Forward Physics in CMS: Recent Results

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Igor A. Golutvin: always looking forward

I.A. Golutvin:
deep mind,
open wide view,
wise,
seeking a perfection …

Outline:

- **Forward Physics at CMS: two selected recent results**

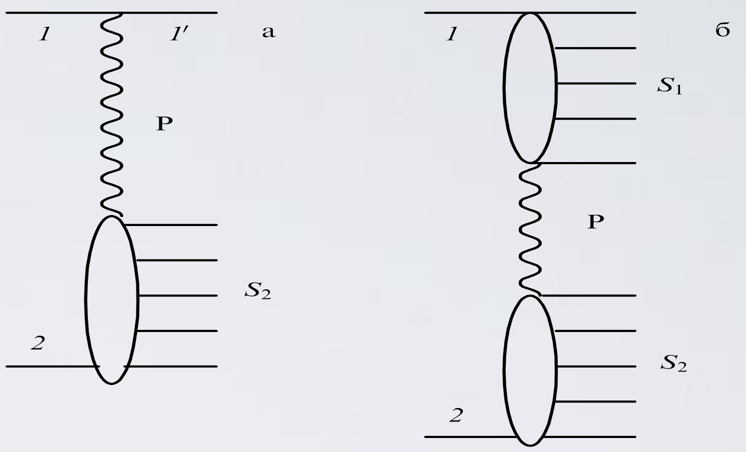
- **The first measurement of forward rapidity gap events in p-Pb collisions at LHC by CMS:**
The first observation when the e-m contribution dominates over the strong one in nuclear diffraction!

- **The first direct evidence for BFKL evolution in forward dijet production at CMS**

High energy collisions: Pomeron

Pomeron at high energies is responsible for:

- elastic scattering
- diffractive scattering
- inelastic scattering
- total x-section



Pomeron

V. Gribov ZhETP 41 (1961) 667; G. Chew, S. Frautschi PRL 7 (1961) 394

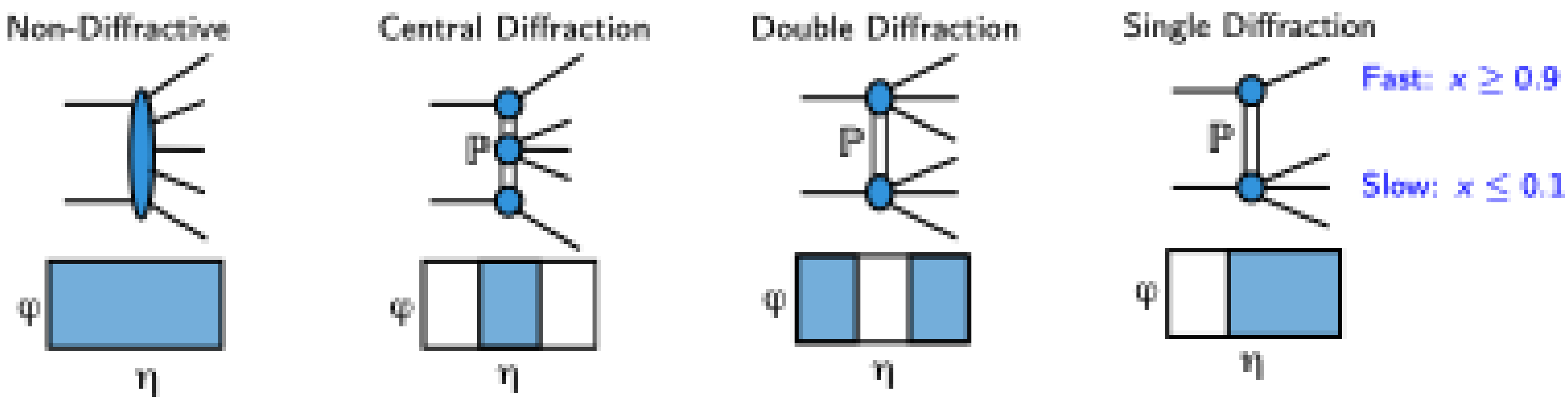
Pomeron in pQCD (BFKL evolution)

L.N. Lipatov, V.S. Fadin, E.A. Kuraev PL (1975), ZhETP (1976-77);
I.I. Balitsky, L.N. Lipatov Yad.Fiz. (1978)

Diffractive collisions are defined as special inelastic collisions in which no quantum numbers are exchanged between colliding particles

Diffraction process markers (observables):

- Fast particle ($\frac{E_{fin}}{E_{in}} = x \geq 0.9$) and slow particle(s) ($x \leq 0.9$)
- Rapidity gap ($\Delta\eta$) – the rapidity region free of final state particles (between slow and fast particles)



CMS pPb forward rapidity gap events and diffractive processes: 300 x higher energy in c.m.s. (80000 x lab.s.)

CMS Coll., A. Tumasyan et al., Phys. Rev. D 108 (2023) 092004

Main HELIOS results

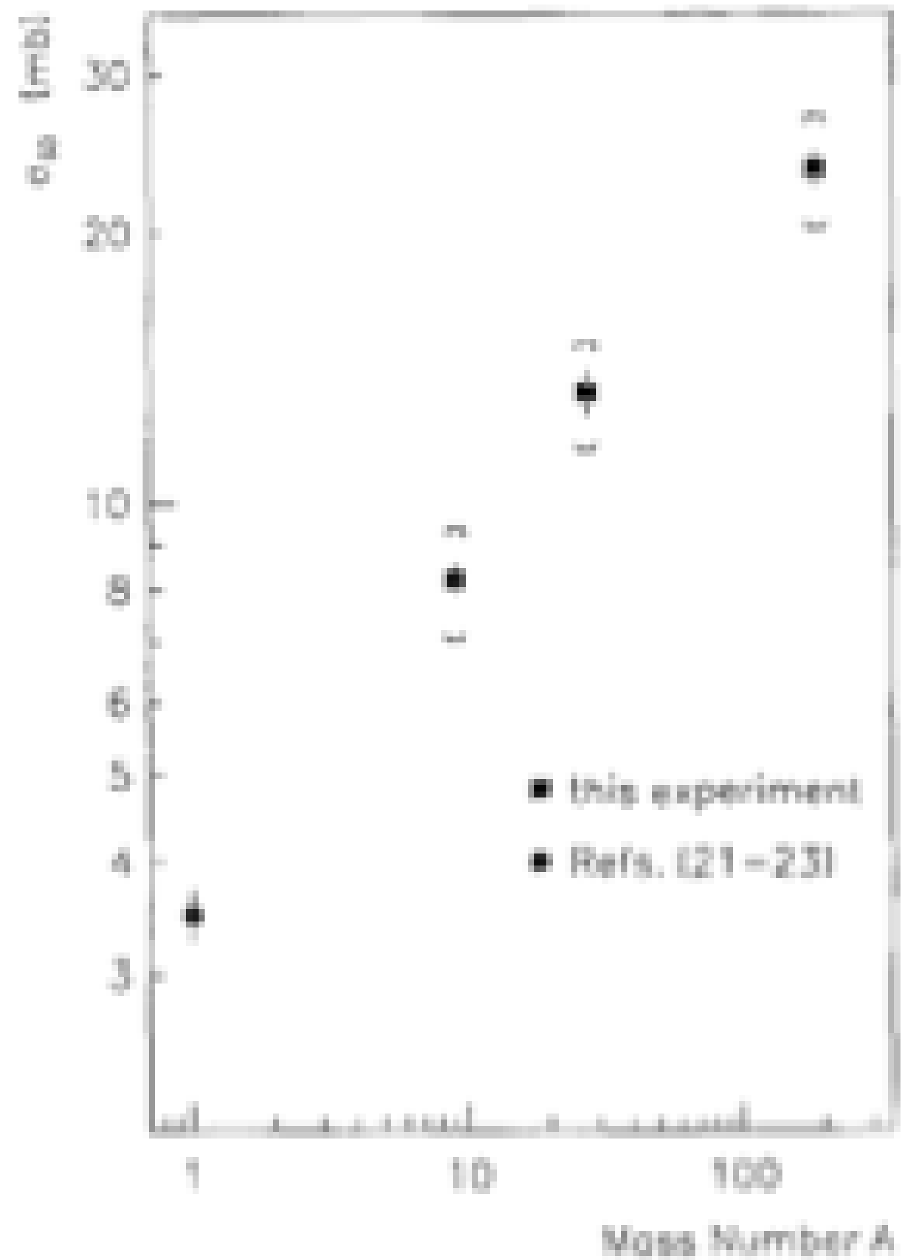
- The latest (before LHC) measurements on diffraction in pA were done by HELIOS with $\sqrt{s} = 27$ GeV Z. Phys. C 49 (1991) 355
- The cross-section of single diffraction is proportional to the nuclear radius, $\sigma_{SD} = \sigma_0 \cdot A^{\alpha}$, $\alpha = 0.35$
  This suggests that diffractive dissociation of nuclei is a peripheral process, predominantly involving nucleons on the rim of the nucleus.

