LHeC:

THE ULTIMATE FACTORIZATION MACHINE

STEFANO FORTE

UNIVERSITÀ DI MILANO & INFN

UNIVERSITÀ DEGLI STUDI DI MILANO
DIPARTIMENTO DI FISICA

INFN
Istituto Nazionale
di Fisica Nucleare

LHeC WORKSHOP

CHAVANNES-DE-BOGIS, JUNE 15, 2012

SUMMARY

- COLLINEAR FACTORIZATION

  – THE BASICS: EW FINAL STATES

  – JETS: THE EVIDENCE

  – THE USES OF EXTENDED FACTORIZATION

- CLASSIC EXTENSIONS OF FACTORIZATION

  – SOFT GLUONS

  – HIGH ENERGY

- BEYOND THE CLASSIC EXTENSIONS

  – UNINTEGRATED AND TMD PDFs

  – DIFFRACTION & FRACTURE FUNCTIONS

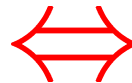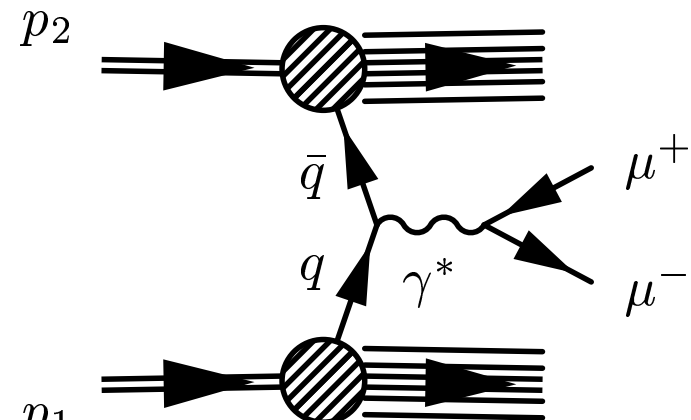- OUTLOOK

(COLLINEAR) FACTORIZATION IN QCD: THE STATEMENT

"The theorems of perturbative QCD are supported not only by proofs, but also by a combination of agreement with the results of particular calculations and agreement with experimental data"
(J.C.Collins, Foundations of Perturbative QCD, 2011)
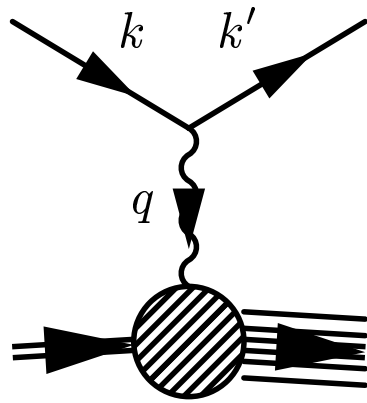
LEPTON-HADRON   HADRON-HADRON

DIMENSIONLESS CROSS SECTIONS $\sigma(x, M^2) = \frac{1}{\tau \sigma_0} \frac{d\sigma}{dM^2}$ FACTORIZE:

LEPTOPRODUCTION $\sigma_{DIS}(x, M^2) = \int_\tau^1 \frac{dz}{z} C_{DIS}(z, \alpha_s(M^2)) f\left(\frac{x}{z}\right); \ x = Q^2/2p \cdot q$

HADROPRODUCTION $\sigma_{DY}(\tau, M^2) = \int_\tau^1 \frac{dz}{z} C_{DY}(z, \alpha_s(M^2)) \mathcal{L}\left(\frac{\tau}{z}\right); \quad \tau = \frac{M^2}{s}$

PARTON LUMINOSITY: $\mathcal{L}(\tau) = \sum_{a,b} \int_\tau^1 \frac{dx}{x} f_{a/h_1}(x) f_{b/h_2}(\tau/x)$ FROM PDFs $f(z)$

IN MELLIN SPACE CONVOLUTIONS $\Rightarrow$ ORDINARY PRODUCTS
$$\sigma_{DY}(N, M^2) = \int_0^1 d\tau\, \tau^{N-1} \sigma(\tau, M^2) = C(N, M^2) \mathcal{L}(N);$$
$$\sigma_{DY}(N, M^2)/\sigma^2_{DIS}(N, M^2) = C_{DY}(N, M^2)/C^2_{DIS}(N, M^2) \text{ PDF INDEP.}$$

(COLLINEAR) FACTORIZATION IN QCD: THE STATUS

- RIGOROUSLY ESTABLISHED FOR INCLUSIVE DIS $\Rightarrow$ WILSON EXPANSION (Gross et al., early 70's)

- FIRMLY ESTABLISHED FOR INCLUSIVE AND RAPIDITY-DIFFERENTIAL PRODUCTION OF ELECTROWEAK FINAL STATES (DRELL-YAN, HIGGS) $\Rightarrow$ POWER COUNTING OF INTEGRATION REGIONS (Collins, Soper, Sterman, mid 80's)

- WELL-ESTABLISHED FOR SUFFICIENTLY INCLUSIVE AND HARD COLORED FINAL STATES (HIGH p_T JETS) $\Rightarrow$ STARTED WITH IR SAFETY (Sterman, Weinberg, mid 70's), ONGOING, WELL ESTABLISHED PHENOMENOLOGICALLY

