
NLL BFKL (with LO impact factors)

S.J. Brodsky, VK, L.N. Lipatov, V.S. Fadin & 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

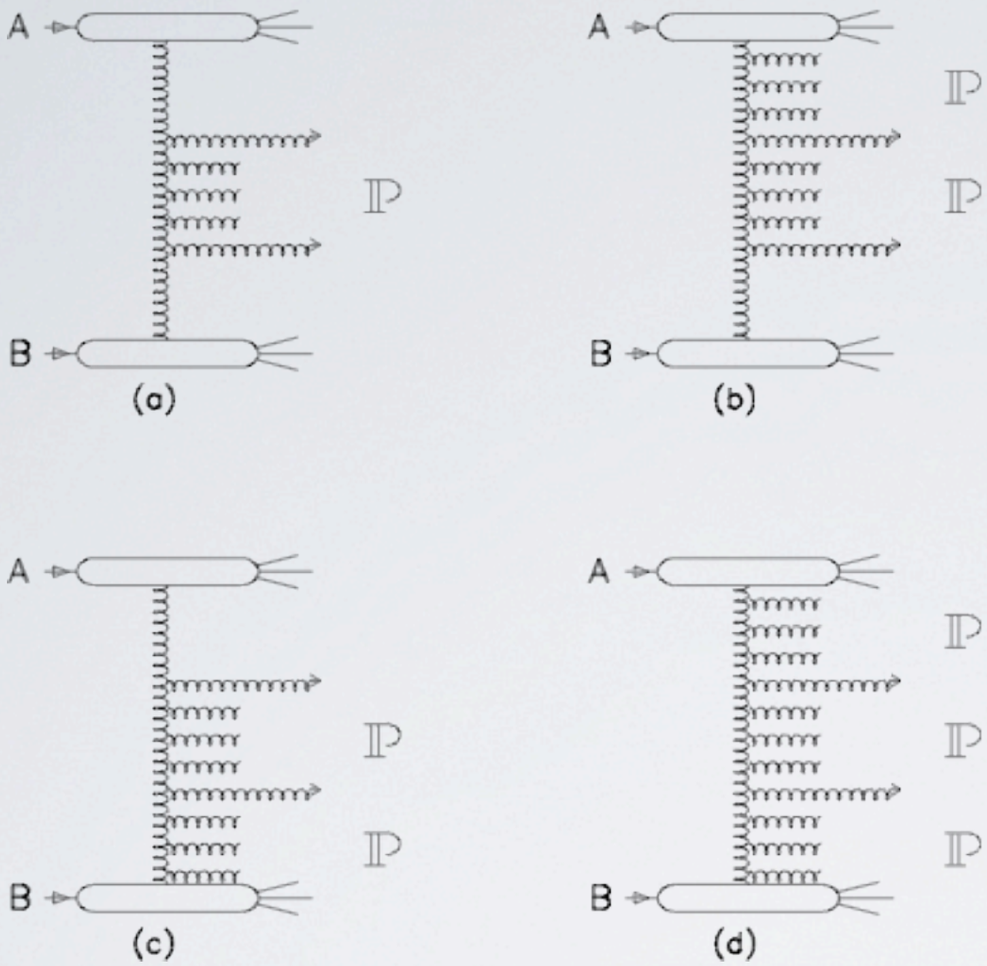


S.J Brodsky, VK, L.N. Lipatov, V.S. Fadin & G.B. Pivovarov (2002)

BFKLP: NLL BFKL + generalized BLM

LL BFKL: ruled out

БФКЛ: 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

Mueller-Navelet (87)

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

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

K-factor =

$$(\text{Born x-section})(1 + C_2/C_1 \alpha_s + C_3/C_1 \alpha_s^3 + \ldots)$$

BFKL → enhanced $(\alpha_s \Delta y)$-terms

$$\text{x-section} \rightarrow B_1 \alpha_s^2 \Delta y + B_2 \alpha_s^3 \Delta y^2 + \ldots =$$
$$(\text{Born x-section}) \ \exp(\alpha_s \Delta y)$$

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

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

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)

