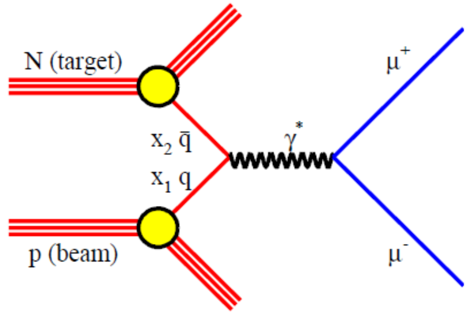


Drell-Yan physics at the LHC

from theory to phenomenology

Roman Pasechnik

Lund University, THEP group

"…our original crude fit did not even remotely resemble the data. Sid and I went ahead to publish our paper because of the model's simplicity … It is gratifying to see that … the QCD improved version has been confirmed by the experiments carried out in the last 28 years."

T-M Yan, at Drell Fest, July 31, 1998, SLAC

Drell Yan Physics Workshop, Trento
May 22^{th}, 2012

Outline

Drell-Yan as an important tool for precision physics at the LHC

- motivation for DY studies at the LHC
- sources of uncertainties and theoretical challenges
- precision SM tests and the potential New Physics searches in DY-like processes

DY theory implications specific for the LHC physics

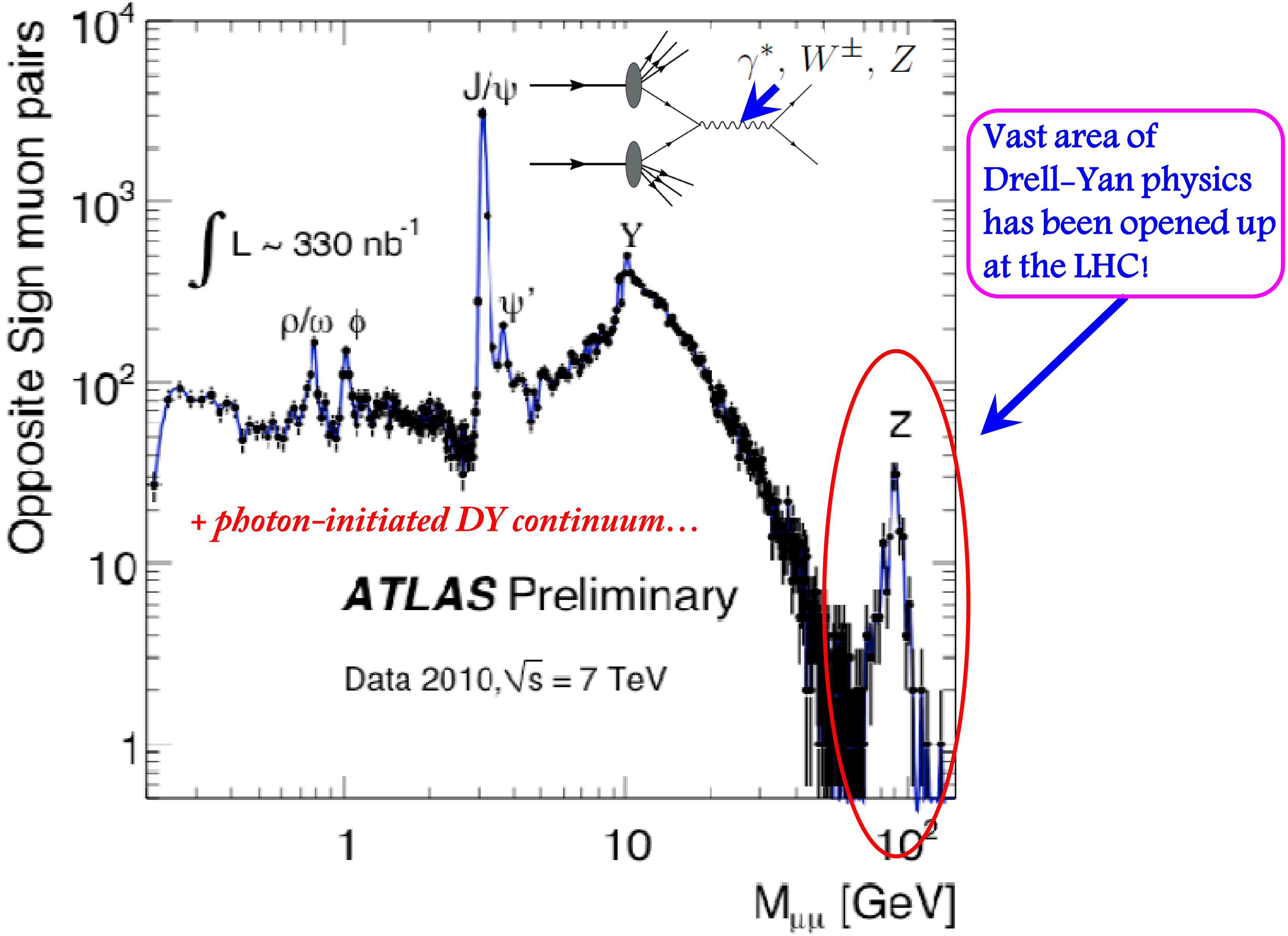
- QCD-improved Parton Model at small-x and uncertainties
- issues of the forward DY and saturation phenomenon
- TMD (kt) factorisation implications at the LHC (cursory, many talks here)
- EW/QCD corrections, large EW (Sudakov) logs, tools development
- color dipole approach for DY (pedagogical overview)
- Semi-inclusive/diffractive DY and Regge factorisation breaking
- still open issues…

Latest results from the LHC measurements

- ATLAS, CMS (cursory, next talk by I. Belotelov), LHCb
- Future prospects

Summary and Outlook

First di-muon measurements at ATLAS



Physics motivation for DY studies at the LHC

At the LHC, both CC/NC DY reactions are of major importance for:

- extraction of PDFs in extended kinematics regions (high sensitivity to PDFs)
- best access to antiquark sea PDFs
- luminosity monitoring
- calibration of detectors (as "standard candles" for both Tevatron/LHC)
- the most precise ever definition of the W mass/width (CC from transverse mass)
- high precision SM tests (e.g. for Higgs physics)
- potential source of (or background for) many New Physics contributions (e.g. contact, 4-fermion interactions, extra W` and Z`, "unparticles" etc)
- we need unpolarised DY measurements from the LHC to use their results in later polarised DY experiments (e.g. will be useful for RHIC spin physics)

Why?

- rather large cross sections (statistics) expected
  - $\sigma(W) = 30\ nb$, i.e. 3×10^8 events with $\mathcal{L} = 10\ fb^{-1}$
  - $\sigma(Z) = 3.5\ nb$, i.e. 3.5×10^7 events with $\mathcal{L} = 10\ fb^{-1}$
- clear experimental signature (efficient for high $p_\perp$ leptons pair or lepton+missing $p_\perp$ typically looking for $p_\perp > 25$ GeV in the central detector)
- no uncertainties from fragmentation functions

Overview of theoretical uncertainties

Are we ready to provide an adequately accurate theoretical description of Drell-Yan processes at LHC?

Experimental accuracy aimed at the LHC for inclusive DY observables is 1 % !

see Frixione & Mangano '04 and references therein

In order to provide a reliable accuracy for LHC data analysis, theoretical models have to reach at most 0.3 % of accuracy → a serious challenge for theory!

Sources for theoretical uncertainties in DY processes (dependent on kinematics!):

- QCD contributions in LO, NLO and NNLO (at small x/scales);
- parton shower and hadronisation effects (e.g. by PYTHIA or HERWIG);
- one-loop (or higher) EW corrections;
- resumed major higher order contributions;
- an interplay of QCD and EW corrections (HO matching issue);
- saturation effects (due to non-linear dynamics in gluon field evolution);
- partonic energy loss in cold nuclear matter (DY in pA collisions)
- couplings, hadronic vacuum polarisation, PDFs and other tuned inputs

DY results from collinear factorisation

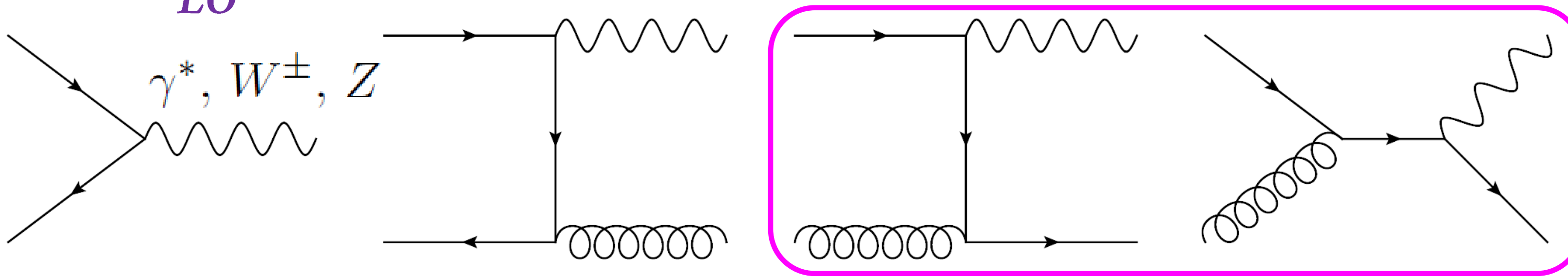
DY reaction is among a few hadron-hadron processes in which the collinear factorisation theorem has been rigorously proven (basics by Collins, Soper, Sterman'82-88)

Result known up to NNLO!

NLO (very important at high qT)

LO

Matrix element



Parton Model results

Of special importance at the LHC (small-x)!

$$\frac{d^2\sigma^{LO}}{dM^2\,dx_F} = \frac{4\pi\alpha_{em}^2}{3N_c M^4}\frac{x_1 x_2}{x_1+x_2}\sum_f e_f^2\left\{q_f(x_1,M^2)\,\overline{q}_f(x_2,M^2) + \overline{q}_f(x_1,M^2)\,q_f(x_2,M^2)\right\}$$

in LO $(x_1 p + x_2 \overline{p})^2 = M^2$ $\quad x_1 x_2 = M^2/s \equiv \tau$ $\quad$ *the hard scale* $\mu^2 = M^2$

$$x_1 = \tfrac{1}{2}\left(\sqrt{x_F^2+4\tau}+x_F\right), \qquad x_2 = \tfrac{1}{2}\left(\sqrt{x_F^2+4\tau}-x_F\right) \qquad x_F = x_1 - x_2$$

$$\frac{d^2\sigma^{NLO}}{dM^2\,dx_F} = \frac{4\pi\alpha_{em}^2}{3N_c M^4}\frac{\alpha_s(M^2)}{2\pi}\int_{z_{min}}^{1} dz\,\frac{x_1 x_2}{x_1+x_2}\sum_f e_f^2\left\{q_f(x_1,M^2)\,\overline{q}_f(x_2,M^2)\,D_q(z)\right.$$