SPS vs LHC energies for pA:

$\sqrt{s} = 27$ GeV $\qquad\qquad \sqrt{s} = 8000$ GeV

Center-of-mass system: 300 times

Laboratory system: 80000 times



CMS pPb collisions:
forward rapidity gap events and diffractive processes

CMS analysis

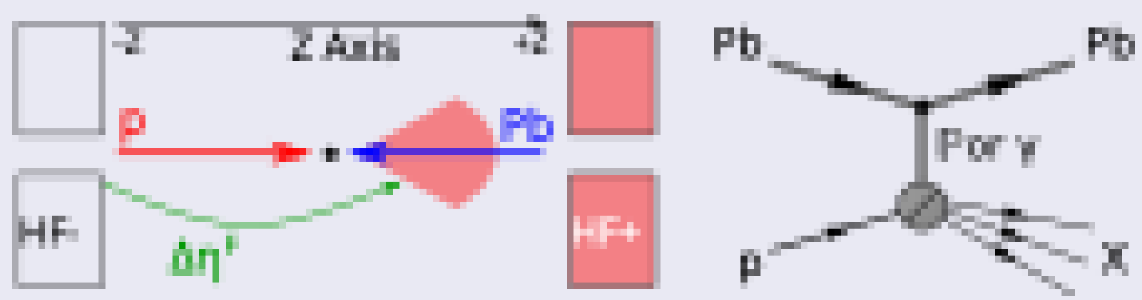
CMS collaboration, "First measurement of the forward rapidity gap distribution in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV",
Phys.Rev.D 108 (2023) 092004

Event topologies

Named as "IPPb $+\gamma Pb$ topology"

Lead dissociation

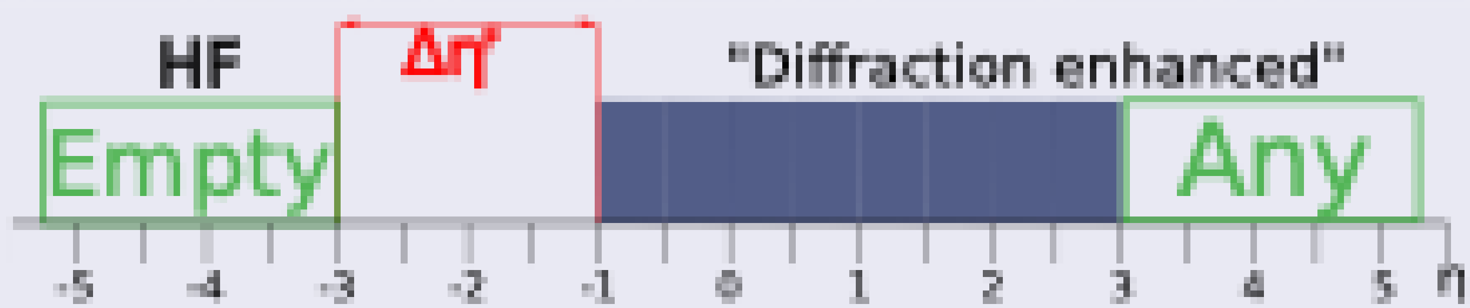
Named as "IPp $+\gamma p$ topology"



Proton dissociation

The photon flux from the Pb is enhanced by a factor of Z^2_{Pb} compared to that of protons