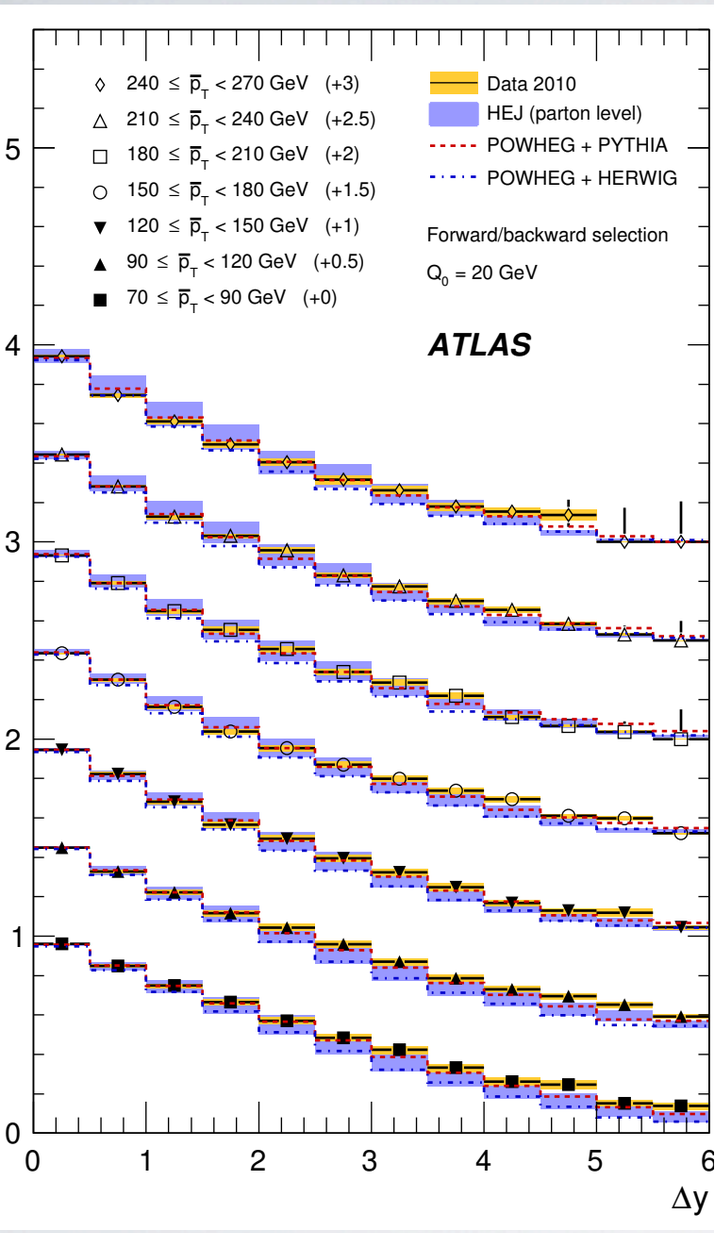
LHC: ATLAS -> $|\Delta y| < 6$ $70 \text{ GeV} < p_T < 90 \text{ GeV}$