$\overline{\text{MS}}$

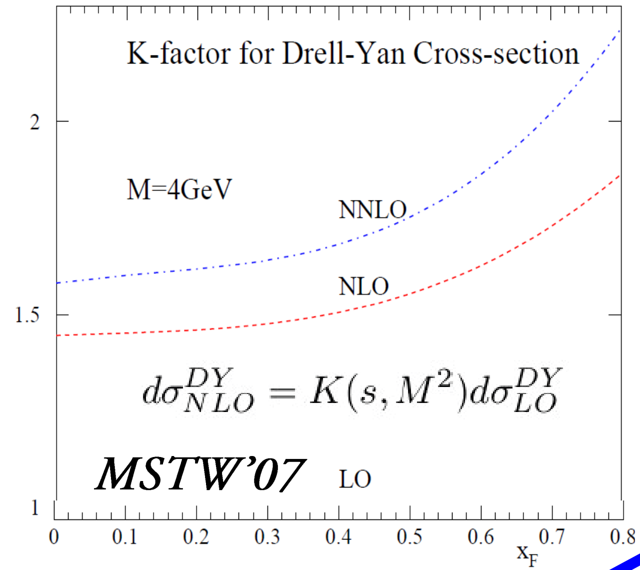
e.g.Altarelli et al '78-79

in NLO

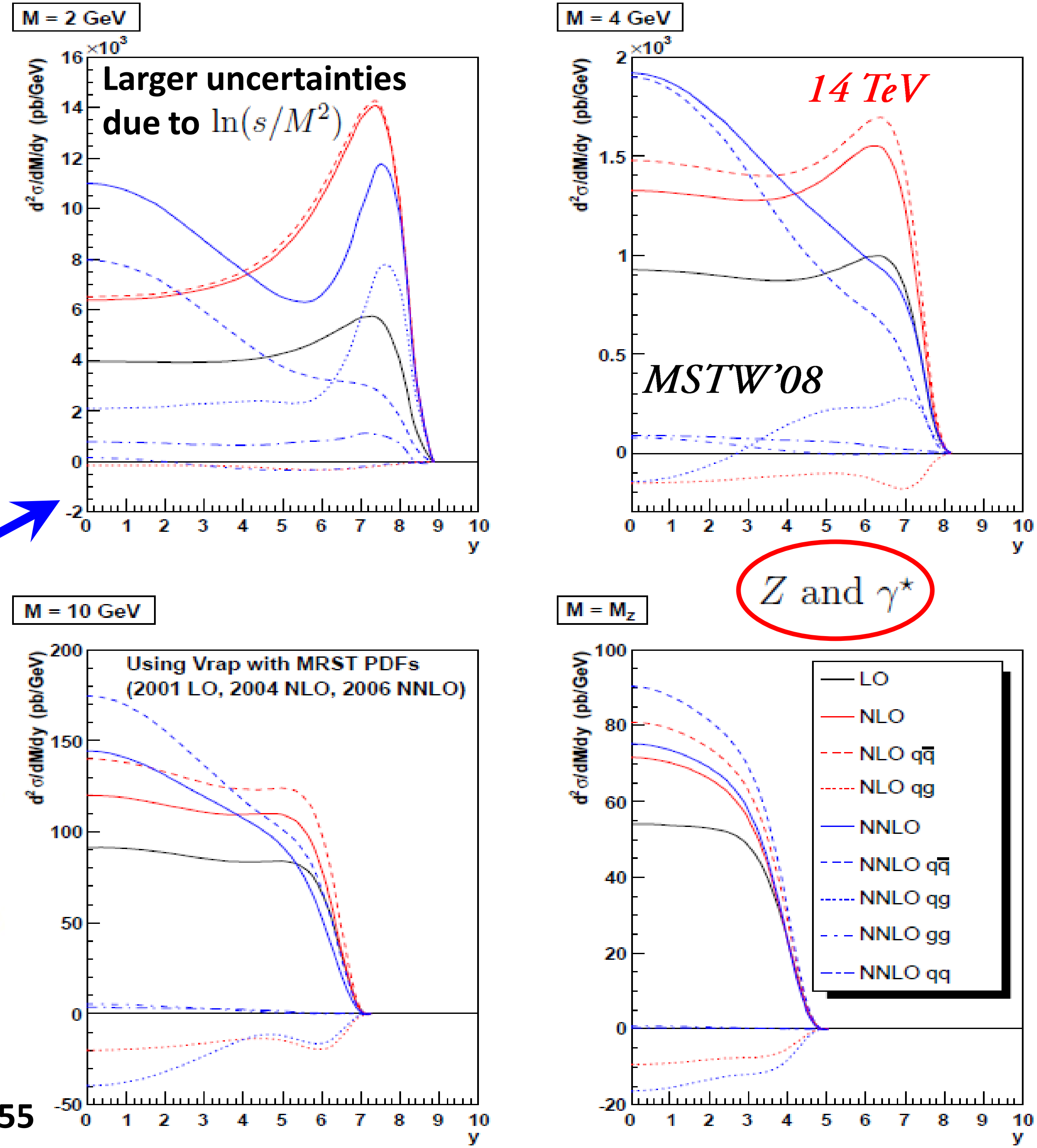
$$\left. + g(x_1,M^2)\left[q_f(x_2,M^2)+\overline{q}_f(x_2,M^2)\right]D_g(z) + (x_1 \leftrightarrow x_2)\right\}$$

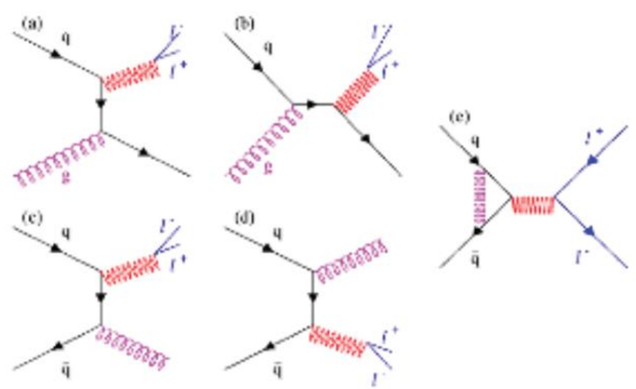
$$x_1 = \tfrac{1}{2}\left(\sqrt{x_F^2+4(\tau/z)}+x_F\right), \qquad x_2 = \tfrac{1}{2}\left(\sqrt{x_F^2+4(\tau/z)}-x_F\right) \qquad z > z_{min} = \tau/(1-x_F)$$

Role of the HO QCD corrections to NC DY at the LHC



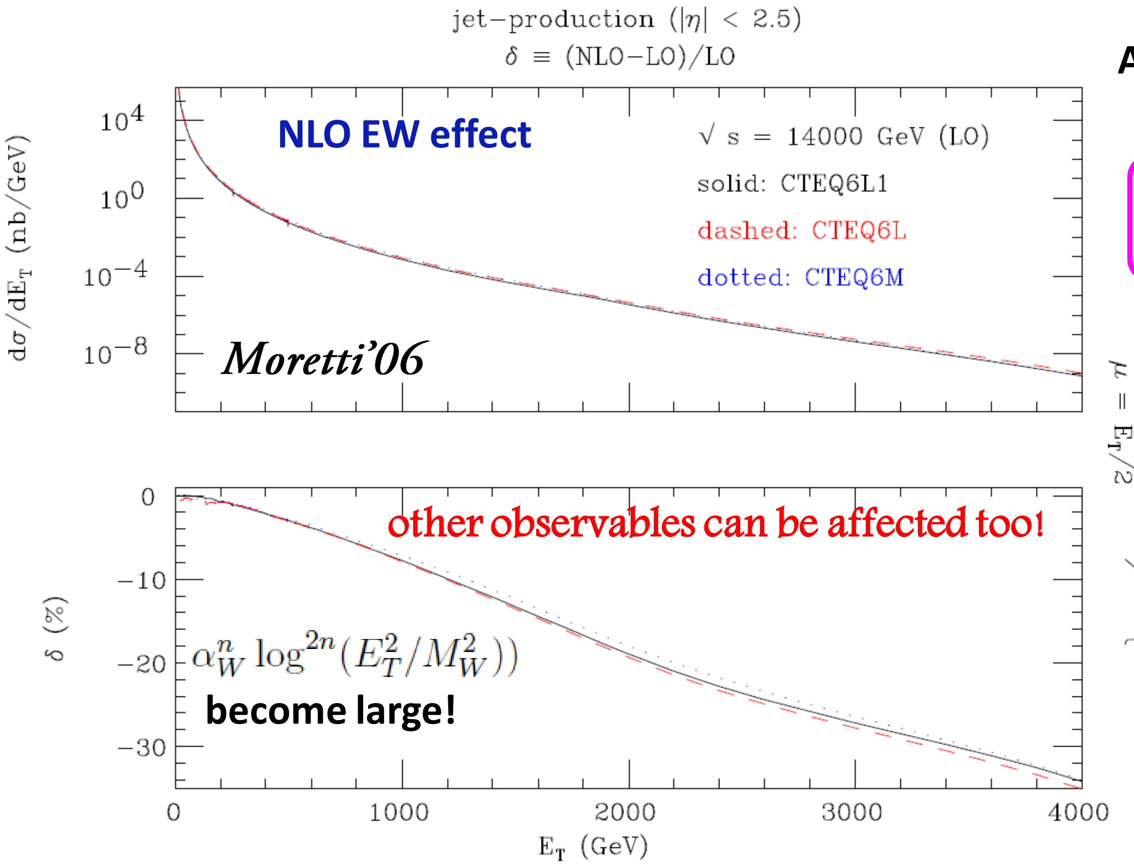
resummation is needed!





For more details, see Roeck, Thorne "Structure Functions", arXiv:1103.0555

Importance of EW corrections and QED-Improved PDFs

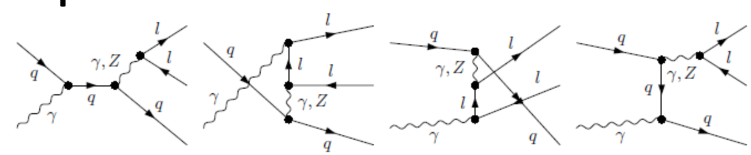


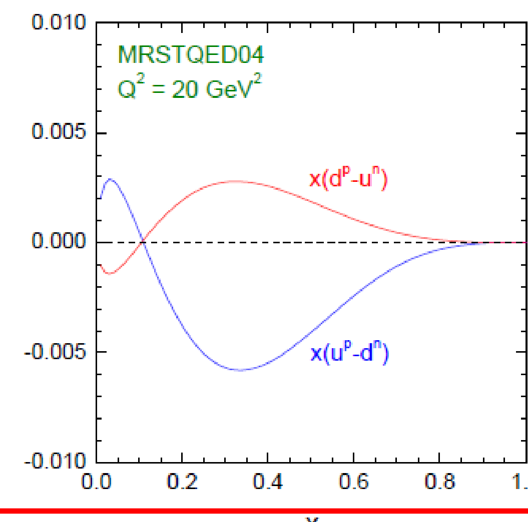
At high scales $\alpha \sim \alpha_S^3$

EW corrections can be as large as NNLO QCD ones!

Large EW logs may affect the extraction of PDFs, so they must be carefully treated!

photon-induced Drell-Yan:





Real/virtual contributions of the all gauge bosons to the initial/final states is necessary at the LHC!

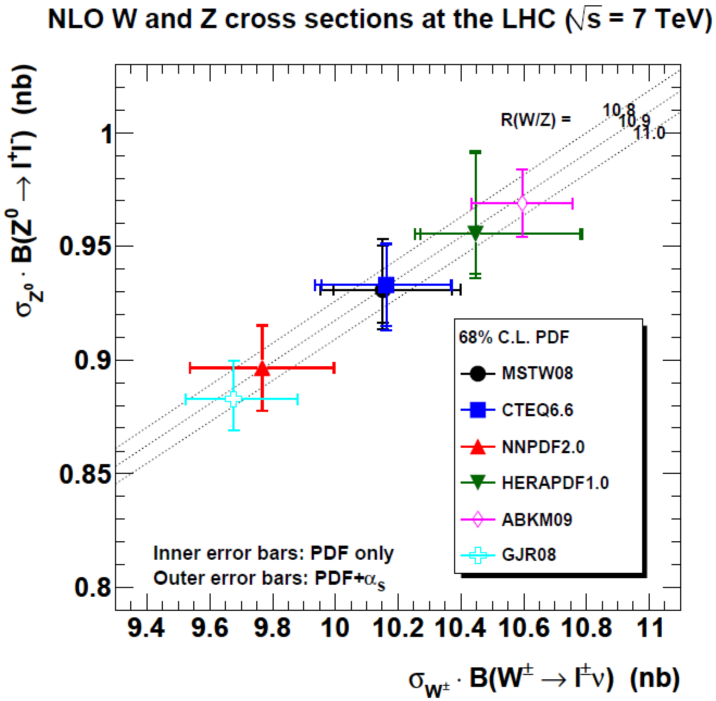
The simplest way: QED-improved DGLAP evolution, e.g. at LO