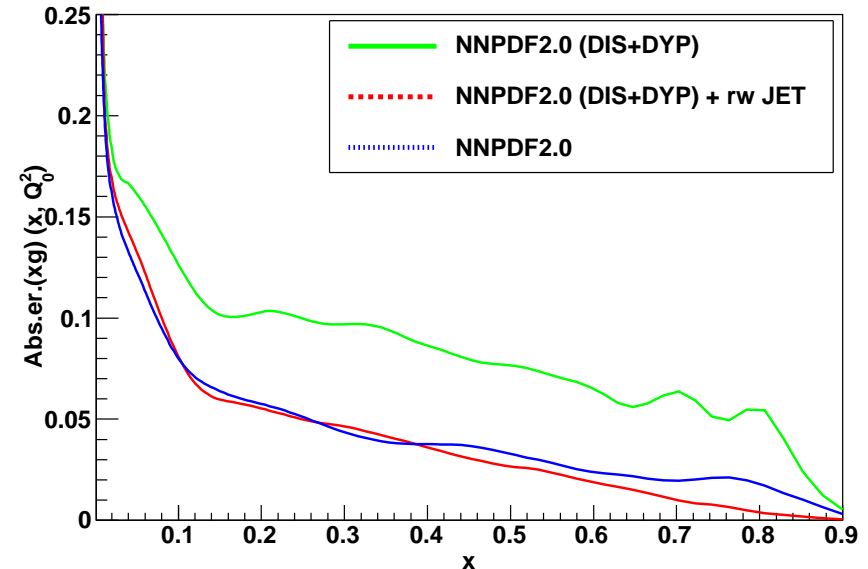- SEVERAL GENERALIZATIONS SOME OF WHICH WILL BE DISCUSSED BELOW

FACTORIZATION FOR JETS: THE EVIDENCE

- COMPARE PDF FIT WITH NO JET DATA (GLUON FROM DIS SCALING VIOLATIONS TO PDF FIT INCLUDING JETS

- CENTRAL VALUES UNCHANGED, UNCERTAINTY REDUCED

- PERFECT CONSISTENCY!
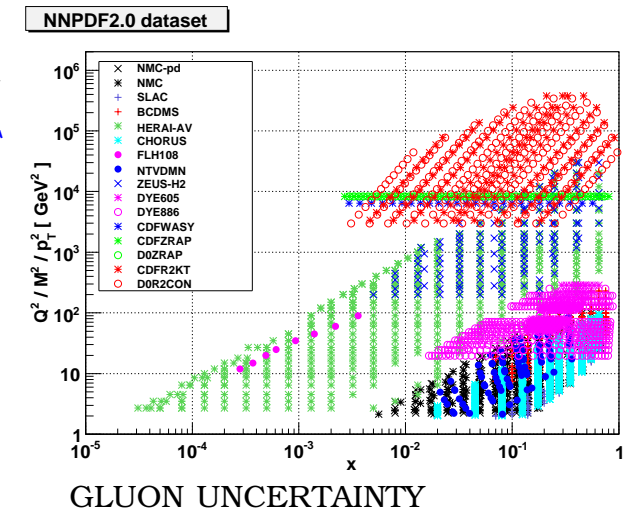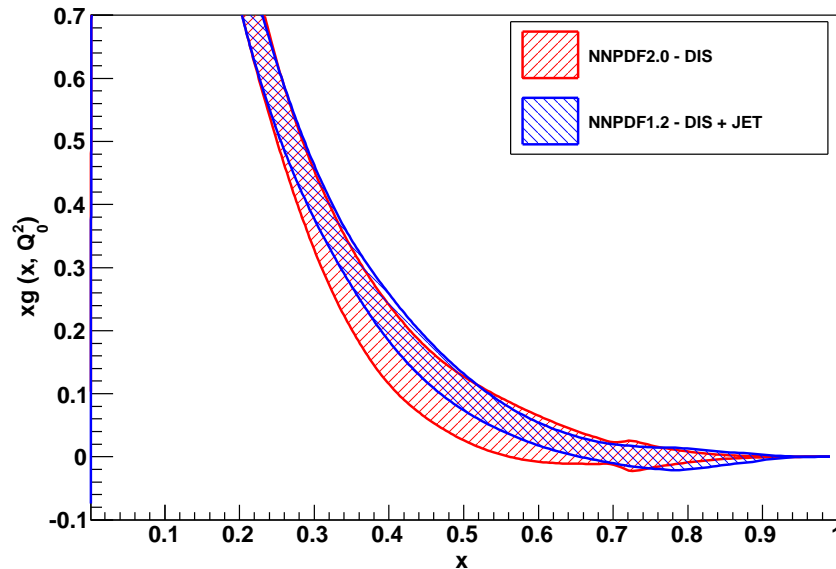

GLUON UNCERTAINTY

GLUON

- TEST OF FACTORIZATION COMES FROM COMPARISON OF ELECTROPRODUCTION & HADROPRODUCTION

- ELECTROPRODUCTION JETS PROVIDE AN INDEPENDENT TEST
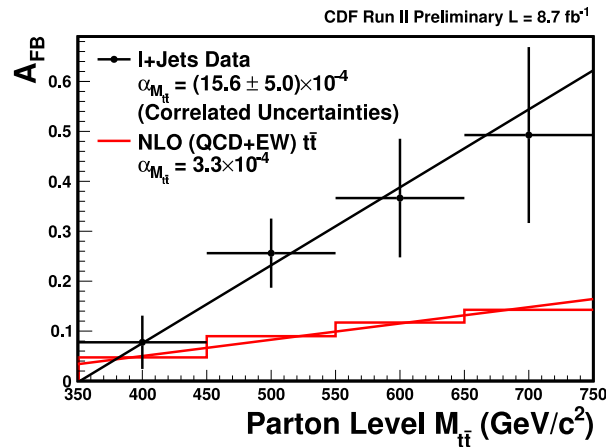
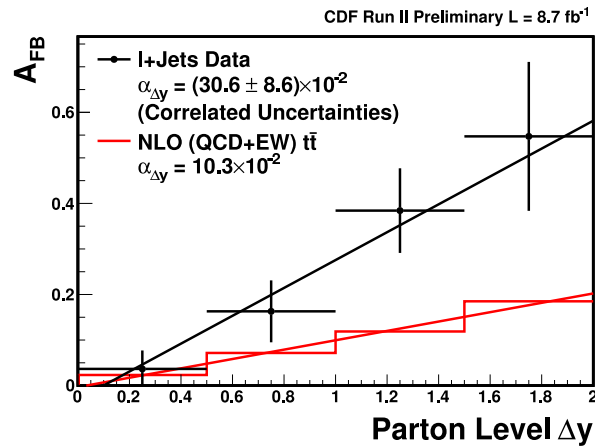# NEW PHYSICS vs FACTORIZATION I
THE TOP FORWARD-BACKWARD ASYMMETRY