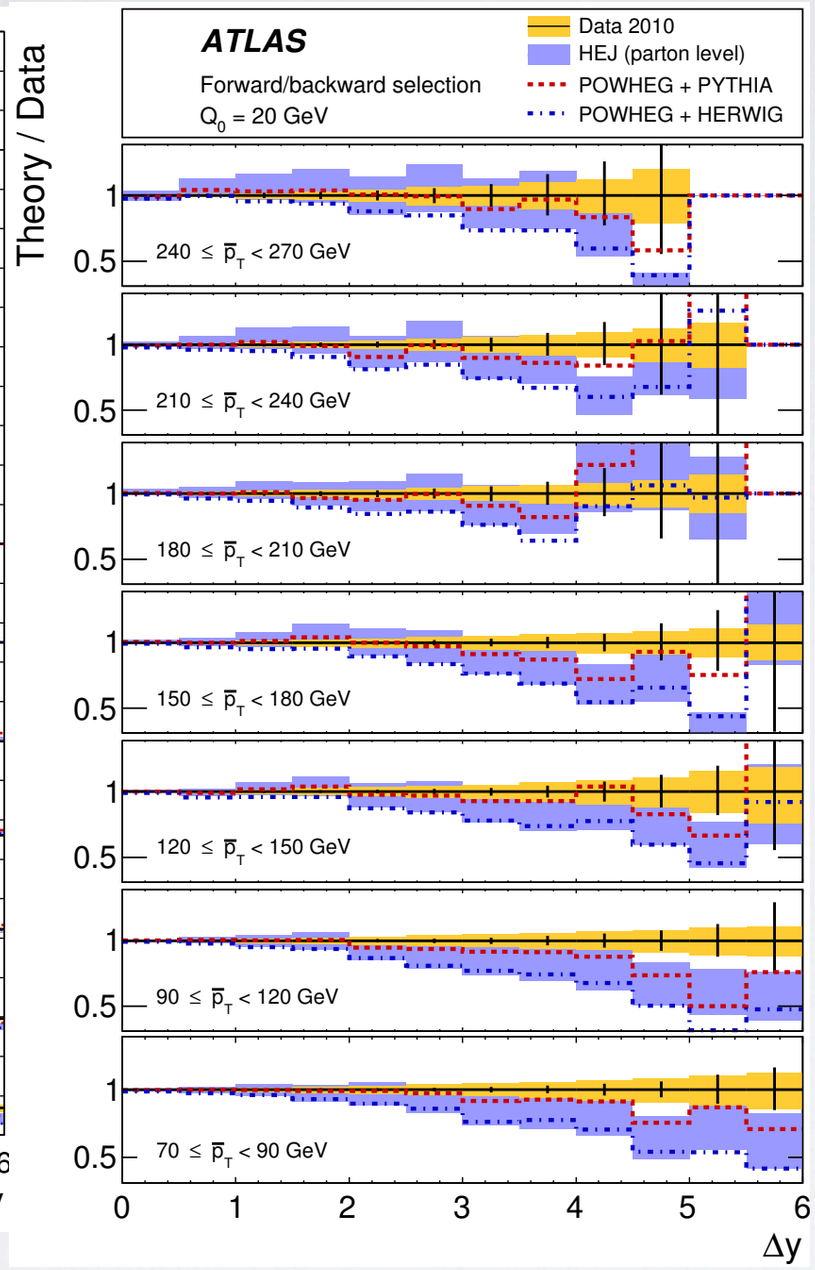
- (inverse) “K-factor” (2011)

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

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

Dijet “K-factor” at 7 TeV





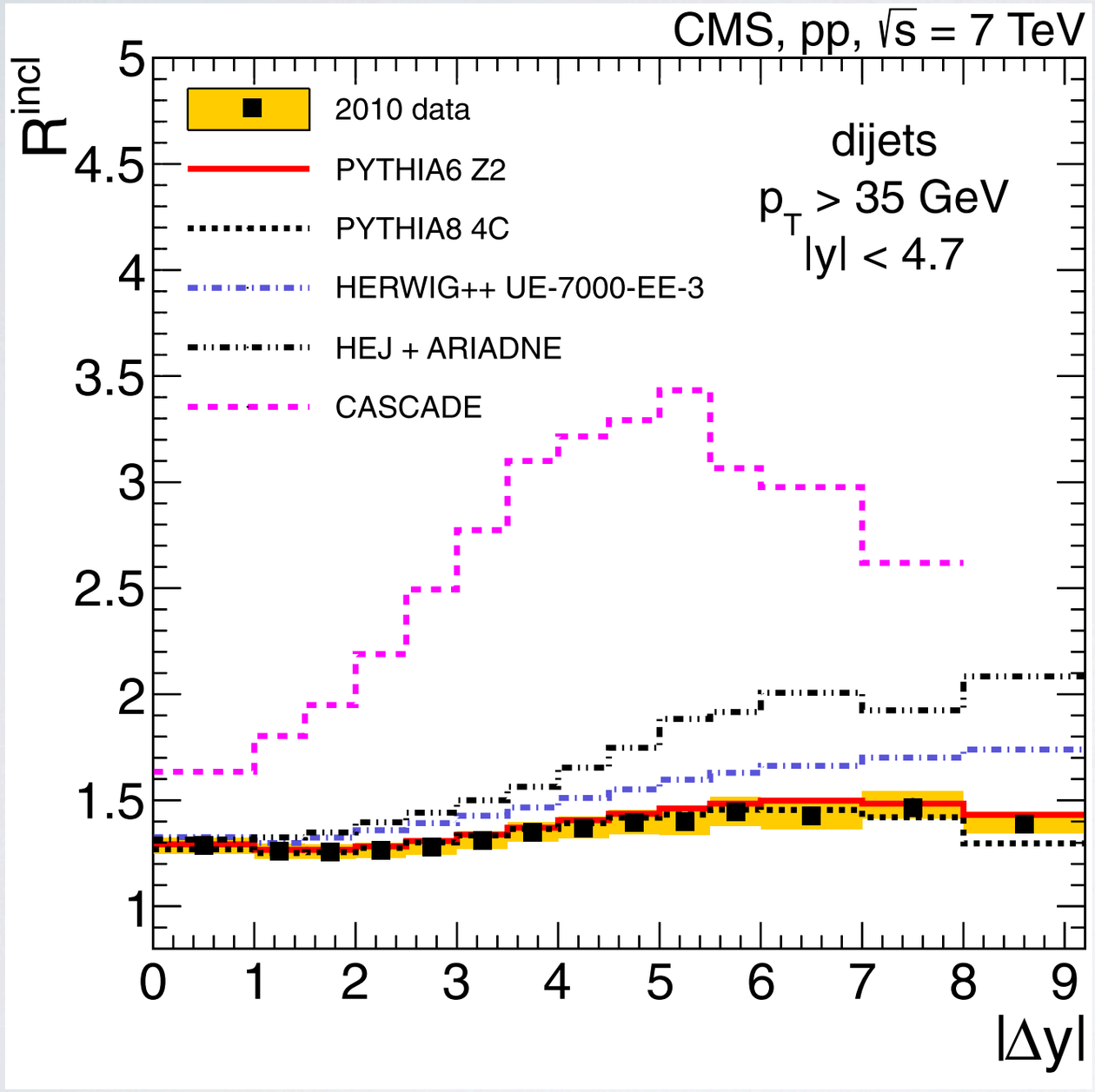
1/ (MN dijet K-factor) = “exclusive” dijet/ MN dijet