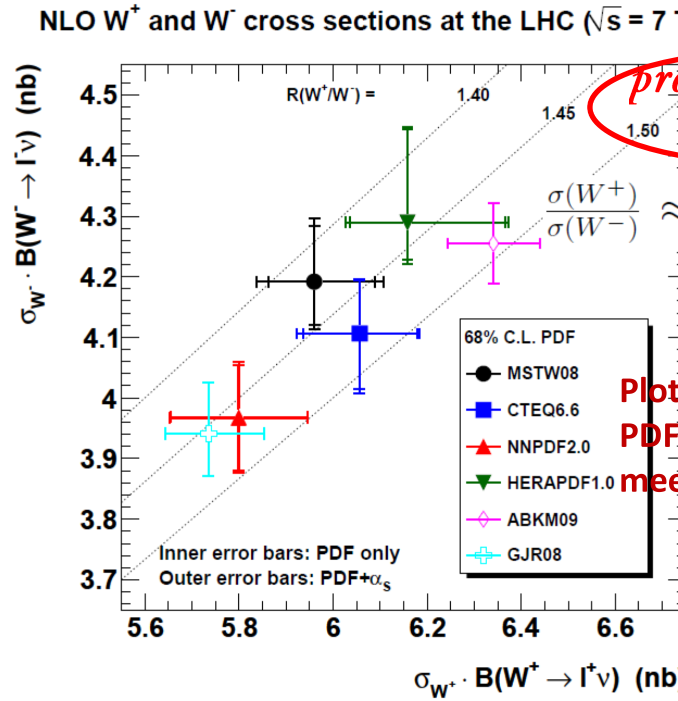
$$\frac{\partial q_i(x,\mu^2)}{\partial \log \mu^2} = \frac{\alpha_S}{2\pi}\int_x^1 \frac{dy}{y}\left\{P_{qq}(y)\, q_i(\frac{x}{y},\mu^2) + P_{qg}(y,\alpha_S)\, g(\frac{x}{y},\mu^2)\right\}$$
$$+ \frac{\alpha}{2\pi}\int_x^1 \frac{dy}{y}\left\{\tilde{P}_{qq}(y)\, e_i^2 q_i(\frac{x}{y},\mu^2) + P_{q\gamma}(y)\, e_i^2 \gamma(\frac{x}{y},\mu^2)\right\}$$

$$\frac{\partial \gamma(x,\mu^2)}{\partial \log \mu^2} = \frac{\alpha}{2\pi}\int_x^1 \frac{dy}{y}\left\{P_{\gamma q}(y)\, \sum_j e_j^2\, q_j(\frac{x}{y},\mu^2) + P_{\gamma\gamma}(y)\, \gamma(\frac{x}{y},\mu^2)\right\}$$

$$\int_0^1 dx\, x\left\{\sum_i q_i(x,\mu^2) + g(x,\mu^2) + \gamma(x,\mu^2)\right\} = 1$$

Sensitivity of predictions for the LHC to PDFs



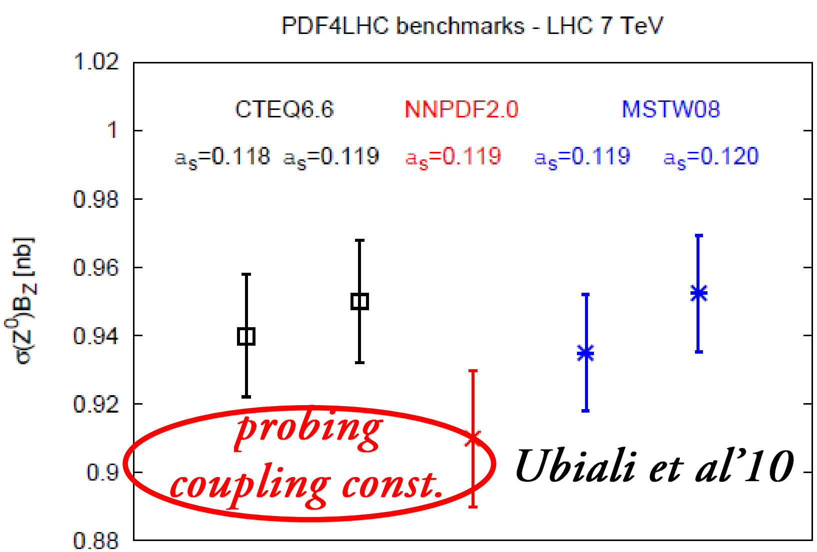


probing valence at small-x

$$\frac{\sigma(W^+)}{\sigma(W^-)} \approx \frac{u(x)\bar{d}(x)}{d(x)\bar{u}(x)} \approx \frac{u(x)}{d(x)}$$

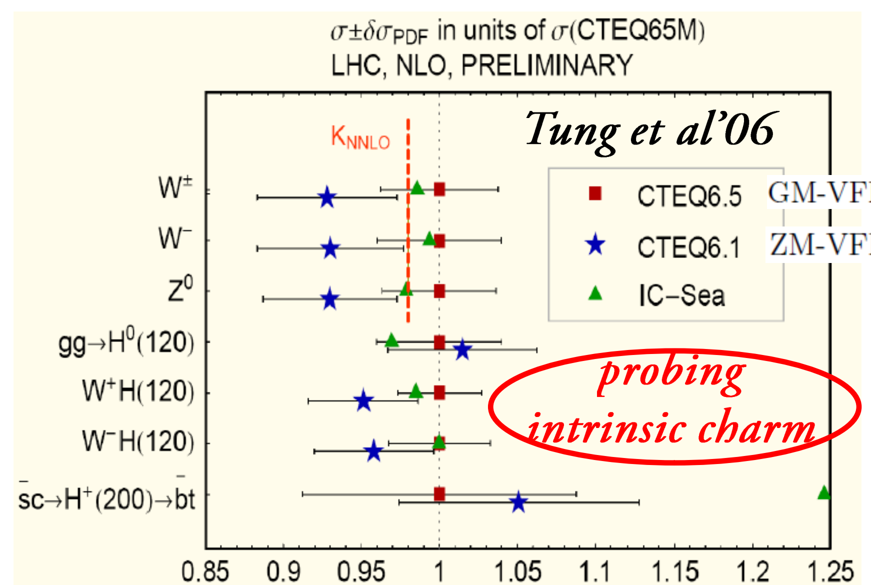
$$x \to 0$$

Plots by G. Watt, PDF4LHC benchmark meeting, CERN 2010



probing coupling const.

Ubiali et al'10



Tung et al'06

GM-VFNS

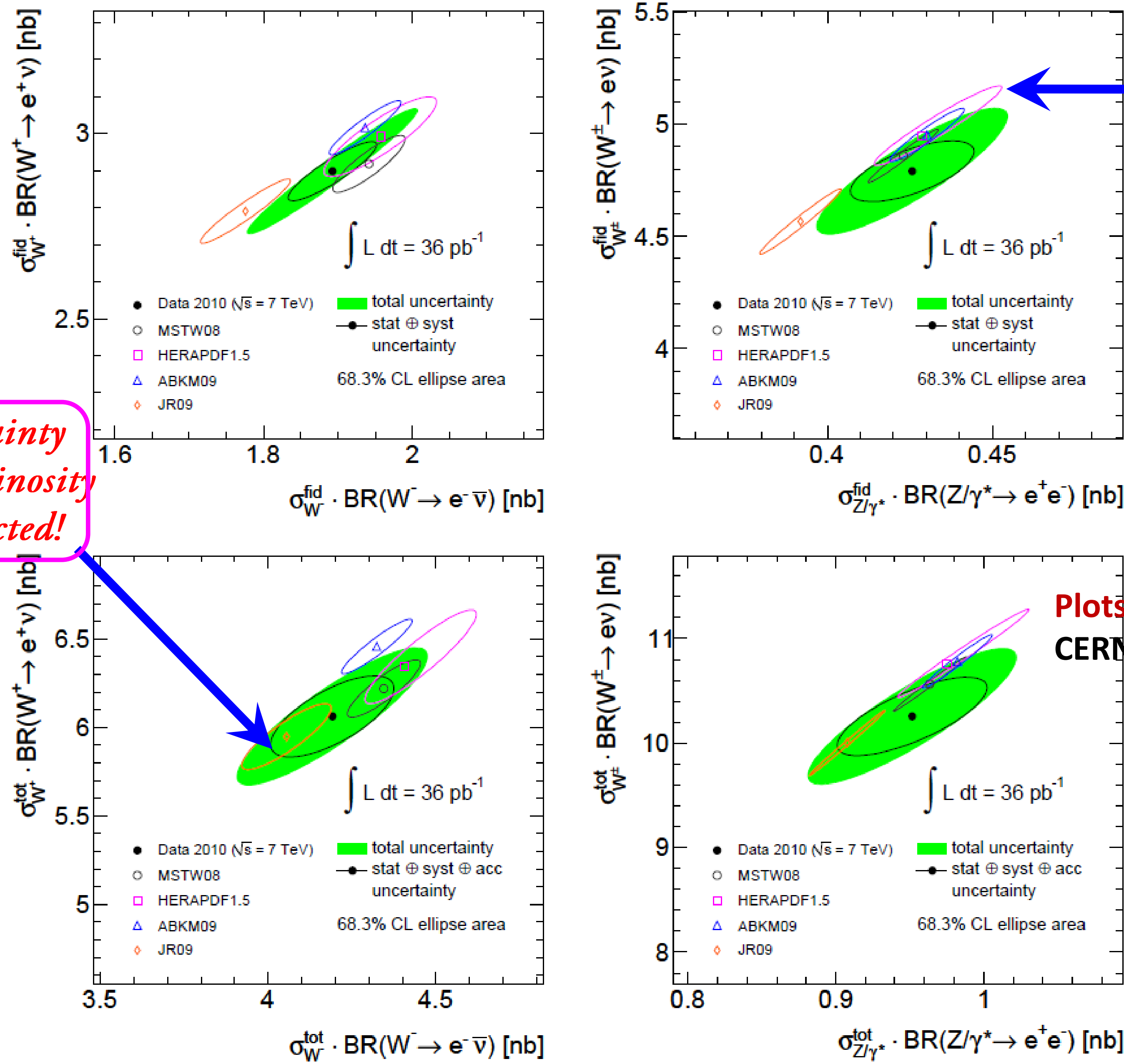
ZM-VFNS

probing intrinsic charm

ATLAS DY data vs theory: total DY CS in electron channel

Predictions reflect PDF uncertainties only!

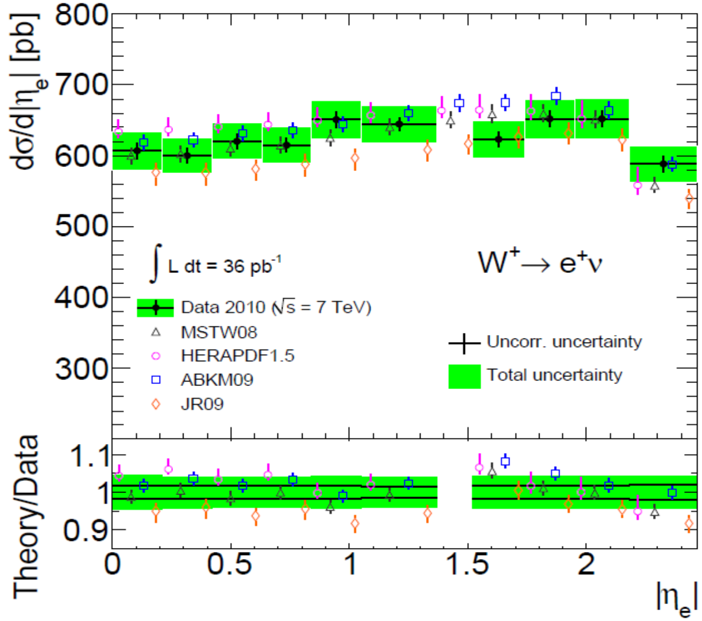
Uncertainty from luminosity is neglected!