- CDF MEASURES ASYMMETRY IN TOP PRODUCTION WHICH IS MUCH LARGER THAN NLO PERTURBATIVE QCD CALCULATION

- IS IT NEW PHYSICS? FIRM CONTROL OF SM & FACTORIZATION NEEDED IN ORDER TO KNOW
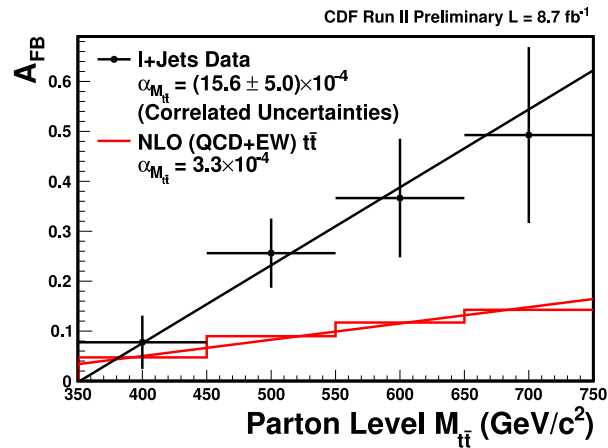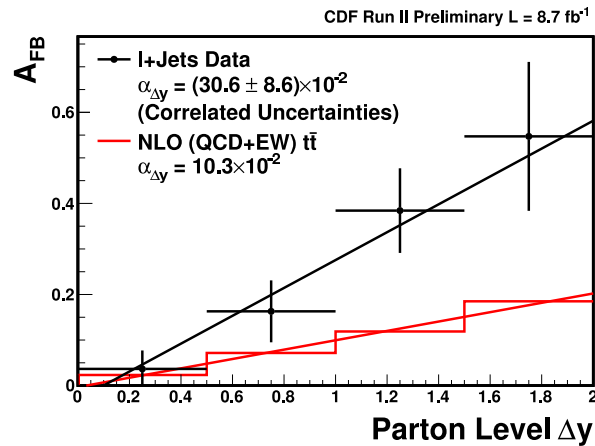
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- ASYMMETRY STARTS AT NLO: SO EFFECTIVELY CALCN IS LO

- (Sterman, SEARCH workshop, 03/2012) ASYMMETRY IS MEASURED IN THE PRESENCE OF ACCEPTANCE CUTS $\Rightarrow$ MAY LEAD TO LARGE LOGS WHICH NEED RESUMMATION (NOT INCLUDED IN STANDARD COLLINEAR FACTORIZATION)

- (Skands, Webber, Winter, 06/2012) ASYMMETRY IS GENERATED BY COHERENT PARTON SHOWERING (AS INCLUDED IN MC GENERATORS, NOT IN STANDARD COLLINEAR FACTORIZATION)

- OTHER STANDARD MODEL EXPLANATIONS BASED ON ELECTROWEAK CORRECTIONS

NEW PHYSICS vs FACTORIZATION II

HIGGS PRODUCTION WITH JET VETO
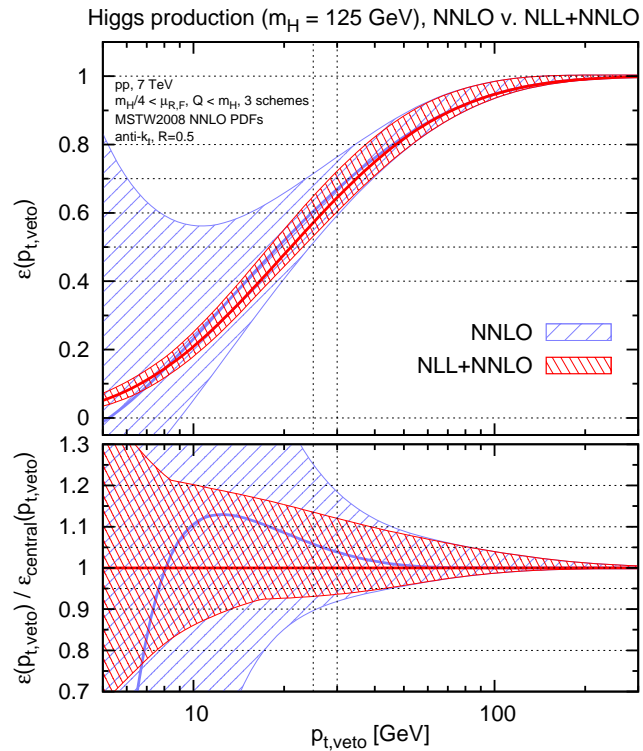
- FOR HIGGS SEARCHES, ADVANTAGEOUS TO DEFINE THE HIGGS+ 0 JET XSECT (JET VETO)