ATLAS, JHEP (2011)
arXiv: 1107.1641
7 TeV

70 < pT < 90 GeV
|Δy| < 6

Dijet “K-factor” at 7 TeV

Inclusive dijet K-factor = inclusive dijet / “exclusive” dijet



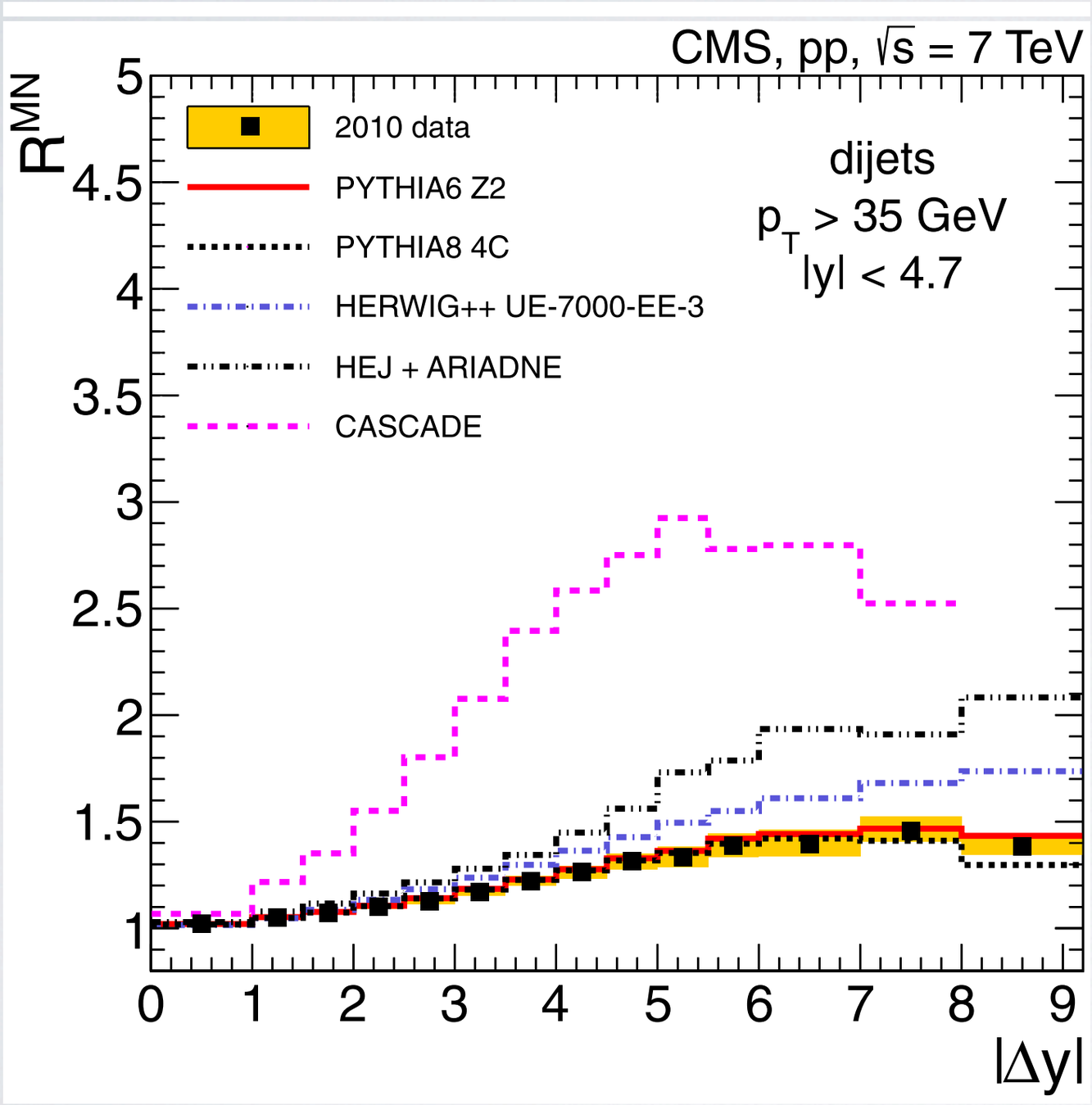
CMS, EPJ C (2012)
arXiv: 1204.0696

7 TeV
pT_min = 35 GeV
| Δy | < 9.2

Dedicated forward dijet trigger: x150