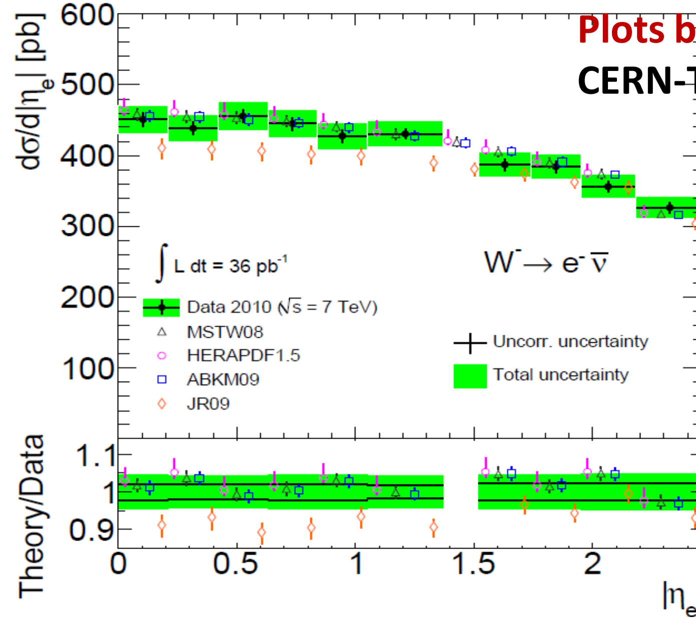


Plots by J. Hartert,
CERN-THESIS-2011-186

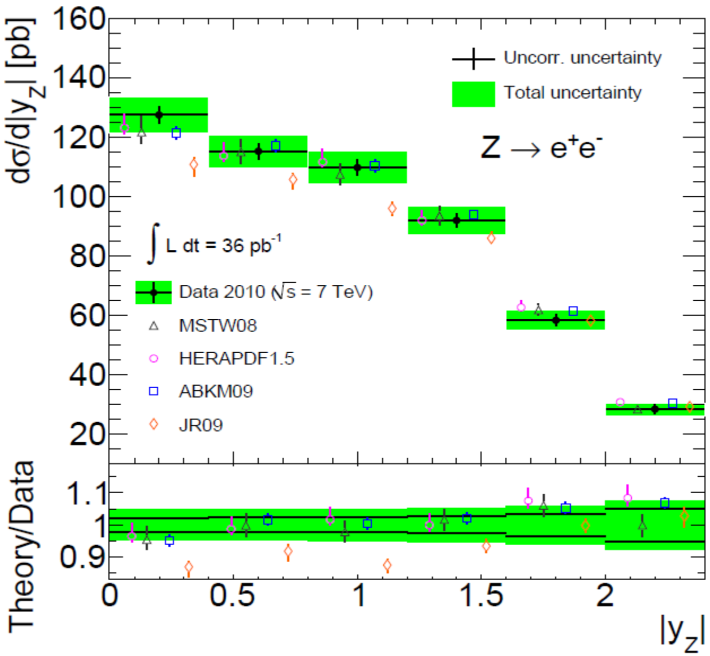
ATLAS DY data vs theory: electron rapidity distributions

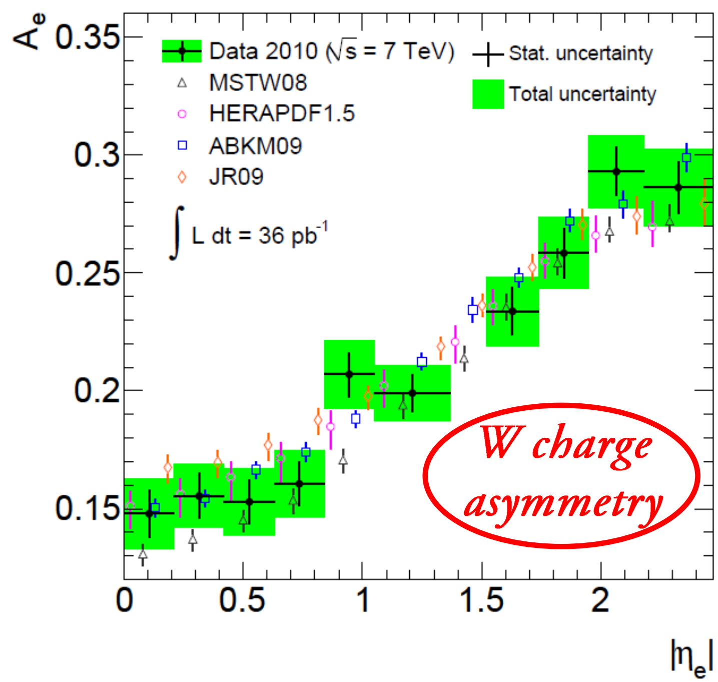
Plots by J. Hartert,
CERN-THESIS-2011-186



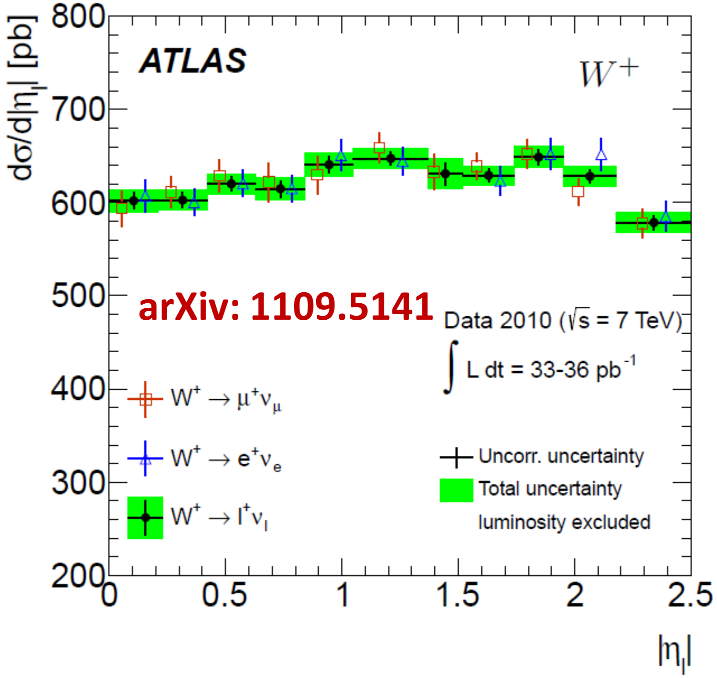


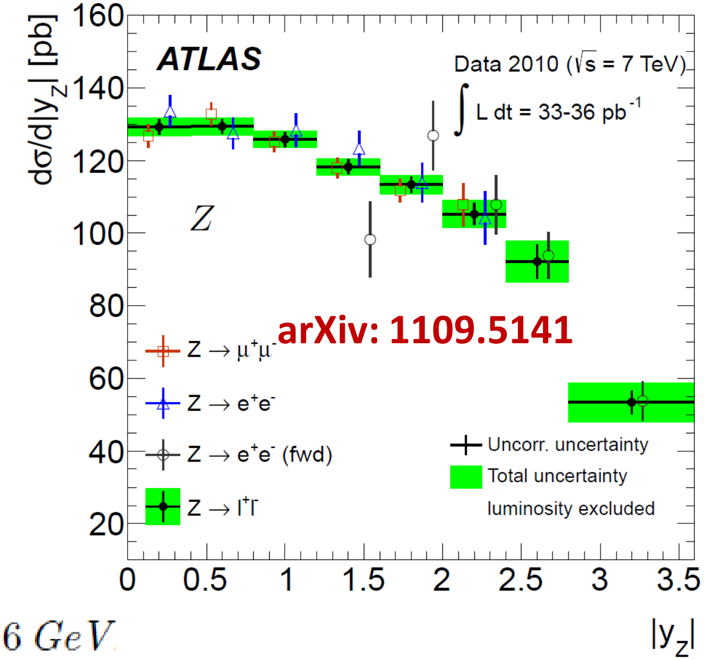
Allow to make a preliminary discrimination of PDF models