- GENERATES LARGE LOGS OF THE VETO P_T CUT

- HUGE UNCERTAINTIES UNLESS RESUMMED (Banfi, Salam, Zanderighi 03/2012), BUT RESUMMATION NOT INCLUDED IN STANDARD COLLINEAR FACTORIZATION
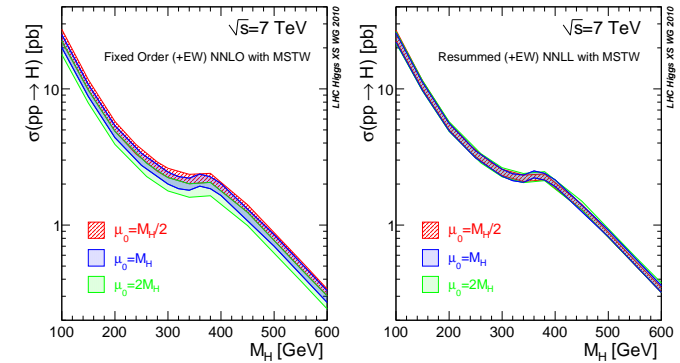
EXTENDING FACTORIZATION: SOFT GLUONS

- CORRECTIONS DUE TO RADIATION OF SOFT (LOW-ENERGY) GLUONS ARE (DOUBLE) LOGARITHMICALLY ENHANCED ($\alpha_s \ln^2$)

- RESUMMATION CAN BE PERFORMED TO ALL ORDERS THANKS TO FACTORIZATION OF SOFT CONTRIBUTIONS (CONTOPANAGOS, LAENEN, STERMAN, 1997) crudely speaking, xsect factorizes into function of M^2 and function of the soft scale

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- IN TOTAL XSECT & RAPIDITY DISTRIBUTIONS, (THRESHOLD) RESUMMATION OF $\ln \sqrt{s} \left(1 - \frac{M_X^2}{s} \right)$ CAN CORRECT SIGNIFICANTLY XSECT EVEN FAR FROM HADRONIC THRESHOLD

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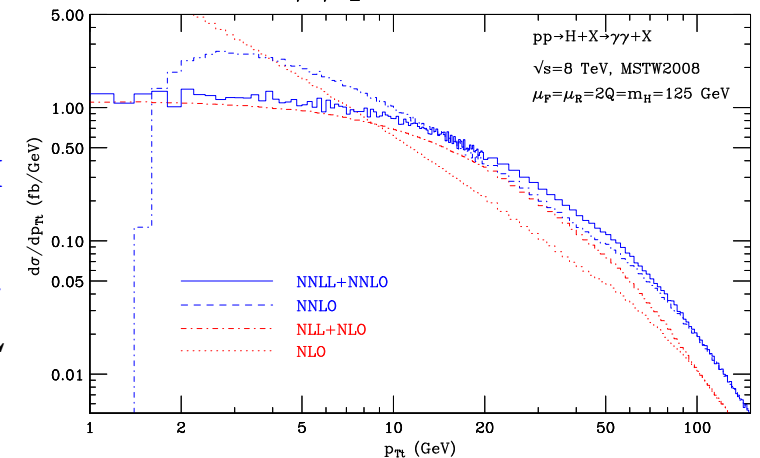
- IN p_t DISTRIBUTIONS, RESUMMATION OF $\ln p_T$ NECESSARY TO GET CORRECT SHAPE IN MEDIUM-SMALL p_T REGION

UNRESUMMED VS RESUMMED
HIGGS$\rightarrow \gamma\gamma$ TOTAL XSECT
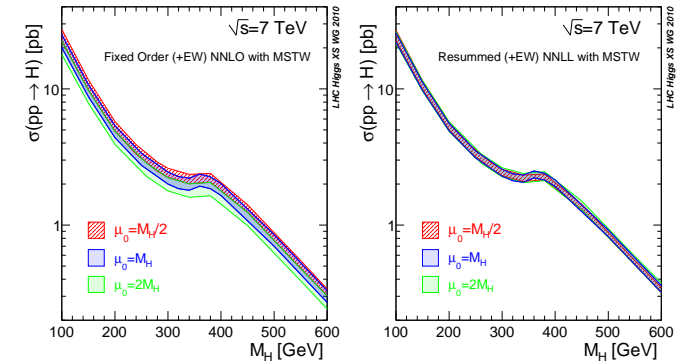
(Higgs WG, 2012)

RESUMMED VS UNRESUMMED
HIGGS$\rightarrow \gamma\gamma$ p_t SPECTRUM


(de Florian, Ferrera, Grazzini, Tommasini, 2012)

SOFT GLUONS: THE ROLE OF PDFS

- IN RESUMMED CALCULATION, MUST USE RESUMMED PDFS!

- CAN ESTIMATE THE EFFECT OF RE-SUMMATION BY DETERMINING THE DOMINANT N-SPACE REGION FOR GIVEN x, Q^2, & COMPUTE RE-SUMMED/UNRESUMMED PARTONIC CROSS SECTION RATIO

- EFFECT OF RESUMMATION FOR PRO-DUCTION OF 1 TeV FINAL STATES AT THE PERCENT LEVEL (LARGER FOR GLUON CHANNELS)