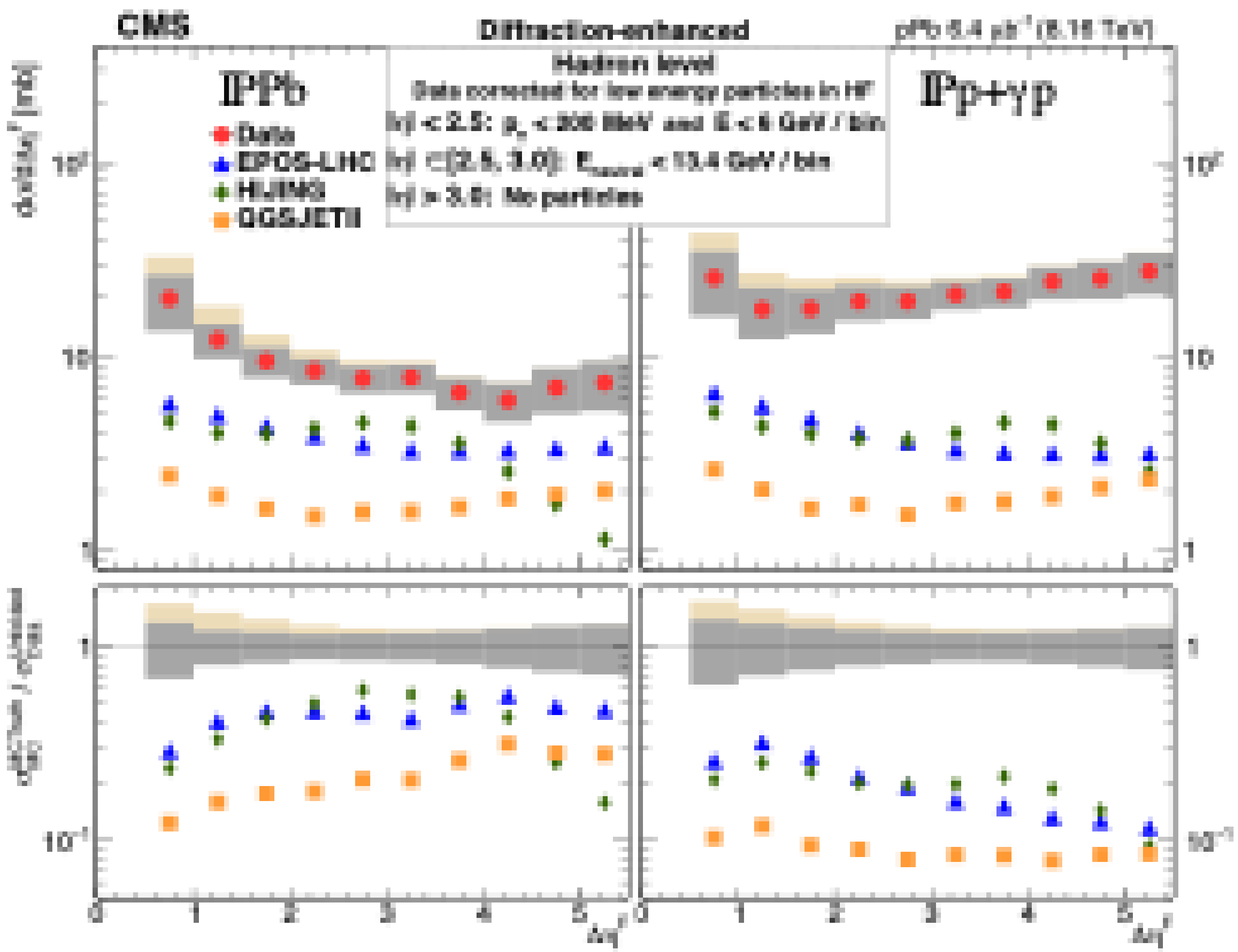
Rapidity gap selection



NRC KI - PNPI (E. Kuznetsova, D. Sosnov, VK), SINP MSU (L. Kheyn)

Forward rapidity gap events and diffractive processes: dominating e-m contribution over strong (Pomeron) one

CMS Coll., A. Tumasyan et al., Phys. Rev. D 108 (2023) 092004



(P/γ)-p topology

- The generators are more than a factor of 5 below the data

(P/γ)-Pb topology

- Predictions of EPOS-LHC and QGSJET II are about a factor of 2 and 4 below the data
- The rapidity spectrum from the HIJING generator falls at large $\Delta\eta^F$ in contradiction to the data

Used generators includes **only** pomeron exchange events

Confirmation from theory:

V. Guzey, M. Strikman, M.Zhalov, Phys. Rev. C 106 (2022) L021901 (based on prelim. CMS@DIS2021)

V. Khoze, M. Ryskin EJPC 83 (2023) 991

Forward dijet production at CMS

**Most direct BFKL observable:
production of forward dijet
with large rapidity separation**

High energy asymptotics of pQCD

- Large-angle scattering (hard processes):

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 ("semi-hard" processes):

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)

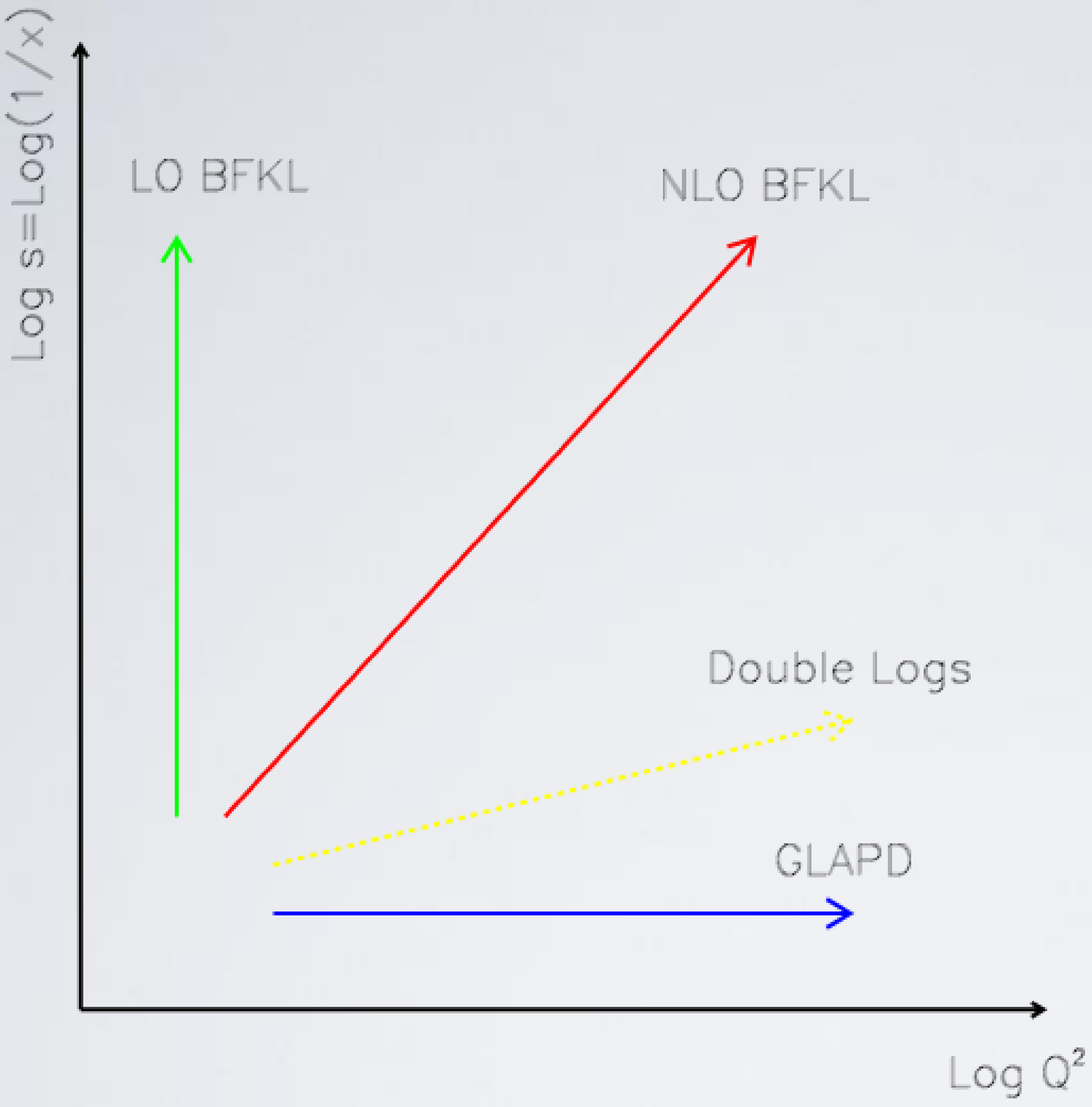
High-energy QCD asymptotics: GLAPD and BFKL

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

pQCD 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

BFKL evolution:
high-energy asymptotics of perturbative QCD

BFKL evolution:

Leading logarithmic approximation: LL BFKL Pomeron

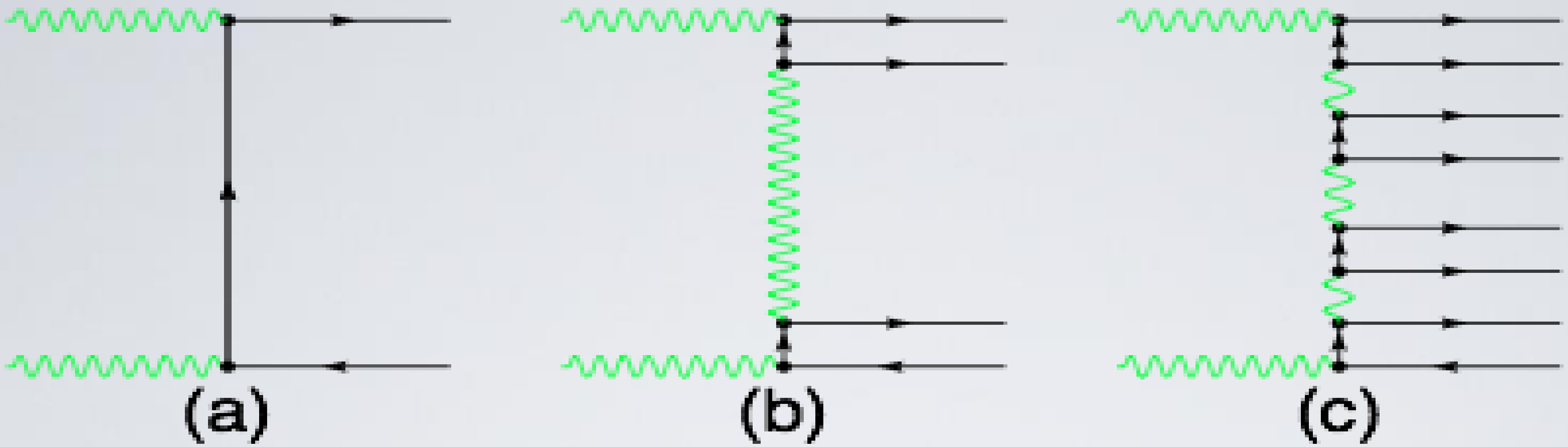
V.S. Fadin, E.A. Kuraev, L.N. Lipatov, Phys. Lett. B 60 (1975) 50
E.A. Kuraev, L.N. Lipatov, V.S. Fadin, ZhETF 71 (1976) 840 [JETP 45 (1977) 79]
E.A. Kuraev, L.N. Lipatov, V.S. Fadin, ZhETF 72 (1977) 377 [JETP 45 (1977) 79]
I.I. Balitsky, L.N. Lipatov, Yad. Fiz. 28 (1978) 1597

Next-to-leading logarithmic approximation: NLL BFKL Pomeron

V.S. Fadin, L.N. Lipatov, Phys. Lett. B 429 (1998) 127
E.A. Camici, L.N. Ciafaloni, Phys. Lett. (1998)

S.J. Brodsky V.S. Fadin, VK, L.N. Lipatov, G.B. Pivovarov, Pisma ZhETF 70 (1999) 161 (BFKLP)

Asymptotics of QED cross sections



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

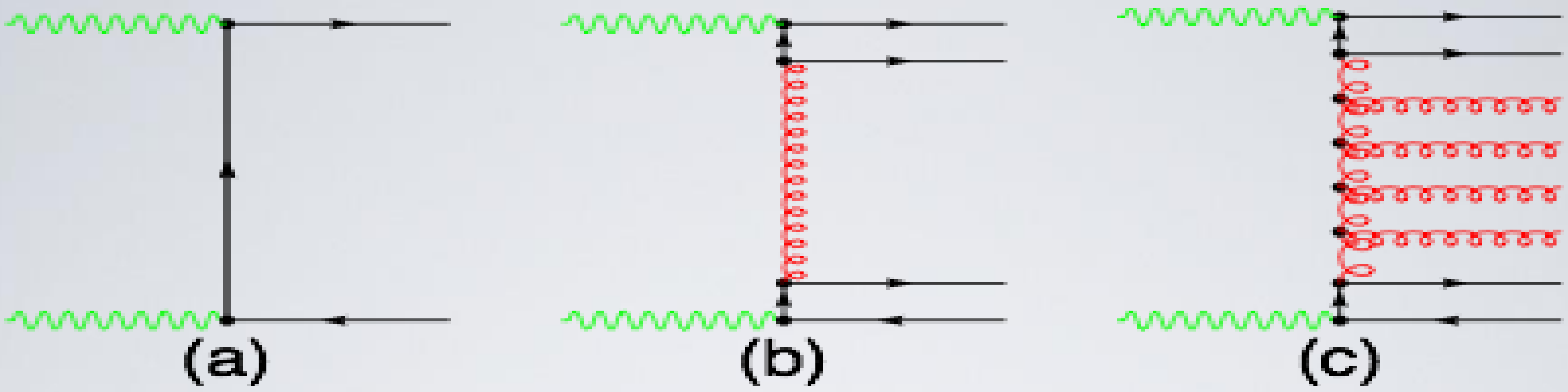
All orders: V.N. Gribov, L.N. Lipatov, G.V. Frolov & V.G. Gorshkov (69-71)
H. Cheng & T.T. Wu (69-70)

Cross section at s -> ∞: $\sim (\alpha_{QED})^4 (S/S_0)^{(aP-1)}$

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

photon: no reggeization!

High-energy limit pQCD as LL BFKL: γγ



$\sigma \sim (\alpha_{QED})^2 \log(s)/s$ $\sigma \sim (\alpha_{QED})^2 (\alpha_S)^2 \, const(s)$

Resummation of all leading logarithms: LL BFKL

gluon: reggeization!

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

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

$a_P = 1 + C\,\alpha_S \approx 1.2$ NLL BFKL

S.Brodsky, V Fadin, VK,L. Lipatov, G. Pivovarov (2001-02)