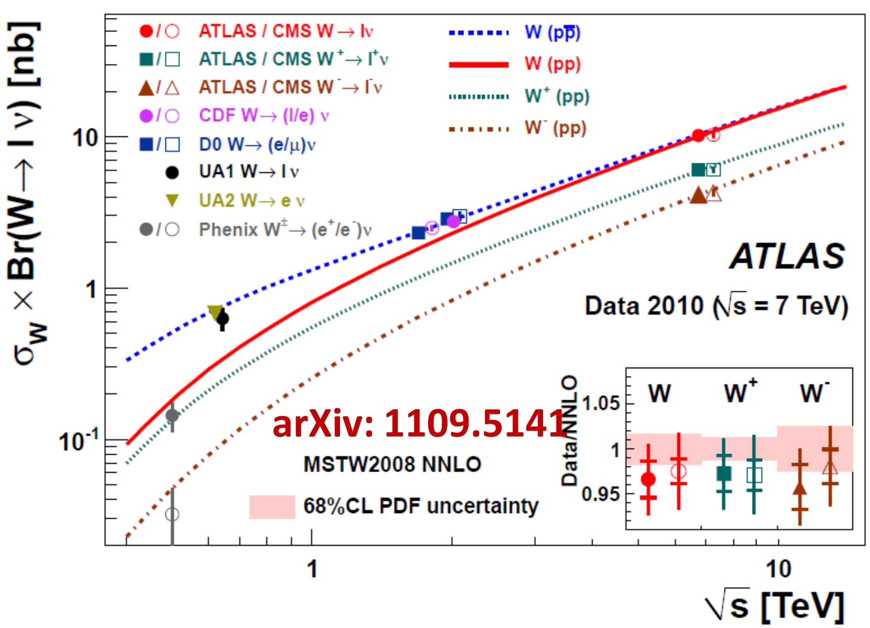


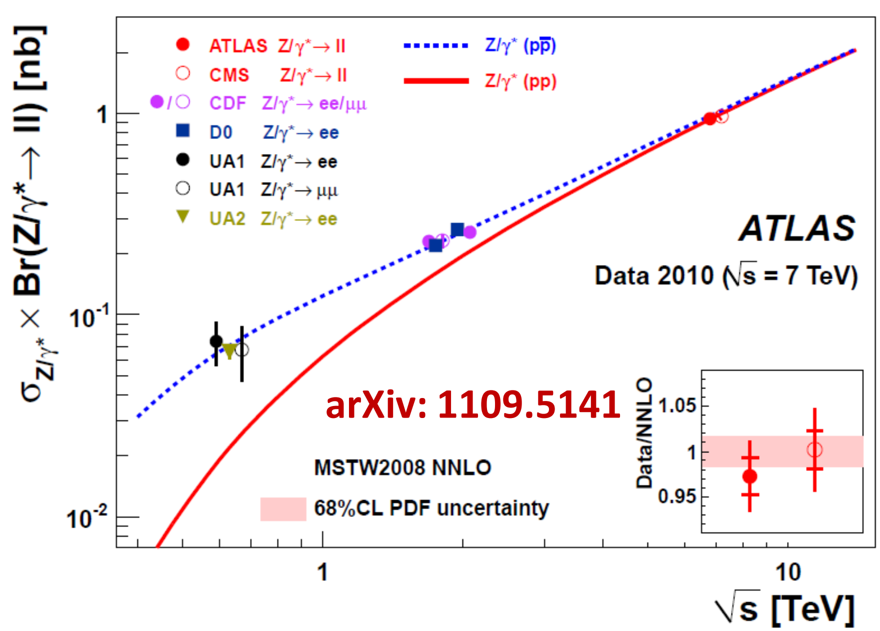
ATLAS DY combined muon/electron data



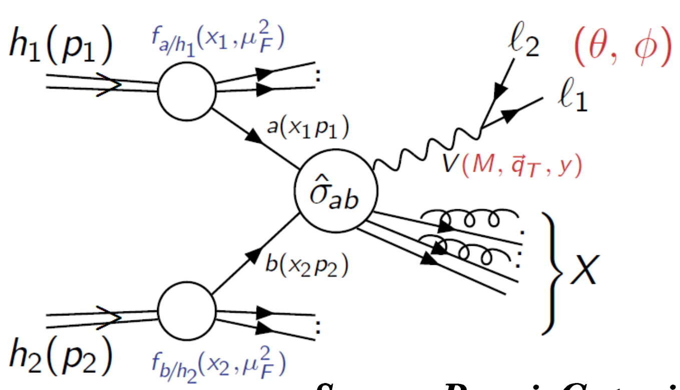


$66 < m_{ll} < 116\ GeV$





qT distribution of DY leptons at the LHC: the neutral current

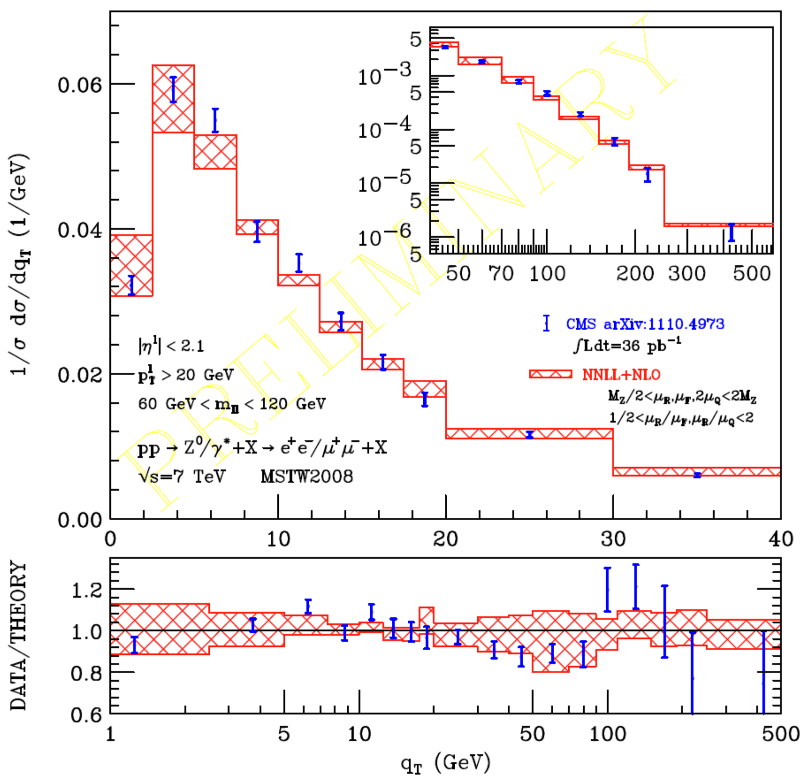


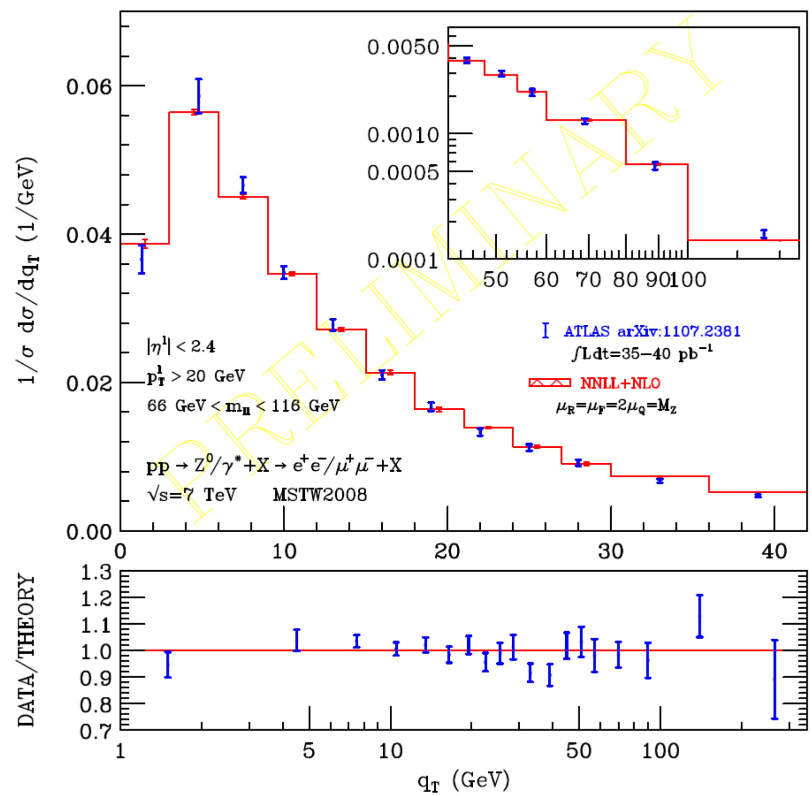
The DY cross section at fixed-order PT can be reliable only for $q_T \sim M_V$

However, at $q_T \to 0$, $\alpha_S^n \log^m(M^2/q_T^2) \gg 1$
the resummation of large logs is necessary!

Methods developed in many papers so far!

See e.g. Bozzi, Catani, de Florian, Ferrera, Grazzini, arXiv: 1007.2351 and refs. therein



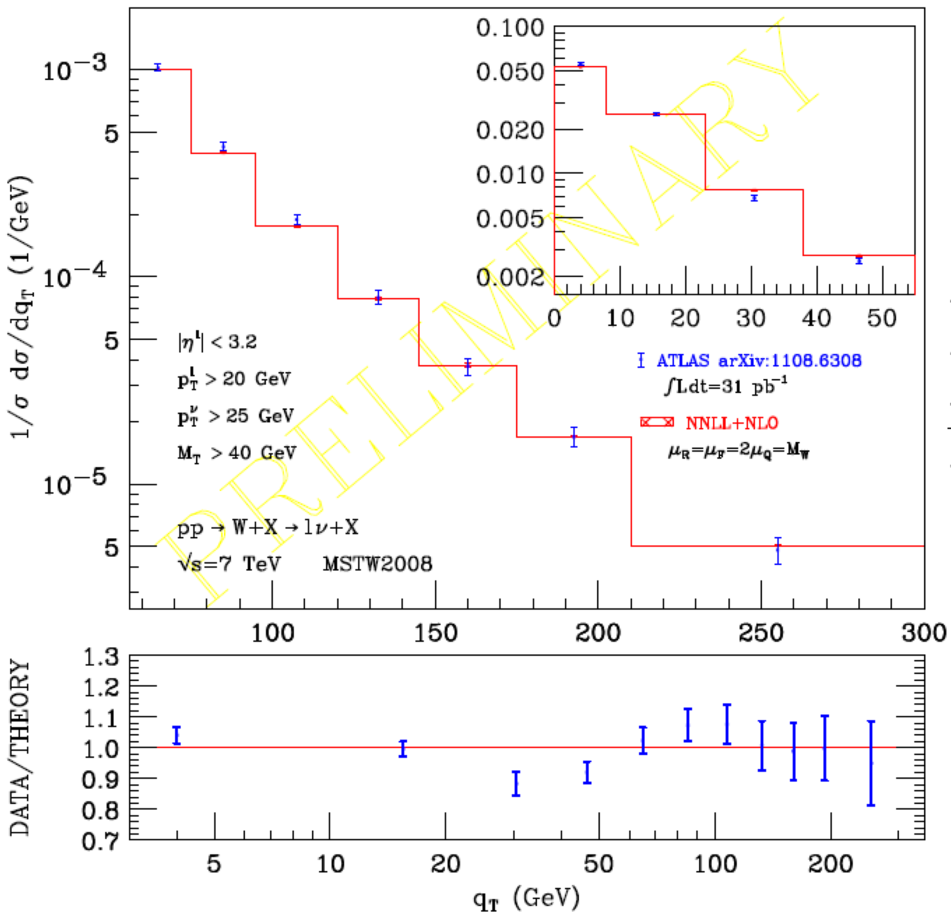


more details and references in the talk by Giancarlo Ferrera at Moriond 2012

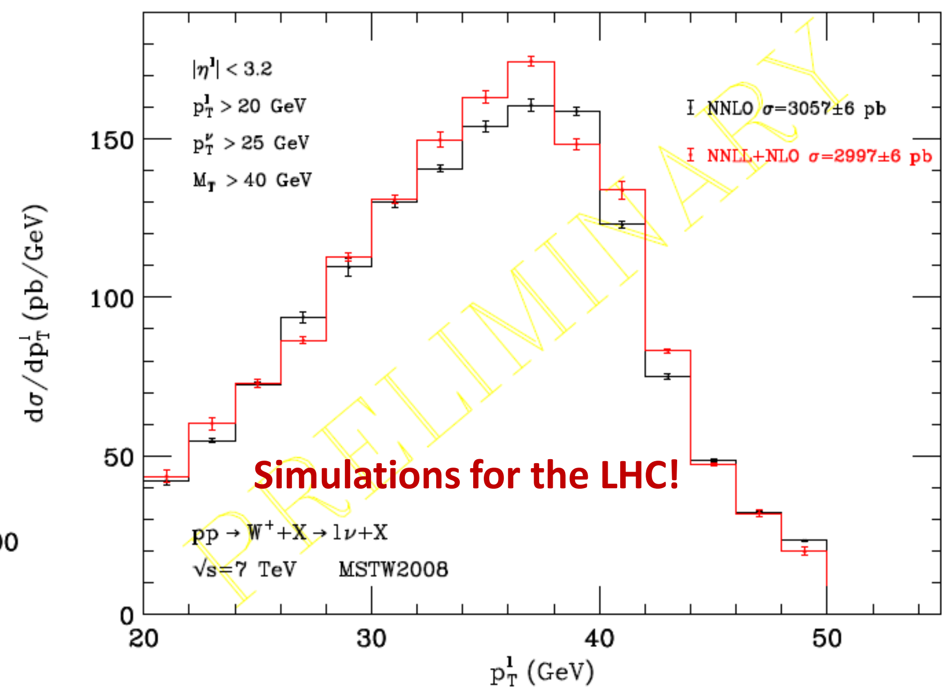
qT distribution of DY leptons at the LHC: the charged current

Based on qT-resummation with leptonic variables dependence

DYNNLO code



Ref. Catani, Cieri, de Florian, Ferrera, Grazzini '09



Lepton transverse momentum spectrum from $W+$ decay (very important for precision W-mass Measurement at the LHC!)

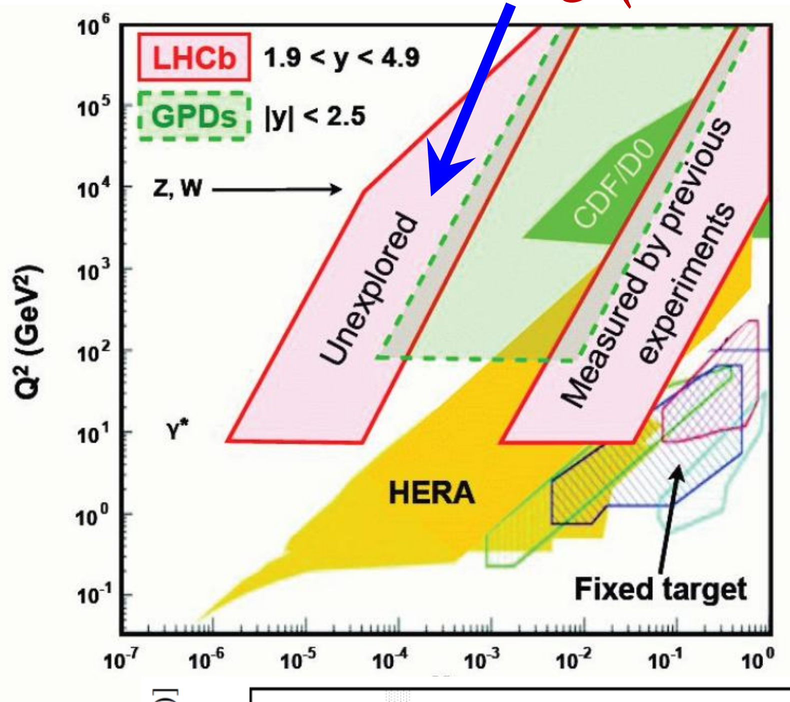
ATLAS data vs. NNLL+NLO predictions!

NNLL+NLO vs. NNLO predictions!

more details and references in the talk by Giancarlo Ferrera at Moriond 2012

Forward DY physics at LHCb: first results

New DY kinematics coverage (low x, large Q)!