- NEED PRECISE DATA IN LARGE x RE-GION TO DETERMINE PDFS ACCU-RATELY IN RESUMMATION REGION

VALUE OF N VS FINAL STATE MASS
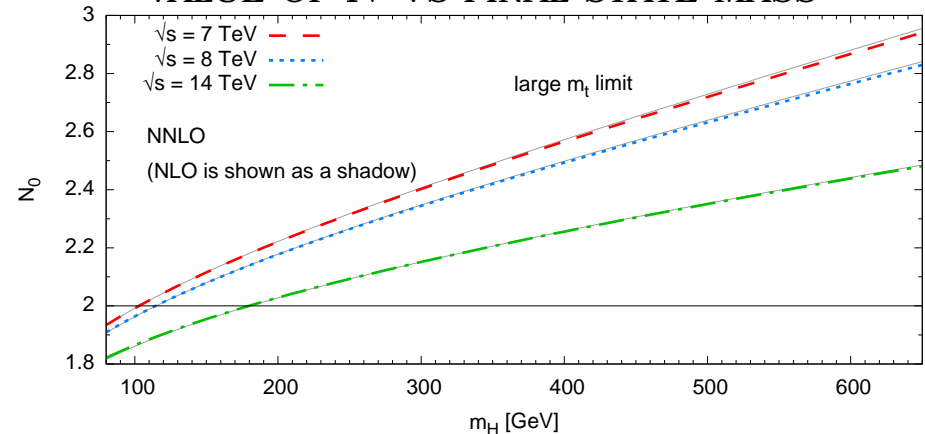
(Bonvini, SF, Ridolfi, 2012)

IMPACT OF RESUMMATION ON u QUARK VS N
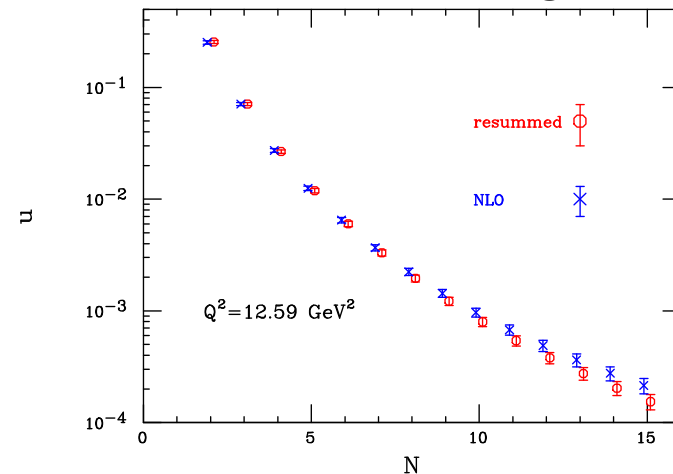
(Corcella, Magnea, 2005)

EXTENDING FACTORIZATION: HIGH ENERGY

- HIGH-ENERGY GLUON RADIATION IS ENHANCED BY $\ln \frac{s}{M^2}$

- HIGH-ENERGY FACTORIZATION
$$\sigma_{DIS}(x, M^2) = \int d^2 \vec{k}_T \int_\tau^1 \frac{dz}{z} \, C_{DIS}(\tfrac{x}{z}, \tfrac{|\vec{k}_T|^2}{M^2}, \alpha_s(M^2)) f\left(z, \vec{k}_T\right)$$
HOLDS AT LL LEVEL FOR TOTAL CROSS SECTION
$\Rightarrow$ USUAL COLLINEAR PDFS, BUT ANOMALOUS DI-MENSION AND COEFFICIENT FUNCTION RESUMMED TO ALL ORDERS (Catani, Ciafaloni, Hautmann, 1990)

- RESUMMED ANOMALOUS DIMENSIONS KNOWN TO LLX (Jaroszewicz 1982 from BFKL 1975) AND NLLX (Fadin-Lipatov 1998)

- EXTENDED TO RAPIDITY DISTRIBUTIONS (Caola, SF, Marzani, 2011)

- RESUMMED COEFFICIENT FUNCTIONS KNOWN FOR HQ PHOTO-, ELECTRO- (1990) AND HADRO-PRODUCTION (2001); DIS (1994); DRELL-YAN (2009); HIGGS INCLUSIVE (1008) AND RAPIDITY DISTN (2011)

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  DISTN (2011)

- COMBINED WITH STANDARD COLLINEAR FACTORIZA-
  TION (Ciafaloni, Colferai, Salam, Stasto, 2004 $n_f = 0$;
  Altarelli, Ball, SF, 2006 also with quarks)

(CCSS, 2006; ABF, 2008)
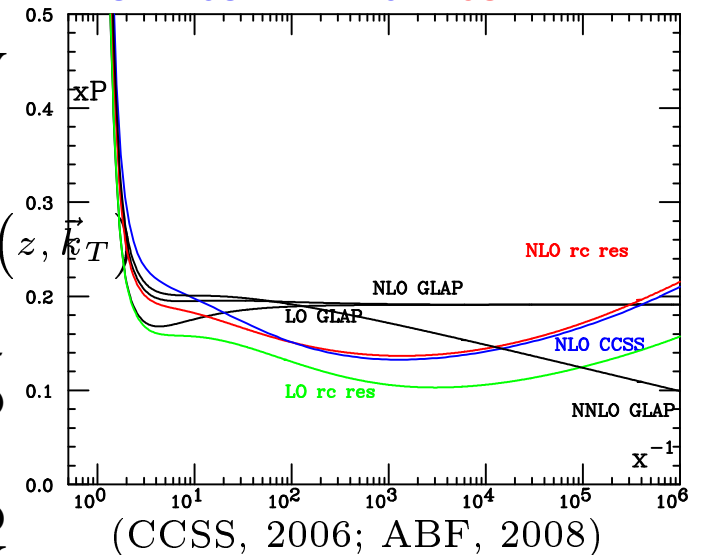
QUARK DIS COEFFICIENT FUNCTION
NLO, NNLO, RESUMMED, $\overline{MS}$, RED, $\overline{Q_0}$
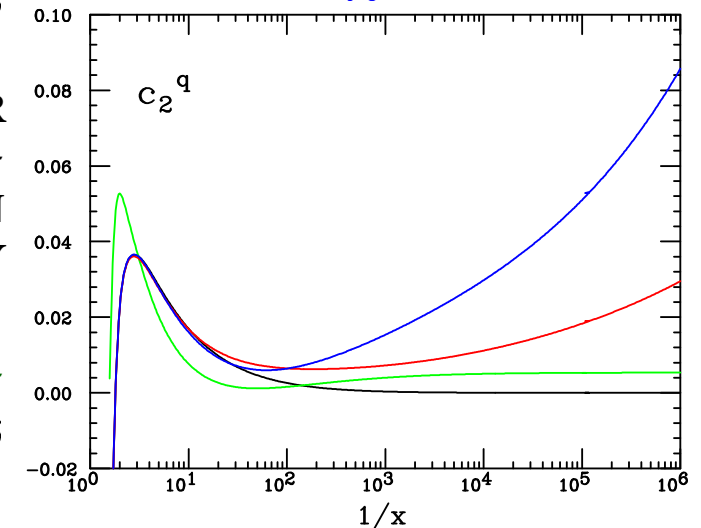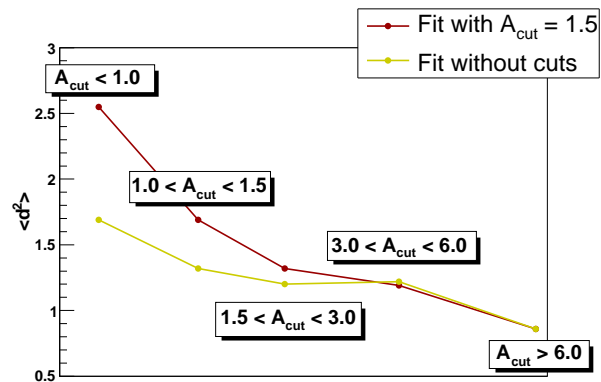