BFKLP: NLL BFKL within generalized BLM

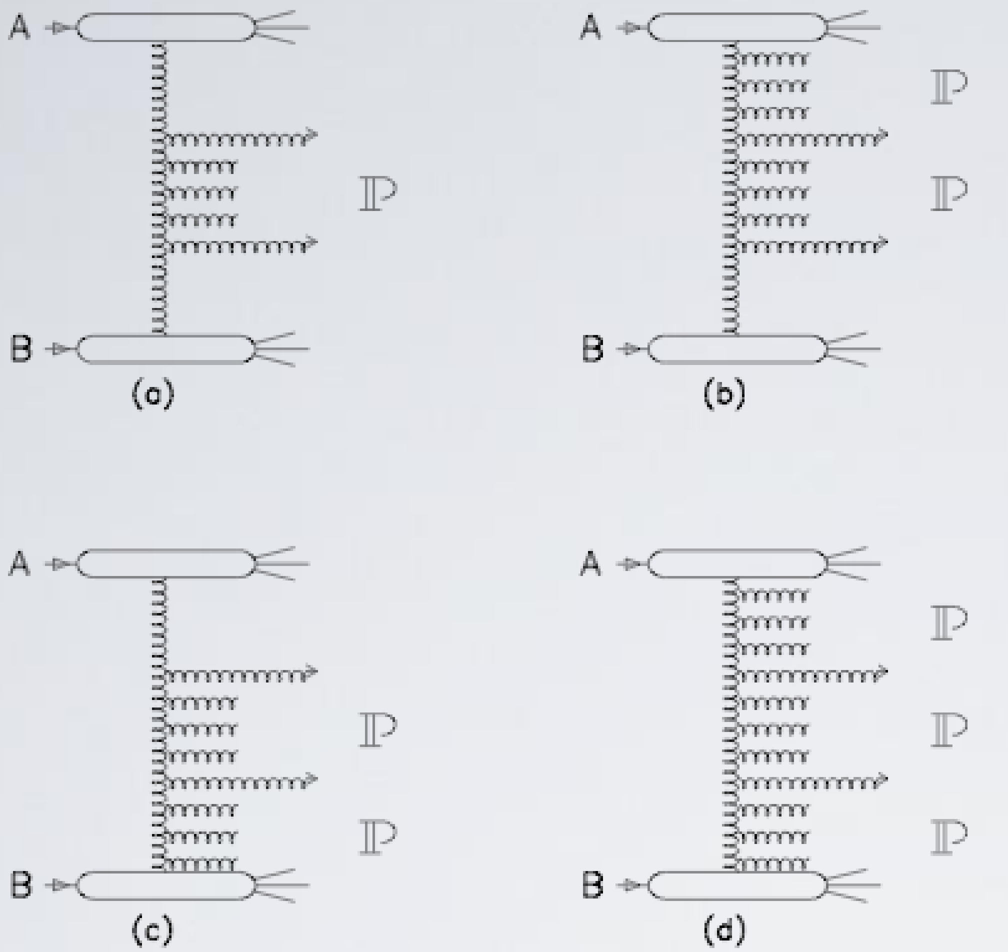
V.S. Fadin & L.N. Lipatov (89-98)
C.Camici & M. Ciafaloni (96-98)
next-to-leading log approximation (NLL) BFKL
MSbar-renormalization scheme: large corrections

S.J. Brodsky, V.S. Fadin, VK, L.N. Lipatov, G.B. Pivovarov(98-99) BFKLP
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

BFKL direct observable: dijet with large rapidity separation between jets



Jet production

GLAPD: ordering on κT
y – no ordering

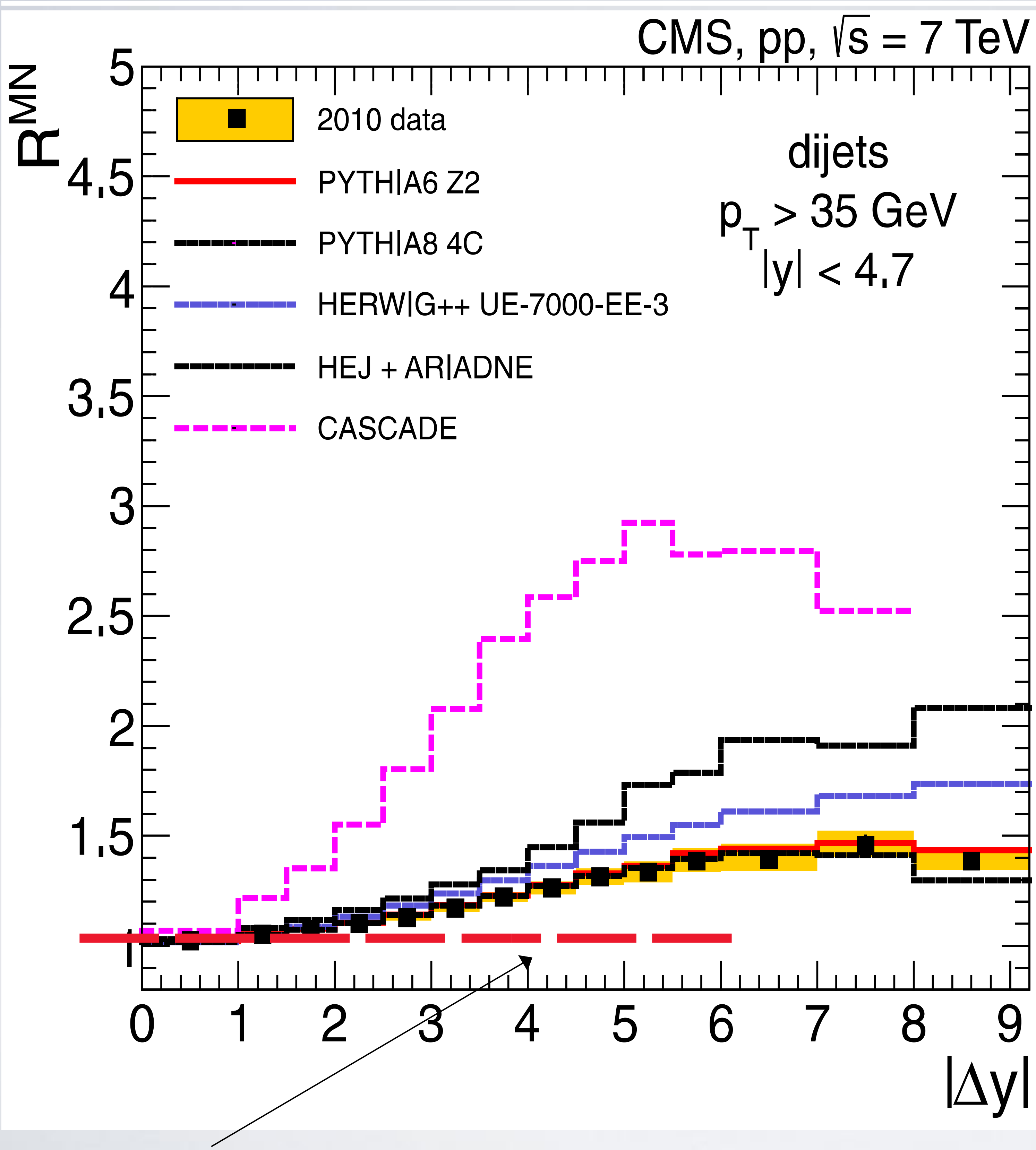
BFKL: ordering on y
κT – no ordering

Most forward/backward (Mueller-Navelet) dijets: x-section ~ exp(|Δ|y)
A. Mueller & H. Navelet, Nucl. Phys. B (1987)

Most forward/backward (Mueller-Navelet) dijets: azimuthal decorrelations
V. Del Duca & C. Schmidt, Phys. Rev. D (1994)
W.J. Stirling, Nucl. Phys. B (1994)

Inclusive dijets
VK & G.B. Pivovarov, Phys. Rev. D (1996)