Dijet “K-factor” at 7 TeV

MN dijet K-factor = MN dijet / “exclusive” dijet



CMS, EPJ C (2012)
arXiv: 1204.0696

7 TeV
pT_min = 35 GeV
| Δy | < 9.2

Data: rise from 1 to 1.5

GLAPD ~ const ?

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

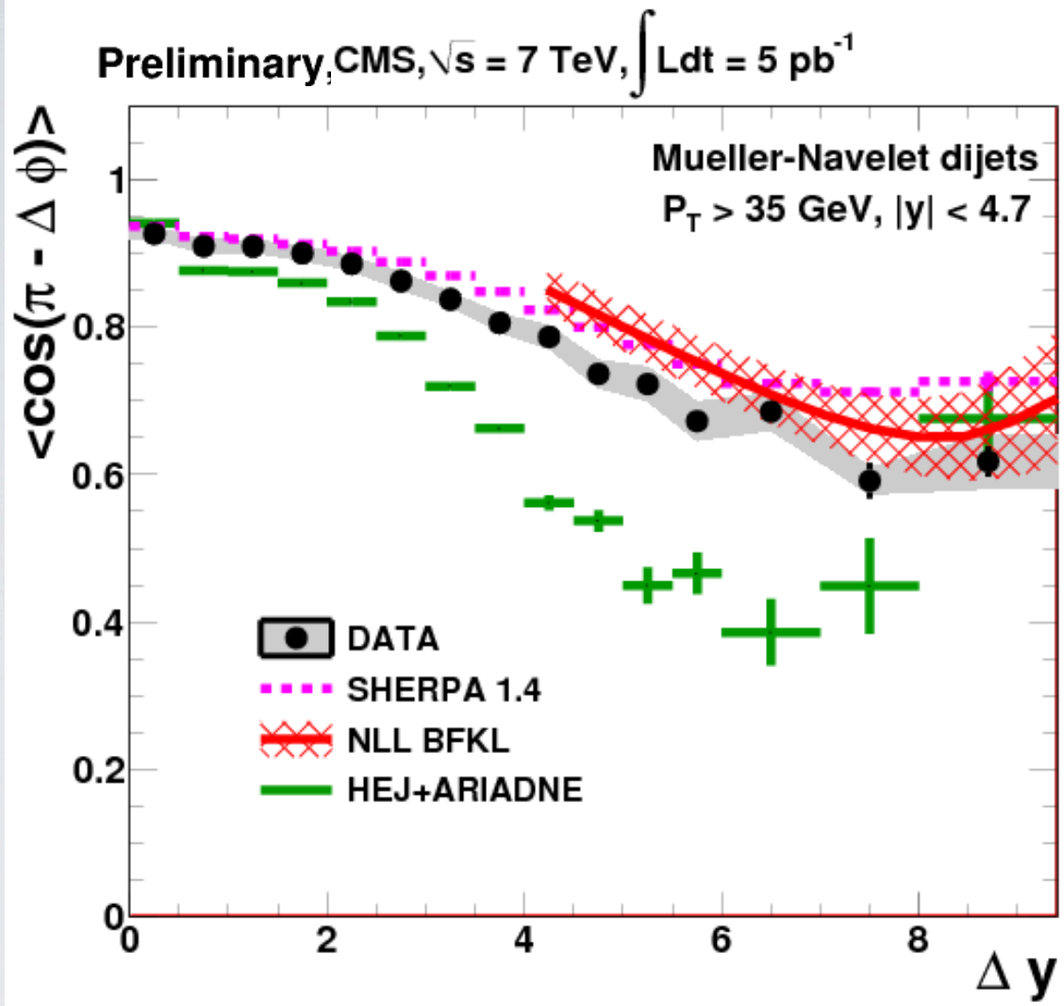
V. Del Duca & C. Schmidt (94)