(ABF, 2008)

HIGH ENERGY: IMPACT AND EVIDENCE

- SOME EVIDENCE OF SMALL x CORRECTIONS COMES FROM PDF FITS: NNPDF AND HERAPDF OBSERVE DETERIORATION OF FIT QUALITY

- RESUMMED PDFs + RESUMMED PREDICTIONS NEEDED FOR PRECISION PHYSICS AT EDGES OF PHASE SPACE & LOW MASS FINAL STATES
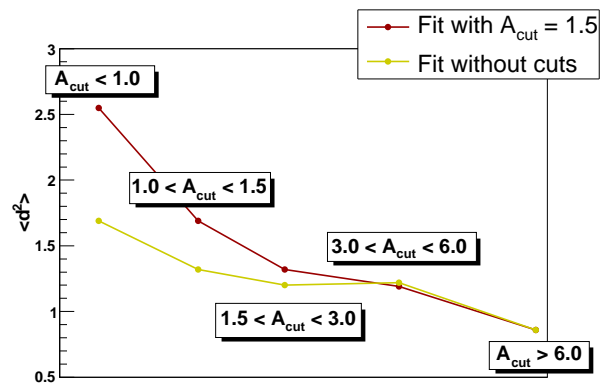
QUALITY OF PDF FIT VS x

(Caola, SF, Rojo, 2010)
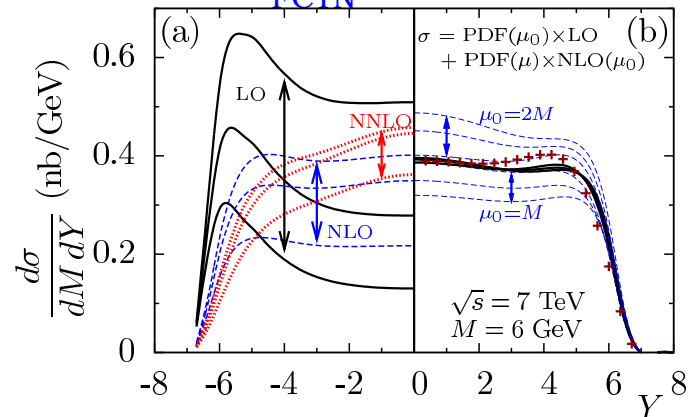
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- LOW-MASS DRELL-YAN: LARGE CORRECTIONS & UNSTABLE PERTURBATIVE EXPANSION

QUALITY OF PDF FIT VS x

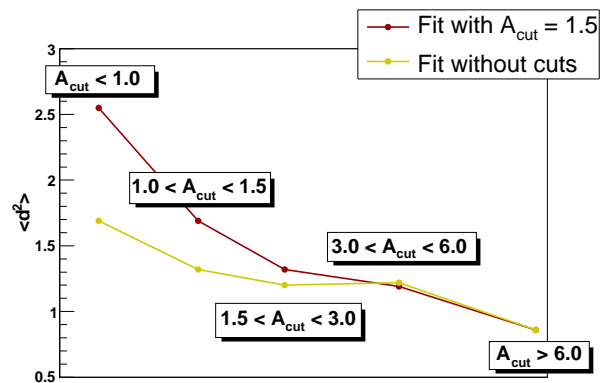LOW-MASS DRELL-YAN: COEFF FCTN

(Caola, SF, Rojo, 2010)

(de Oliveira, Martin, Ryshkin, 2012)

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- LOW-MASS DRELL-YAN: LARGE CORRECTIONS & UNSTABLE PERTURBATIVE EXPANSION