CMS dijet "K-factor": indication on BFKL



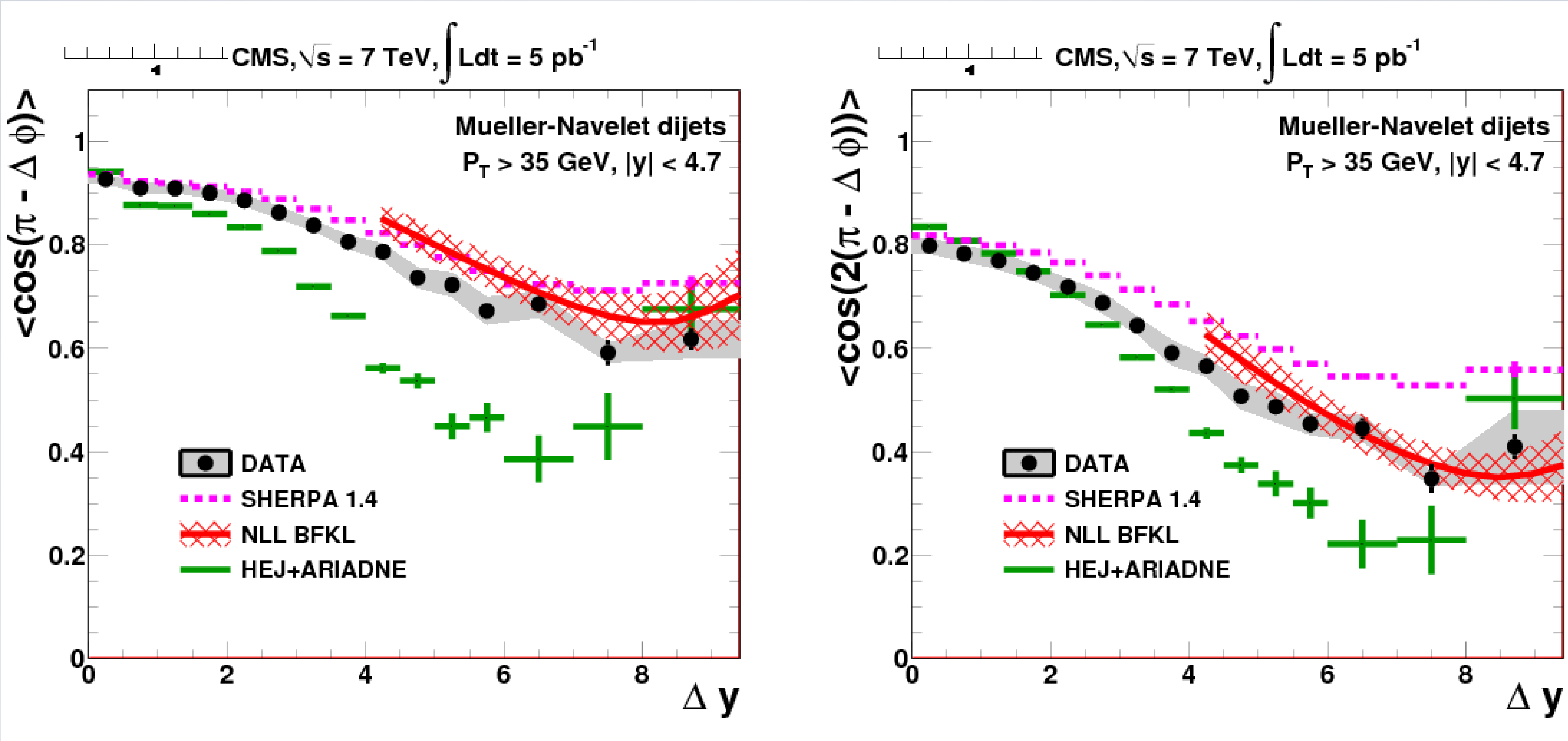
EPJ C 72 (2012) 2216
7 TeV, pT_min = 35 GeV
Δy = | | < 9.4

MC generators: contain terms beyond GLAPD

GLAPD

NRC KI - PNPI (V. Murzin, V. Oreshkin, A. Egorov, VK),
NRC KI - ITEP (V. Gavrilov, G. Safronov, I. Pozndnyakov,) INR RAS (G. Pivovarov)

Dijets: <cos> vs NLL BFKL+BFKLP



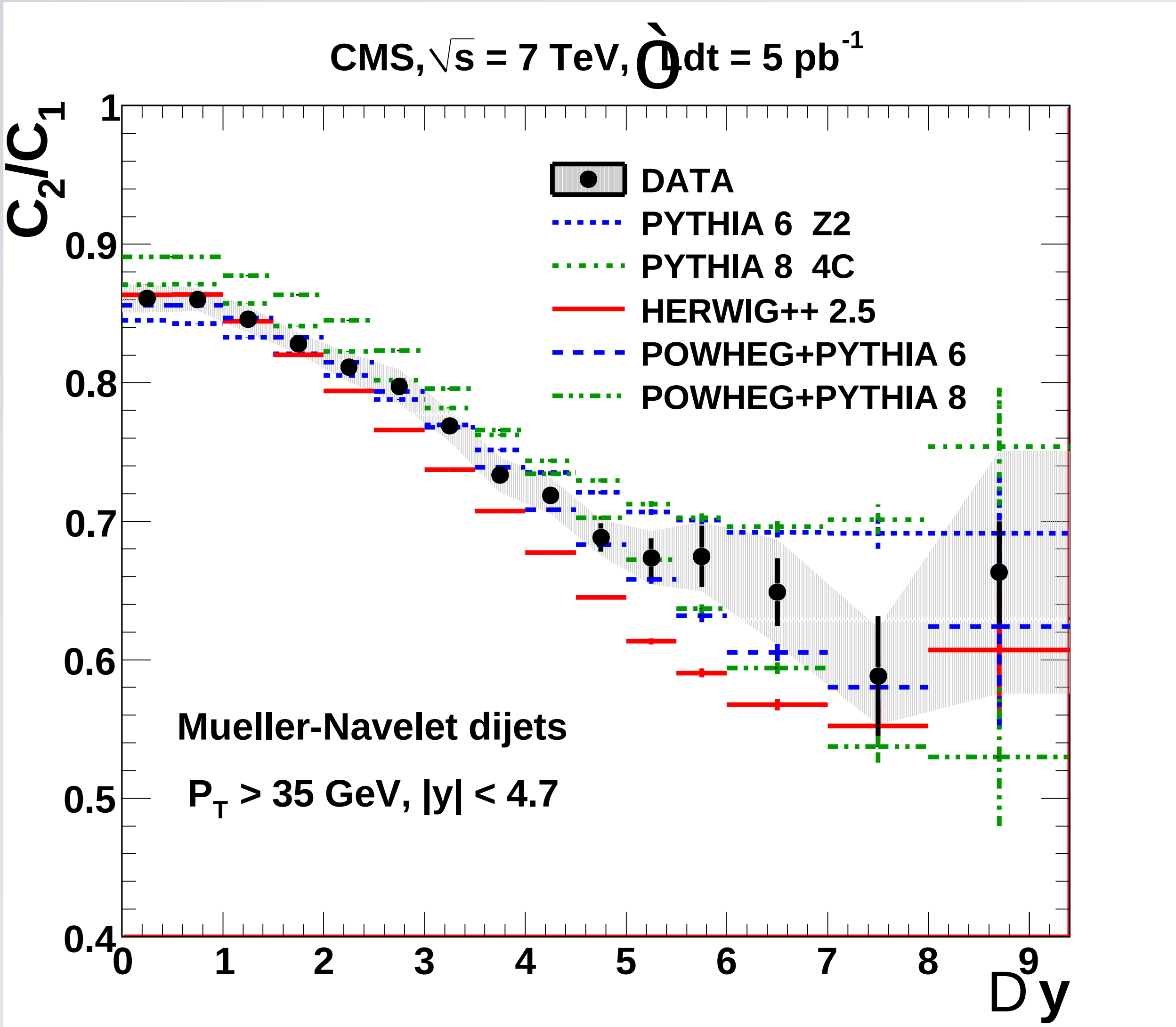
CMS (2016)
7 TeV, pT_min = 35 GeV
Δy = | | < 9.4