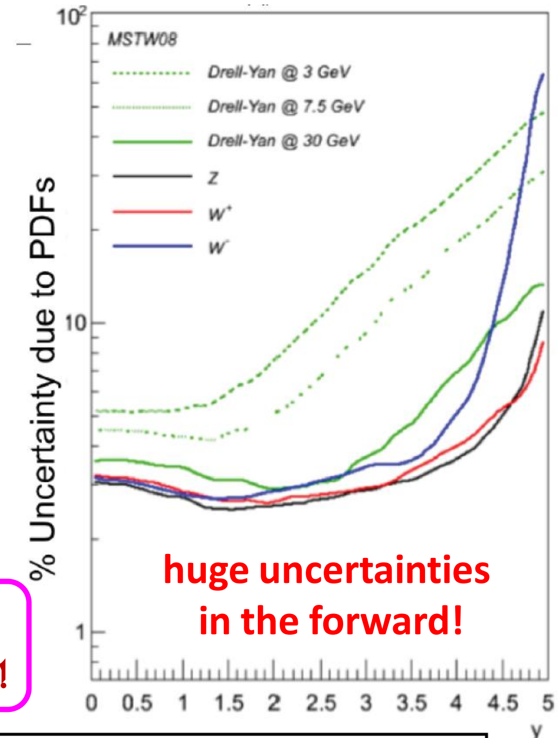


$p_T > 10$ GeV muon

2010 dataset
- 37.7 pb^{-1} $\sqrt{s} = 7$ TeV

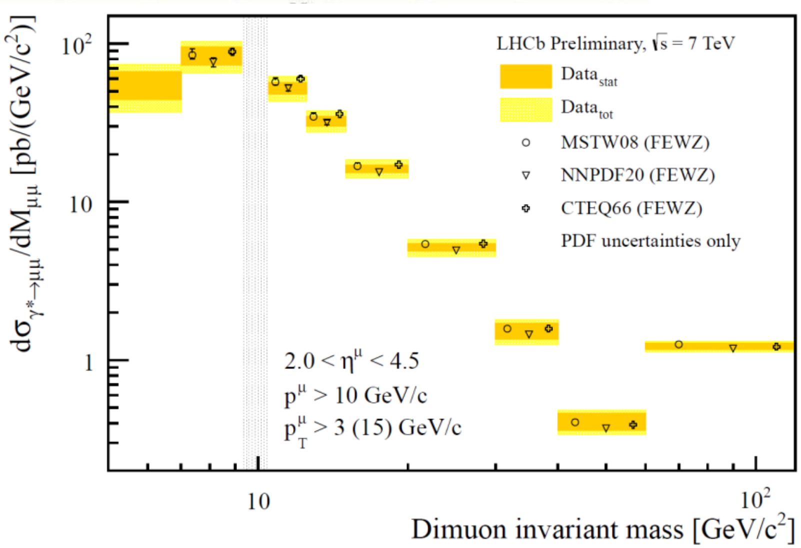
2011 dataset
- 1.0 fb^{-1} $\sqrt{s} = 7$ TeV

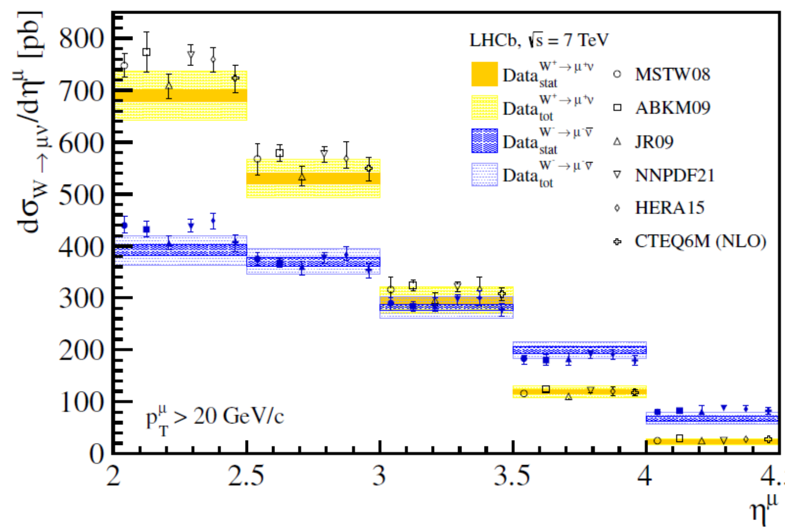
2012 dataset
- 1.5 fb^{-1} $\sqrt{s} = 8$ TeV



huge uncertainties in the forward!

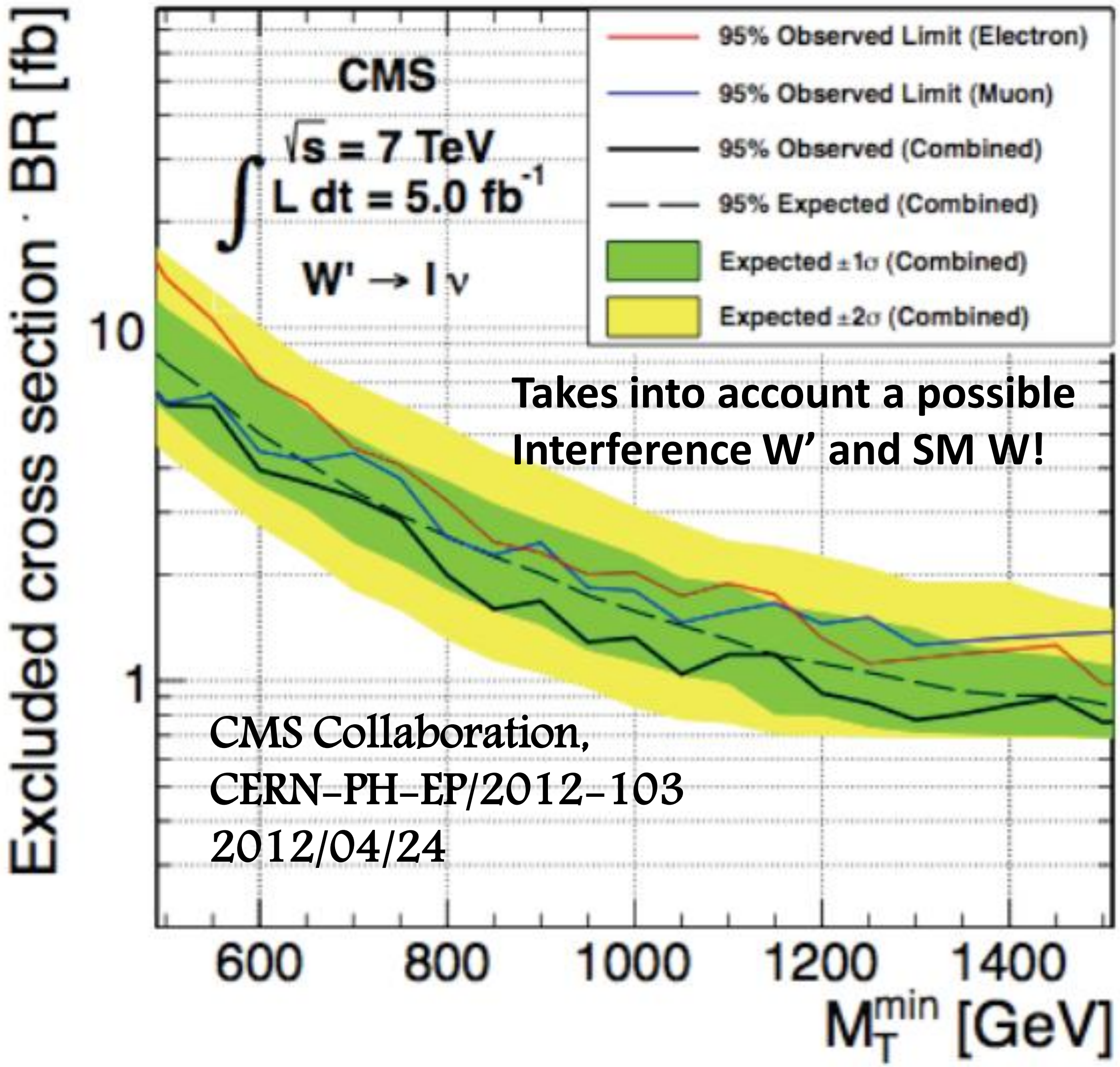
Good agreement with NNLO predictions so far!





more details e.g. in the talk by Philip Ilten, at Phenomonology 2012, Pittsburgh

EWSB tests with DY: latest W' exclusion limits



Takes into account a possible Interference W' and SM W!

CMS Collaboration,
CERN-PH-EP/2012-103
2012/04/24

Why to go beyond collinear factorisation?

- **Transverse spin physics**:

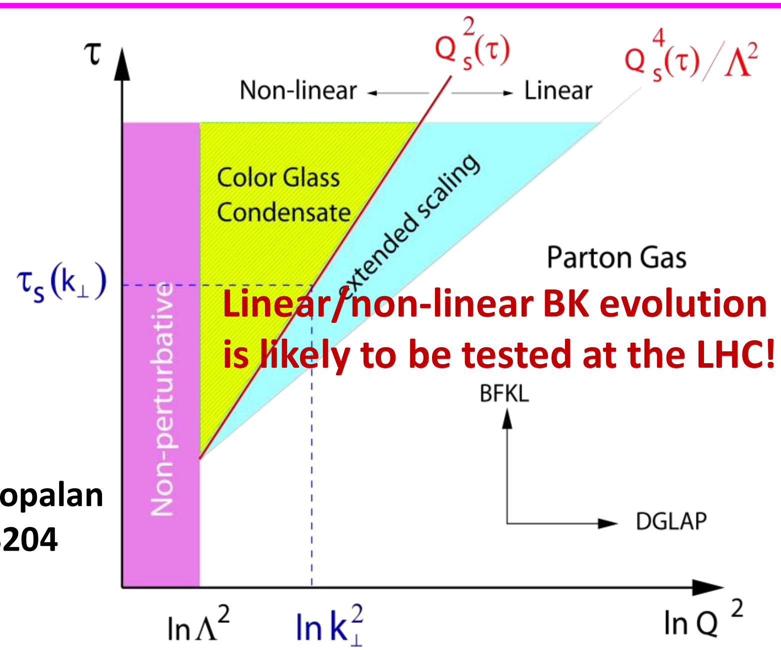
present understanding requires spin-correlated transverse momentum in distribution functions (Sivers effect) and fragmentation functions (Collins effect). Most important motivation for polarized fixed-target experiments with LHC beams (see *Brodsky et al'12*)

Many talks about spin physics here!

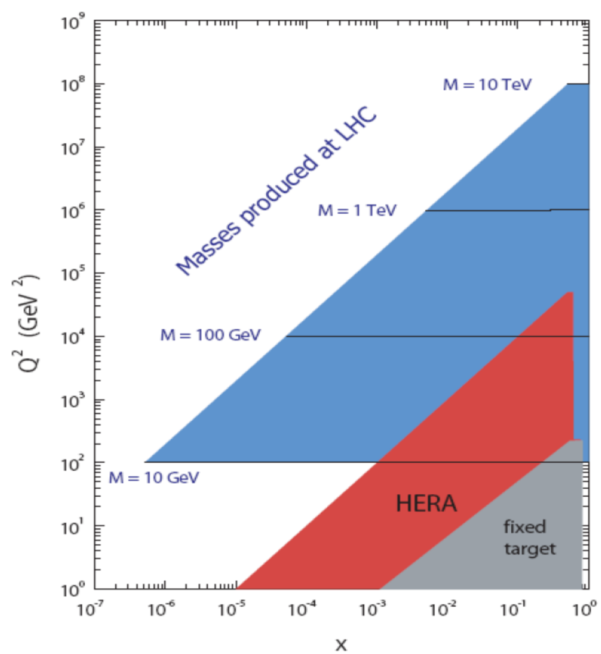
- **Small-x physics**:

the gluon density cannot continue its growth as $x \to 0$ (unitarity violation). Small-x physics is the major focus of the LHC DY. One can probe the universality of TMDs at small-x and non-linear effects (e.g. gluon recombination/saturation phenomena). Semi-inclusive and diffractive Drell-Yan are the most sensitive to these phenomena observables!

$\tau = \ln(1/x)$



Iancu, Venugopalan hep-ph/0303204



Color dipole framework for forward (small-x_2) DY

Proposed and initially developed by

S. J. Brodsky, A. Hebecker and E. Quack, Phys. Rev. **D55**, 2584 (1997), [hep-ph/9609384].
B. Z. Kopeliovich, J. Raufeisen and A. V. Tarasov, Phys. Lett. **B503**, 91 (2001), [hep-ph/0012035].
B. Z. Kopeliovich, A. V. Tarasov and A. Schafer, Phys. Rev. **C59**, 1609 (1999), [hep-ph/9808378].

Motivation:

…probing small x_2, at large x_F

- best for forward dilepton rapidities
- access to large-x valence/sea antiquark distributions
- incorporates higher-twist effects due to multiple scattering of a dipole off target
- at high energies, one of the incoming partons has very small x probing dense gluonic fields in the target (difficult or impossible to incorporate in QCD parton evolution)

Higher-powers $Q_s(x)^2/M^2$ (HT) become important (for not very large M) → ***The dipole approach is a promising attempt to account for saturation***

At LHC x can be as low as 10^{-6} for low mass DY

↓

One of the main interest for the QCD studies at the LHC!

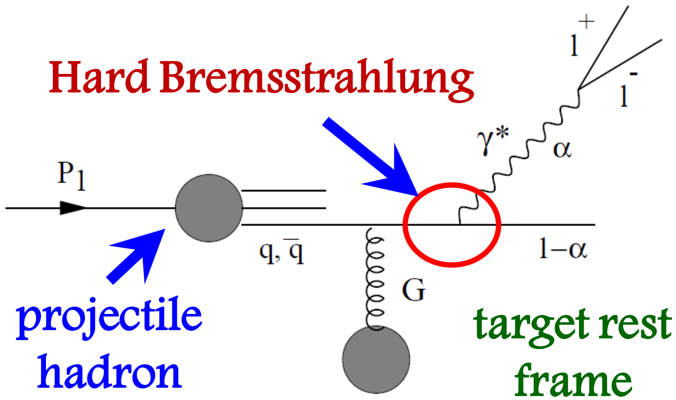
Note: LHCb has unique opportunities for tests of higher twist effects!