- LHCB DATA SEEM TO AGREE WITH NLO! MORE THEORETICAL/EXPERIMENTAL UNDERSTANDING NEEDED!
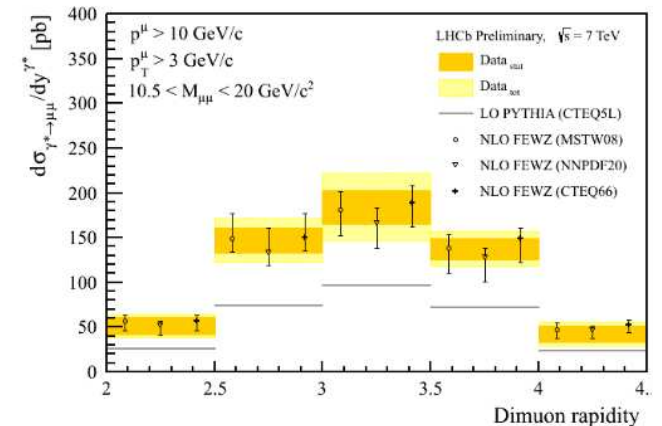
QUALITY OF PDF FIT VS x

(Caola, SF, Rojo, 2010)

LOW-MASS DRELL-YAN: COEFF FCTN
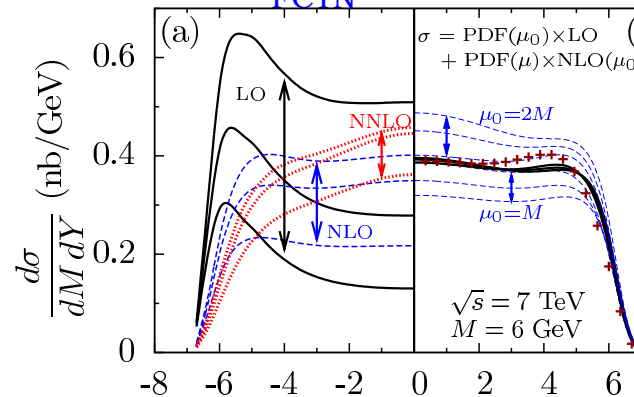
(de Oliveira, Martin, Ryshkin, 2012)

LHCB DATA

(LHCb, preliminary)

UNINTEGRATED AND TMD PDFS

- INTERPRET HIGH-ENERGY FACTORIZATION

$$\sigma_{DIS}(x, M^2) = \int d^2\vec{k}_T \int_\tau^1 \frac{dz}{z} C_{DIS}(\frac{x}{z}, \frac{|\vec{k}_T|^2}{M^2}, \alpha_s(M^2)) f\left(z, \vec{k}_T\right)$$

AS A k_T FACTORIZATION
& ASSUME IT TO BE MORE GENERALLY VALID

- PDFS BECOME k_T DEPENDENT (TMD)

UNINTEGRATED AND TMD PDFS

FORWARD JETS:
k_t-FACT VS COLLINEAR

(Deak, Hautmann, Jung, Kutak, 2010)

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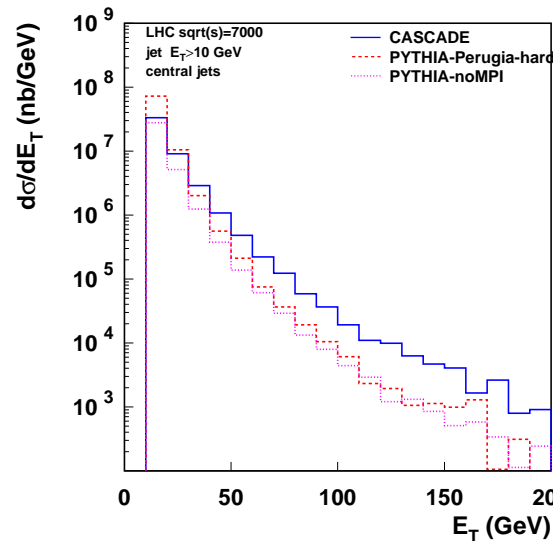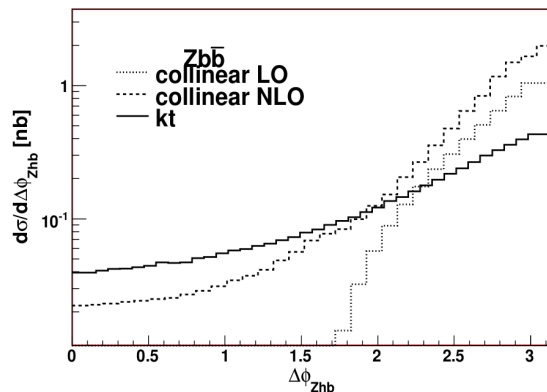AS A k_T FACTORIZATION
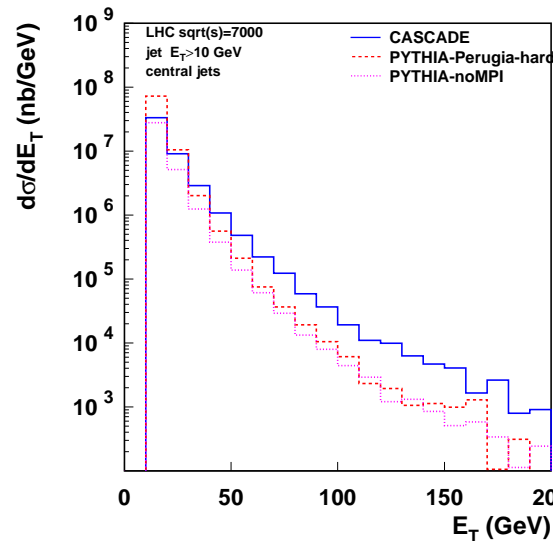& ASSUME IT TO BE MORE GENERALLY VALID

- PDFS BECOME k_T DEPENDENT (TMD)

- k_T-DEP PDF CAN BE USED FOR PARTON SHOWER-ING (COLLINS, HAUTMANN, 2000)

- IMPLEMENTED IN MONTE CARLO GENERATORS (CASCADE, H.Jung)