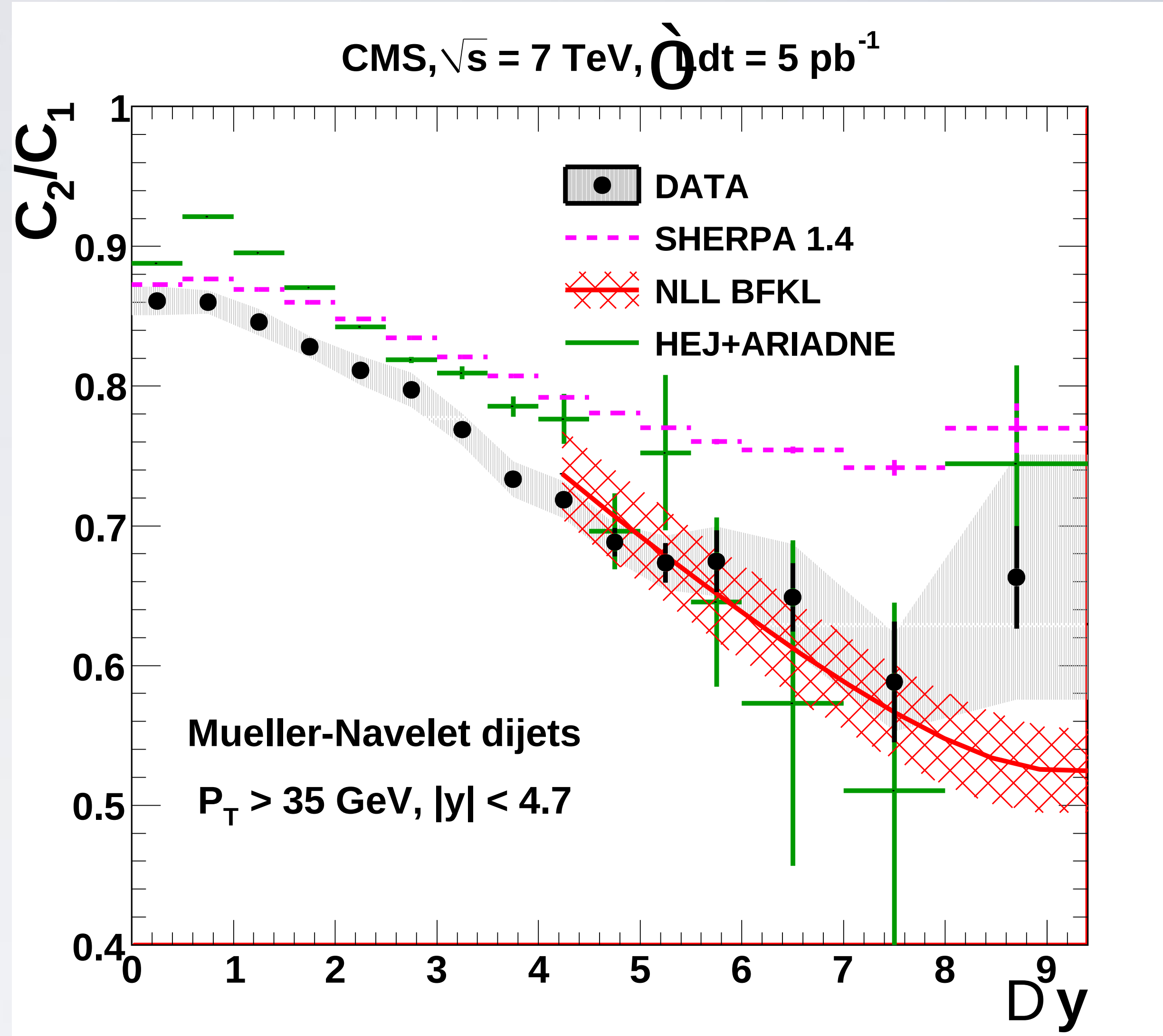
NLL BFKL + BFKLP (2014)
B. Ducloue, L. Szymanowski & S. Wallon

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

BFKL conformal feature: cosine ratio

A. Sabio Vera et al (2007)





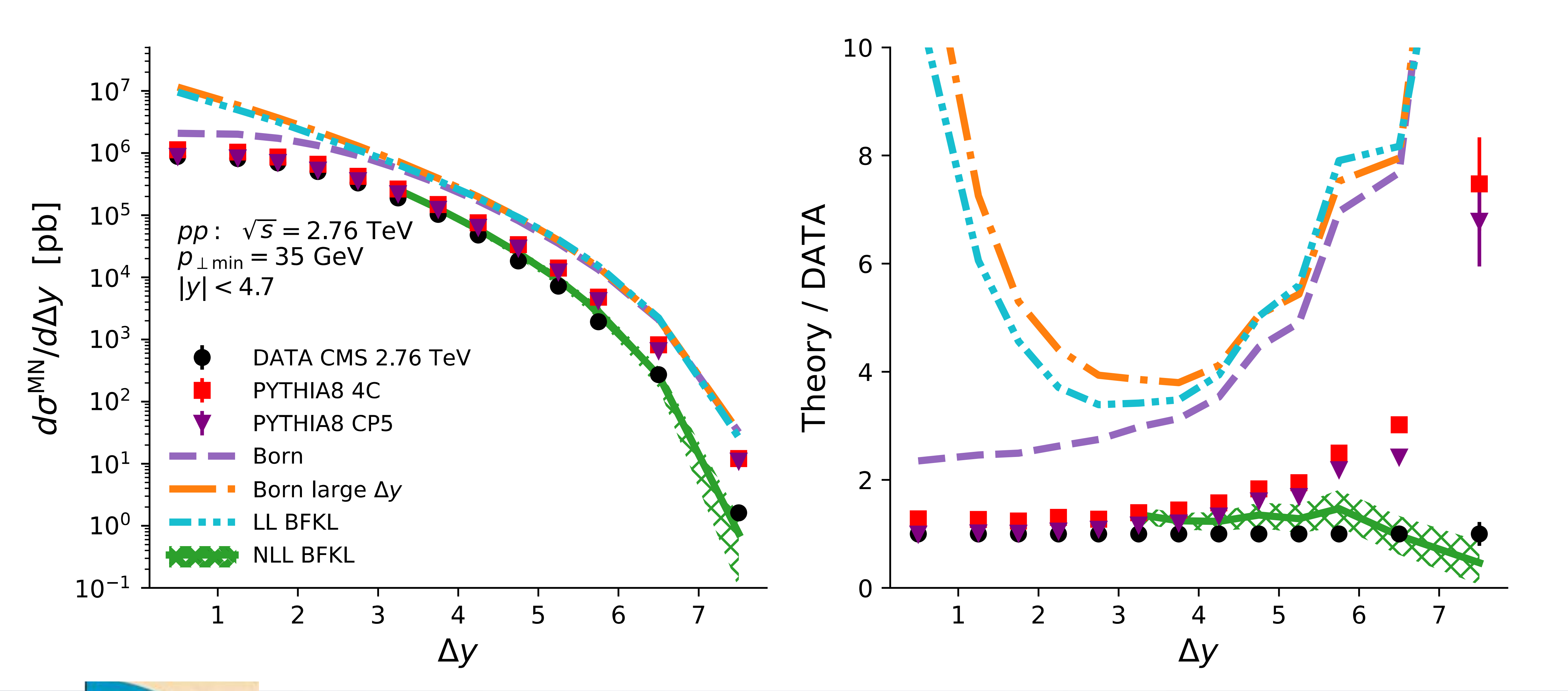
CMS (2016)
7 TeV, pT_min = 35 GeV
Δy < 9.4