1. **High purities/efficiencies down to** $M_{\mu\mu}$=2.5GeV
2. **High rapidities coverage** $2.5 < \eta < 4.9$

The color dipole approach for DY: pedagogical overview

In this frame, in the high energy limit: *the DY cross section can be given in terms of the dipole cross section (similarly to DIS)*

Hard Bremsstrahlung



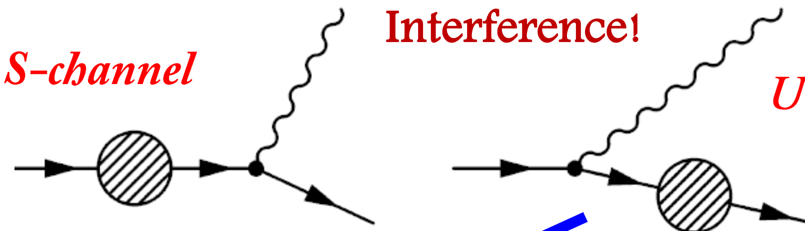
projectile hadron

target rest frame

Interference!

S-channel

U-channel



Photon (time-like) virtuality

Cross section of the dilepton production in quark-target scattering:

$$d^8\sigma(qN \to ql^+l^-X) = \sum_X \sum_{\lambda\lambda'} \epsilon^*_\mu(\lambda)\epsilon_\nu(\lambda')\overline{\mathcal{M}}^{\mu\nu} \frac{d\alpha d^2q_\perp d^2p_{f\perp}}{(2\pi)^5 8(p_i^0)^2\alpha(1-\alpha)} \qquad q^2 = M^2 > 0$$

$$\times \quad \alpha_{em}\epsilon_\kappa(\lambda)\epsilon^*_\rho(\lambda')L^{\rho\kappa}\frac{dM^2 d\Omega}{16\pi^2 M^4}, \qquad \lambda \in \{\pm 1, 0\}$$

Spin-color averaged ME squared (hadronic part):

$$\overline{\mathcal{M}}^{\mu\nu} = \frac{1}{2}\sum_{\sigma_f\sigma_i}\frac{1}{N_c}\sum_{c_f c_i}(\mathcal{M}^\mu_s + \mathcal{M}^\mu_u)(\mathcal{M}^{*\nu}_s + \mathcal{M}^{*\nu}_u)$$

Leptonic tensor:

$$L^{\mu\nu} = 4(p^\mu_{l+}p^\nu_{l-} + p^\nu_{l+}p^\mu_{l-} - g^{\mu\nu}p_{l+}p_{l-})$$

Solid angle of the leptonic pair can be integrated out

transverse *longitudinal*

$$d\Omega = d\phi d(\cos\theta)$$

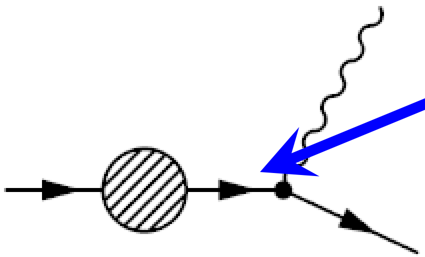
$$\boxed{\frac{d^4\sigma(qN \to l^+l^-X)}{d\ln\alpha dM^2 d^2q_\perp} = \frac{\alpha_{em}}{3\pi M^2}\left\{\frac{d^3\sigma_T(qN\to\gamma^*X)}{d\ln\alpha\, d^2q_\perp} + \frac{d^3\sigma_L(qN\to\gamma^*X)}{d\ln\alpha\, d^2q_\perp}\right\}}$$

Wave function of the forward photon radiation

Photon polarisations contributions

$$\frac{d^3\sigma_T(qN\to\gamma^*X)}{d\ln\alpha\, d^2q_\perp} = \int d^2p_{f\perp}\sum_X\sum_{\lambda\in\{\pm1\}}\frac{\epsilon^*_\mu(\lambda)\epsilon_\nu(\lambda)\overline{\mathcal{M}}^{\mu\nu}}{(2\pi)^5 8(p_i^0)^2(1-\alpha)} \qquad \frac{d^3\sigma_T(qN\to\gamma^*X)}{d\ln\alpha\, d^2q_\perp} = \int d^2p_{f\perp}\sum_X\frac{\epsilon^*_\mu(\lambda=0)\epsilon_\nu(\lambda=0)\overline{\mathcal{M}}^{\mu\nu}}{(2\pi)^5 8(p_i^0)^2(1-\alpha)}$$

Can be dropped in the high energy limit!



Quark propagator:

$$\frac{\not{p}_f+\not{q}+m_f}{(p_f+q)^2-m_f^2} = \sum_\sigma\frac{u_\sigma(p_f+q)\bar{u}_\sigma(p_f+q)}{(p_f+q)^2-m_f^2} - \frac{\gamma^+}{2(p_f^+ + q^+)}$$

The s-channel amplitude:

$$\mathrm{i}\mathcal{M}_s^\mu = e\sum_\sigma\frac{\bar{u}_{\sigma_f}(p_f)\gamma^\mu u_\sigma(p_f+q)}{(p_f+q)^2-m_f^2}\, t_{q,\sigma\sigma_i}((p_f^0+q^0),\vec{k}_\perp)$$

where the quark-nucleon scattering amplitude is

normalisation condition

$$u_\sigma^\dagger(p)u_{\sigma'}(p) = 2p^0\delta_{\sigma,\sigma'}$$

$$t_{q,\sigma\sigma_i}((p_f^0+q^0),\vec{k}_\perp) = \bar{u}_\sigma(p_f+q)\,\gamma^0\,V_q(\vec{k}_\perp)\,u_{\sigma_i}(p_i) \approx 2p_i^0\delta_{\sigma,\sigma_i}V_q(\vec{k}_\perp)$$

it incorporates all non-perturbative and soft physics!

In impact parameter space, we get

$$\begin{aligned}\widetilde{\mathcal{M}}_s^\mu(\vec{b},\vec{\rho}) &= \int\frac{d^2l_\perp d^2k_\perp}{(2\pi)^4}\mathrm{e}^{-\mathrm{i}\vec{l}_\perp\cdot\alpha\vec{\rho}-\mathrm{i}\vec{k}_\perp\cdot\vec{b}}\mathcal{M}_s^\mu(\vec{l}_\perp,\vec{k}_\perp)\\ &= -\mathrm{i}\sqrt{4\pi}\frac{\sqrt{1-\alpha}}{\alpha^2}\boxed{\Psi^\mu_{\gamma^*q}(\alpha,\vec{\rho})}2p_i^0\widetilde{V}_q(\vec{b}),\end{aligned} \qquad \widetilde{V}_q(\vec{b}) = \int\frac{d^2k_\perp}{(2\pi)^2}\mathrm{e}^{-\mathrm{i}\vec{k}_\perp\cdot\vec{b}}V_q(\vec{k}_\perp)$$

The LC wave-function of gamma radiation!

can be absorbed into the dipole CS!

DY in quark-target scattering

The propagators can be transformed as

$$\frac{1}{(p_f+q)^2-m_f^2} = \frac{\alpha(1-\alpha)}{\alpha^2 l_\perp^2+\eta^2} \qquad \frac{1}{(p_i-q)^2-m_f^2} = -\frac{\alpha}{\alpha^2(\vec{l}_\perp+\vec{k}_\perp)^2+\eta^2}$$

$$\vec{l}_\perp = \vec{p}_{f\perp} - (1-\alpha)\,\vec{q}_\perp/\alpha$$

$$\eta^2 = (1-\alpha)M^2+\alpha^2 m_f^2$$

The DY cross section in quark-hadron scattering then is

$$\frac{d^3\sigma_{T,L}(qN\to\gamma^* X)}{d\ln\alpha\, d^2q_\perp} = \frac{1}{(2\pi)^2}\int d^2\rho_1 d^2\rho_2\, e^{i\vec{q}_\perp\cdot(\vec{\rho}_1-\vec{\rho}_2)}\Psi^{*T,L}_{\gamma^* q}(\alpha,\vec{\rho}_1)\Psi^{T,L}_{\gamma^* q}(\alpha,\vec{\rho}_2)$$
$$\times\ \frac{1}{2}\left\{\sigma^N_{q\bar q}(\alpha\rho_1)+\sigma^N_{q\bar q}(\alpha\rho_2)-\sigma^N_{q\bar q}(\alpha(\vec{\rho}_1-\vec{\rho}_2))\right\}.$$

... or integrated over photon momentum

$$\frac{d\sigma(qN\to\gamma^* X)}{d\ln\alpha} = \int d^2\rho\, |\Psi_{\gamma^* q}(\alpha,\rho)|^2\, \sigma^N_{q\bar q}(\alpha\rho, x)$$

in terms of the LC wave functions

$$\Psi^T_{\gamma^* q}(\alpha,\vec{\rho}_1)\Psi^{T*}_{\gamma^* q}(\alpha,\vec{\rho}_2) = \sum_{\lambda=\pm1}\frac{1}{2}\sum_{\sigma_f\sigma_i}\epsilon^*_\mu(\lambda)\Psi^\mu_{\gamma^* q}(\alpha,\vec{\rho}_1)\epsilon_\mu(\lambda)\Psi^{\mu*}_{\gamma^* q}(\alpha,\vec{\rho}_2)$$
$$= \frac{\alpha_{em}}{2\pi^2}\Big\{m_f^2\alpha^4 \mathrm{K}_0(\eta\rho_1)\,\mathrm{K}_0(\eta\rho_2)$$
$$+\ \left[1+(1-\alpha)^2\right]\eta^2\frac{\vec{\rho}_1\cdot\vec{\rho}_2}{\rho_1\rho_2}\mathrm{K}_1(\eta\rho_1)\,\mathrm{K}_1(\eta\rho_2)\Big\},$$

$$\Psi^L_{\gamma^* q}(\alpha,\vec{\rho}_1)\Psi^{L*}_{\gamma^* q}(\alpha,\vec{\rho}_2) = \frac{1}{2}\sum_{\sigma_f\sigma_i}\epsilon^*_\mu(\lambda=0)\Psi^{\lambda=0}_{\gamma^* q}(\alpha,\vec{\rho}_1)\epsilon_\mu(\lambda=0)\Psi^{*\lambda=0}_{\gamma^* q}(\alpha,\vec{\rho}_2)$$
$$= \frac{\alpha_{em}}{\pi^2}M^2(1-\alpha)^2\,\mathrm{K}_0(\eta\rho_1)\,\mathrm{K}_0(\eta\rho_2).$$

Dipole properties:

- cannot be excited
- experience only elastic scattering
- have no definite mass, but only separation
- universal – elastic amplitude can be extracted in one process and used in another

Fitted to data!

and the universal dipole cross section:

$$\sigma_{q\bar q}(\alpha\rho) = \sum_X \frac{1}{N_c}\sum_{c_f c_i}\int d^2b\left|\widetilde{V}_q(\vec{b})-\widetilde{V}_q(\vec{b}+\alpha\vec{\rho})\right|^2$$

The universal dipole CS

$$\boxed{\frac{d\sigma^{\gamma}(pp \to \gamma X)}{dx_F d^2\vec{p}_T} = \frac{1}{x_1 + x_2}\int_{x_1}^{1}\frac{d\alpha}{\alpha}F_2^p\left(\frac{x_1}{\alpha}, Q\right)\frac{d\sigma^{qN}(q \to q\gamma)}{d(ln\alpha)d^2\vec{p}_T}}$$

probing proton structure function in DY at large x!

In Regge phenomenology, the dipole approach accounts for only Pomeron part of the cross section: the dipole CS is governed by gluon interactions and applicable at small-x only!

To the LO (two-gluon exchange + resumed log(1/x)), in the Weizsacker-Williams approximation

color transparency!

$$\sigma_{q\bar{q}}(x_2, \rho) = \frac{4\pi}{3}\alpha_s\rho^2\int\frac{d^2k_\perp}{k_\perp^2}\frac{\boxed{\left[1 - \exp(i\vec{k}_\perp\cdot\vec{\rho})\right]}}{k_\perp^2\rho^2}\frac{\partial G(x_2, k_\perp^2)}{\partial\ln(k_\perp^2)}$$

cancellation of IR divergences!