- SIGNIFICANT IMPLICATIONS FOR LHC OBSERVABLES & SEARCHES

UNINTEGRATED AND TMD PDFS

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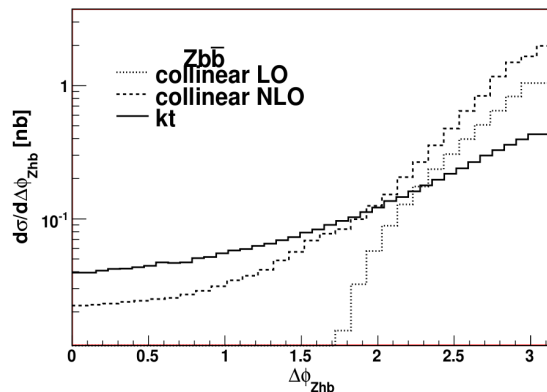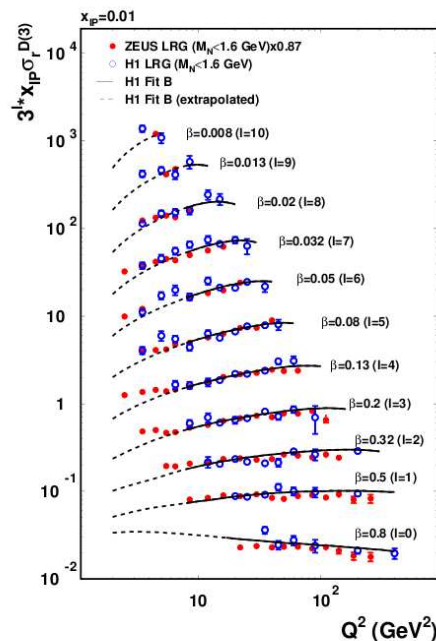
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- TMD FACTORIZATION BROKEN FOR HIGH p_T JETS (Mulders, Rogers, 2010)

- FACTORIZATION MUST BE ESTABLISHED BY COM-PARING ELECTRO- AND HADROPRODUCTION

DIFFRACTION AND FRACTURE FUNCTIONS

HERA inclusive diffraction

(Newman, Ruspa,
HERALHC Whsop 2009)

- FACTORIZATION CAN BE PROVEN FOR DIFFRACTIVE DIS (Collins, 1997; Grazzini, Trentadue, Veneziano, 1997):
$$\sigma_{DIS}^{diff}(x, M^2; x_p, t) =$$
$$\int_\tau^1 \frac{dz}{z} C_{DIS}^{diff}\left(\frac{x}{z}, \alpha_s(M^2)\right) f\left(z, \vec{k}_T; x_P, t\right)$$
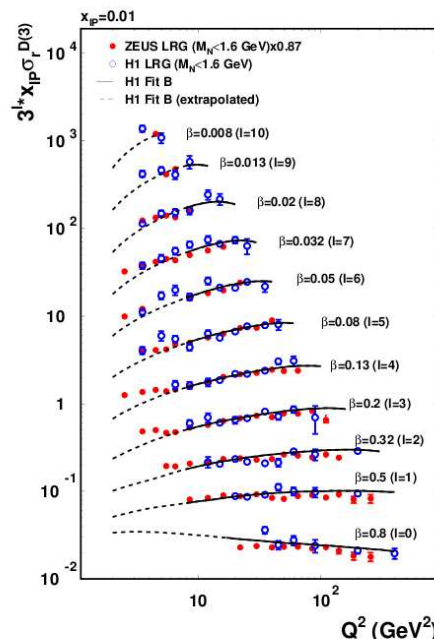WHERE $f(x, Q^2; x_P, t)$ IS A DIFFRACTIVE PDF, OR FRACTURE FUNCTION, DEP. ON THE LONGITUDINAL AND TRANSVERSE (x_P, t) MOMENTUM TRANSFERRED TO THE INTACT TARGET

- SUCCESFULLY APPLIED AT HERA, WHERE DIFFRACTION IS A SIZABLE PART OF THE CROSS SECTION

- EXPECTED TO FAIL IN HADROPRODUCTION, AND INDEED PHENOMENOLOGICALLY NOT VIABLE FOR DIFFRACTIVE JET PRODUCTION (Collins, 2001)
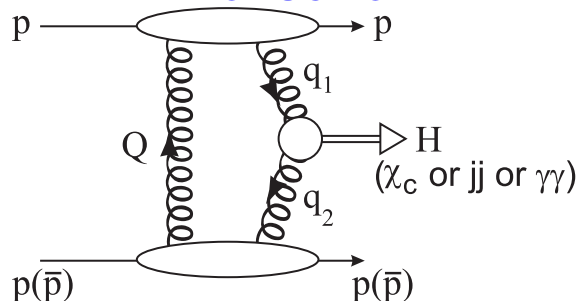
DIFFRACTION AND FRACTURE FUNCTIONS

DIFFRACTIVE PDFS AT HERA

(Newman, Ruspa,
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DIFFRACTIVE HIGGS
PRODUCTION

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- HOWEVER, DIFFRACTIVE PRODUCTION OF HIGGS (& BSM PARTICLES) SUGGESTED BECAUSE OF ITS CLEAN SIGNAL (Khoze, Martin, Ryskin)

THE ROAD AHEAD

- SOLID CONTROL OF FACTORIZATION IS A NECESSARY INGREDIENT FOR PRECISION DISCOVERY PHYSICS

- FACTORIZATION, BEYOND THE SIMPLEST CASES, IS ESTABILSHED BY AN INTERPLAY OF THEORY AND PHENOMENOLOGY

- THE CAPABILITY OF TESTING FACTORIZATION IN ELECTROPRODUCTION ALLOWS FOR DETAILED QCD STUDIES AND ENABLES NEW DISCOVERY CHANNELS AT THE LHC