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

MN dijets within NLL BFKL improved by BFKLP

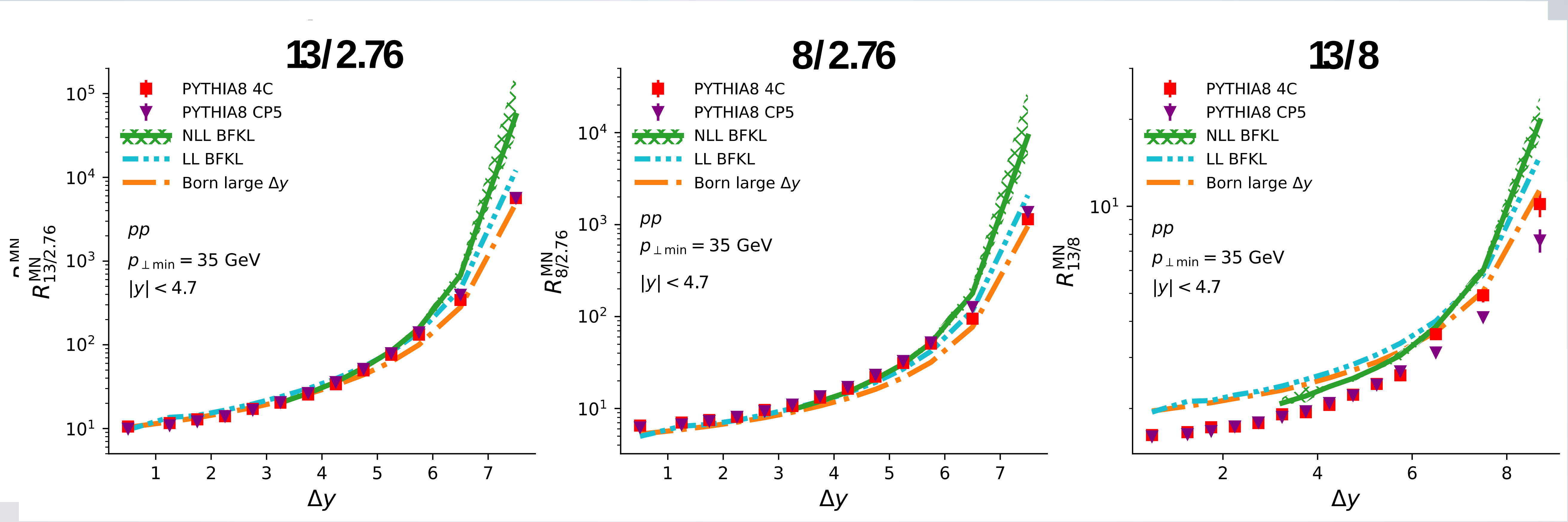
NLL BFKL with BFKLP **F. Caporale, D.Yu. Ivanov, B. Murdaca, A. Papa, Phys. Rev. (2015)**

NLL BFKL with BFKLP: 2.76 TeV dijet x-section
A. Egorov & VK, Phys. Rev. D 108 (2023) 014010



CMS Coll., A. Tumasyan, JHEP 03 (2022) 089
2.76 TeV, pT_min = 35 GeV

MN dijet x-section ratio within NLL BFKL with BFKLP: collision energy dependence at LHC



A. Egorov & VK, Phys. Rev. D 108 (2023) 014010

NLL BFKL with BFKLP prediction: strong energy dependence

BFKL evolution in pQCD: established NLL BFKL in dijets CMS 2.76 TeV

New Physics:

- new particles and interactions beyond SM
- new dynamics within SM

New dynamics within SM:

- phase transitions at dense baryon matter
-

NB. New Physics beyond SM should manifest above new high energy SM dynamics!

LL BFKL motivated approaches

LL BFKL Pomeron
2D conformal symmetry and 1/N expansion
➥ factorization into integrable theory

high-energy QCD -> integrable system!

L.N. Lipatov (1994)
L.D. Faddeev, G.P. Korchemsky (1994)

LL BFKL Pomeron with 1/N expansion
Dipole Pomeron

A.H. Mueller (1994)
N.N. Nikolaev, B.G. Zakharov (1994)

Reggeon field theory with BFKL Pomeron

E.M. Levin, A. Kovner, M. Lublinsky (2024)

LL BFKL motivated approaches

kT-factorization

S. Catani, M. Ciafaloni, F. Hautmann (1991)
J.C. Collins, R.K. Ellis (1991)
E.M. Levin, M.G. Ryskin, Yu. Shabelski, M.G. Shuvaev (1991)
G. Salam, H. Jung, N. Raicevic
S.P. Baranov, A.V. Lipatov, M.A. Malyshev, N.P. Zotov, G.I. Lykasov,
V.A. Saleev, A. Shipilova, A. Nefedov, …

CCFM evolution: interpolates with color coherence between LL BFKL and DGLAP

M. Ciafaloni (1988), S. Catani, F. Fiorani, G. Marchesini (1990)

KMR evolution: interpolates between LL BFKL and DGLAP

M.A. Kimber, A.D. Martin, M.G. Ryskin (1999)

NLL BFKL motivated approaches

SUSY N=2 NLL BFKL Pomeron
A.V. Kotikov, L.N. Lipatov (2000)

AdS/CFT-correspondence test with anomalous dimensions
A.V. Kotikov, L.N. Lipatov, A. Onischenko, V. Velizhanin (2002-2006)

Graviton-Pomeron duality
C.-I. Tan, C. Brower (2006)
L. Alvarez-Gaume et al. (2007)

Summary

- CMS measured for the first time forward rapidity events in pPb collisions at the LHC energy 8.16 TeV/pN

- CMS: for the first time e-m contribution dominates over strong one in the pPb diffractive events at high energies

- CMS: observation of NLL BFKL evolution in dijet production with large rapidity separation at LHC 2.76 TeV

- BFKL evolution reproduces main classical Pomeron properties bringing new remarkable features: conformality, integrability, AdS/CFT duality, holographic properties …

- New Physics beyond SM should manifest itself over BFKL: the new high energy SM dynamics!