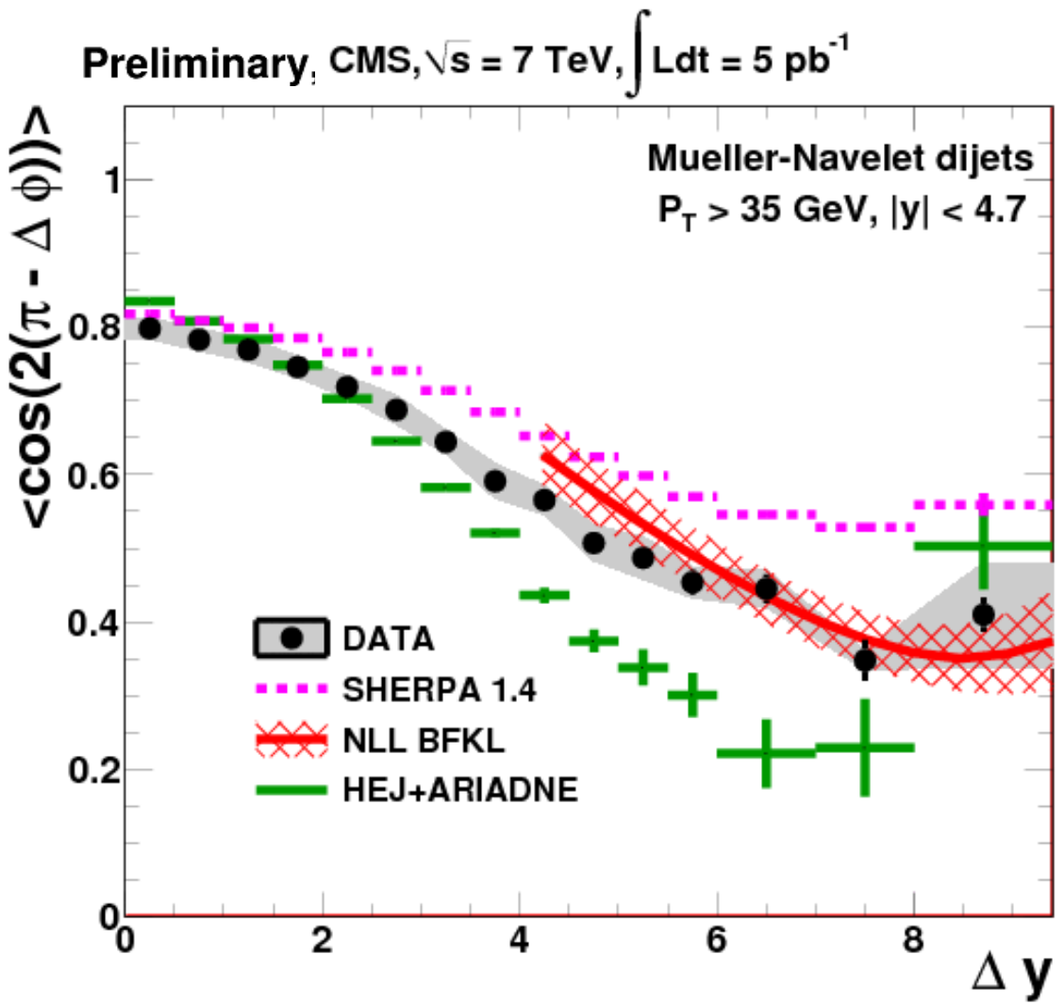
J. Stirling (94)

Cosine ratios –> more sensitive to BFKL (!)

A. Sabio Vera et al (2011)

Dijets: <cos> vs NLL BFKL+BFKLP

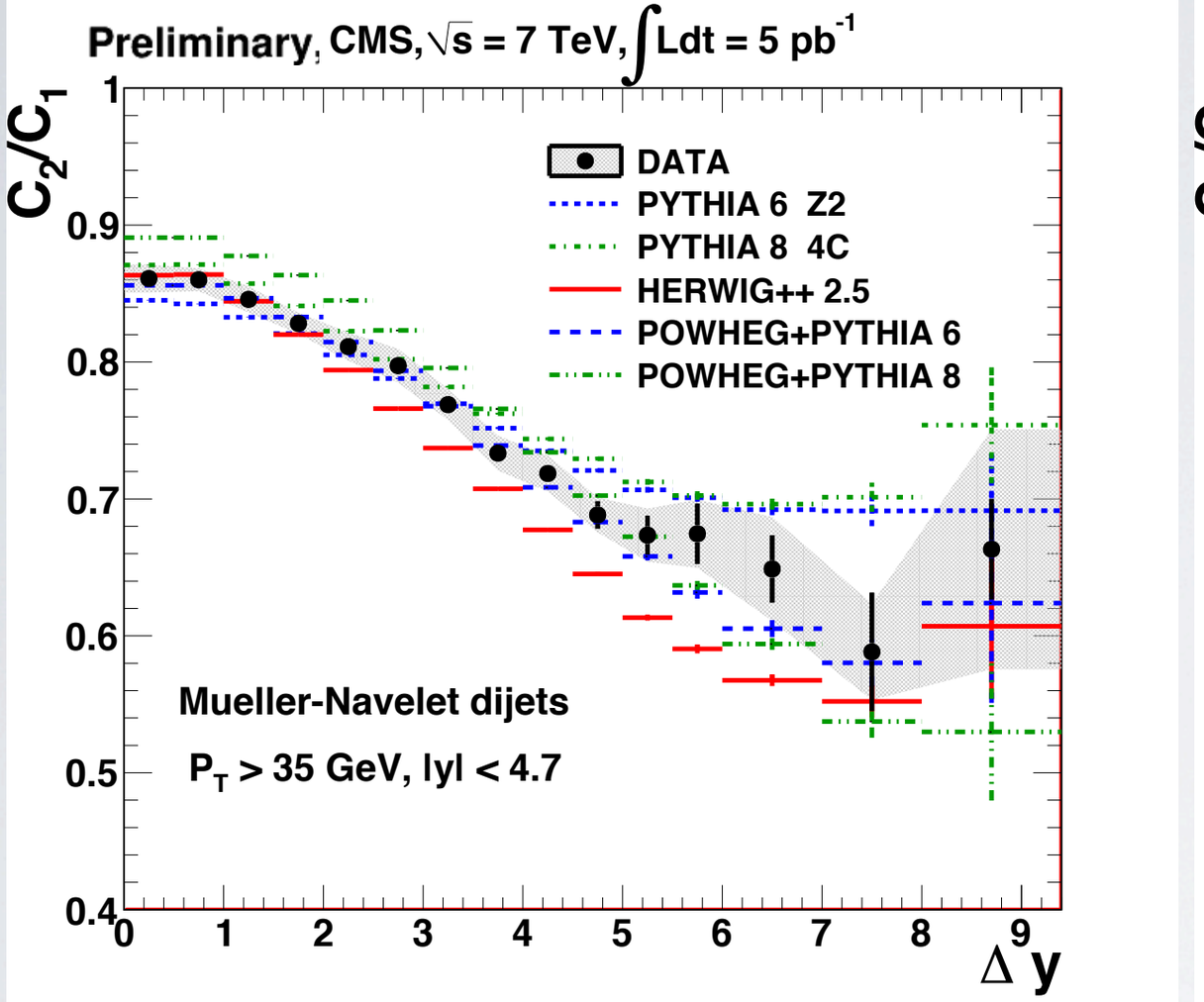


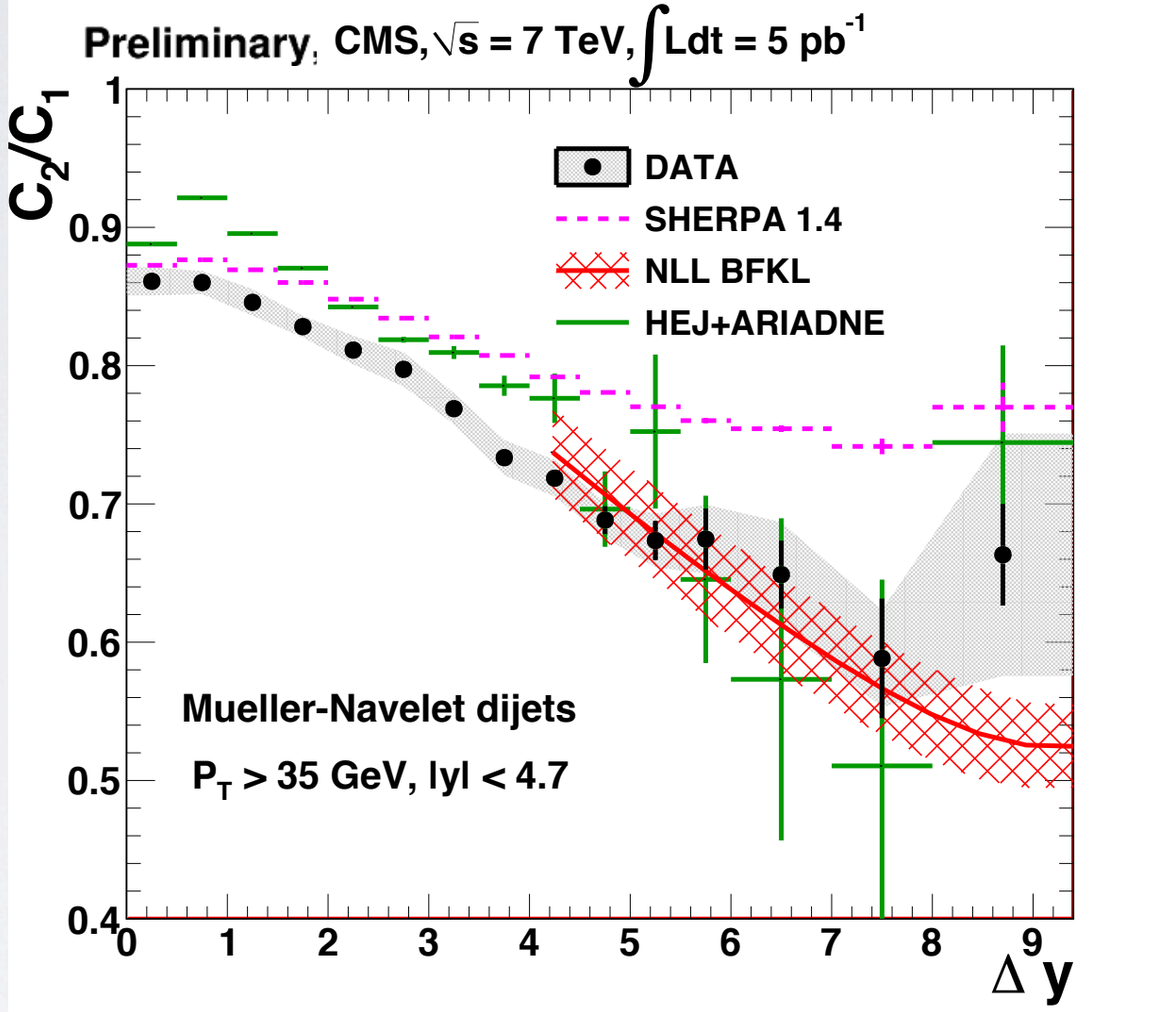


CMS PAS-FSQ-12-002
7 TeV, pT_min = 35 GeV
Δy = | | < 9.4

NLL BFKL + BFKLP (Sept. 2013)
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 (Sept. 2013)
B. Ducloue, L. Szymanowski & S. Wallon

Forward dijets: MPI & hadronization

MPI and hadronization for dijet ratios and azimuthal angle decorelations at 7 TeV: noticeable but not exceed CMS systematic and statistical uncertanties

PYTHIA 6 and 8

HERWIG++

-> Direct comparison with parton level calculations

NLL BFKL B. Ducloue, S. Szymanowski & S. Wallon (2012-13):

- parton level

- no MPI

still can be compared with the data

Summary:

- **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
  - Herwig describes AAD (almost) reasonably,
  but Pythia doesn't

-> first indication on BFKL at LHC ?
No pure GLAPD predictions

Other observables:
- K-factor with extra jet veto, number of extra jets, ... ?