UGDF at small x

GBW model (fitted to DIS only):

$$\sigma_{q\bar{q}}^N(\rho, x) = \sigma_0\left[1 - \exp\left(-\frac{\rho^2 Q_s^2(x)}{4}\right)\right]$$

$$Q_s^2(x) = 1\,\mathrm{GeV}^2\left(\frac{0.0003}{x}\right)^{0.288}$$

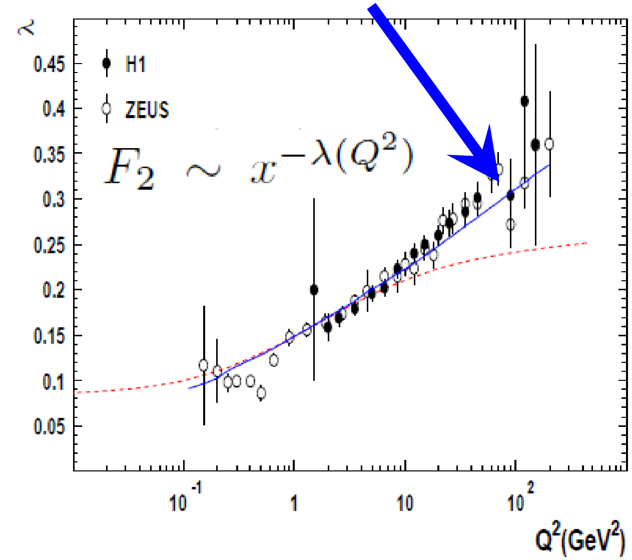
Not good at large-x and large Q!

GBW-DGLAP model (with LO DGLAP evolution):

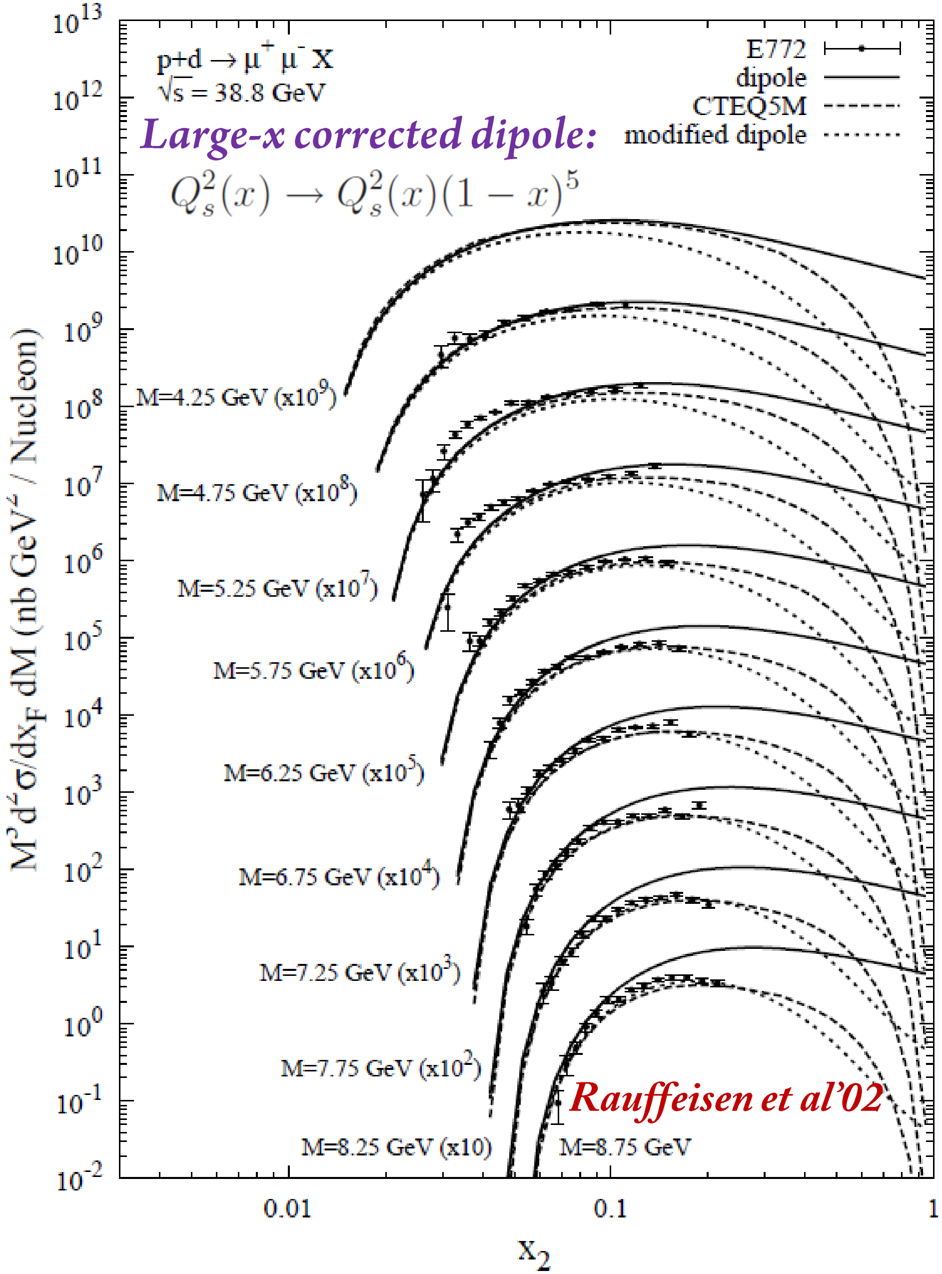
Bartels et al '02

$$\sigma_{q\bar{q}}(x, \vec{r}) = \sigma_0\left(1 - exp\left(-\frac{\pi^2 r^2\alpha_s(\mu^2)xg(x, \mu^2)}{3\sigma_0}\right)\right)$$

GBW-DGLAP preserves success of the GBW model while modifying large-Q behavior by evolution



Parton Model versus Dipole Approach

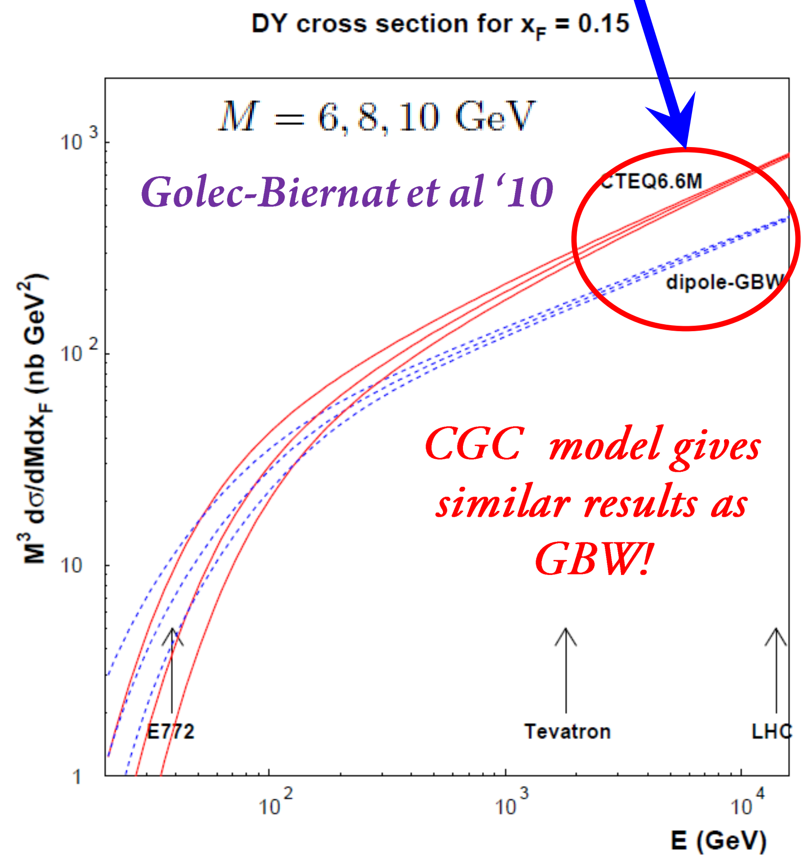


Large-x corrected dipole:

$$Q_s^2(x) \rightarrow Q_s^2(x)(1-x)^5$$

Rauffeisen et al'02

Saturation at work (can change the DY CS at the LHC by a factor of 3)!



$M = 6, 8, 10$ GeV

Golec-Biernat et al '10

CGC model gives similar results as GBW!

Leading twist is OK at the LHC if M>6 GeV, below – resummation of higher twists is important!

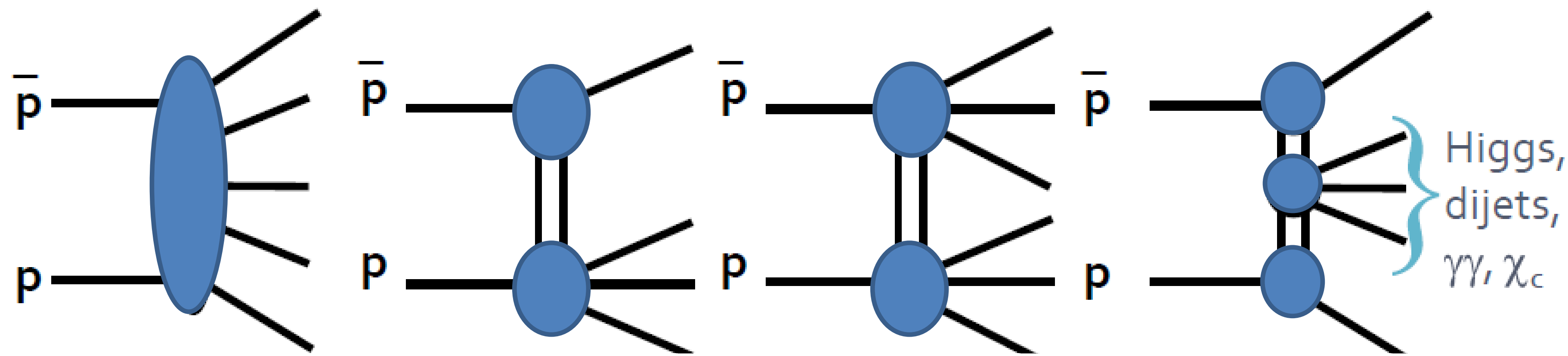
Motivation for diffractive Drell-Yan at the LHC

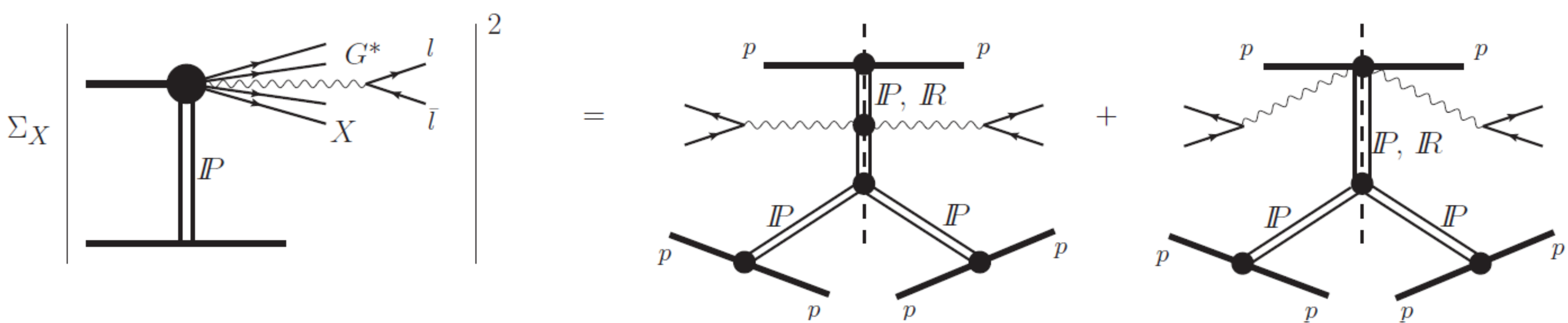
- *Diffraction cannot be accessed in collinear factorisation (transverse (TMD) evolution is crucial)*
- *Strongly sensitive to the soft physics – small x and small transverse momenta!*
- *Excellent probe for QCD factorisation breaking effects!*

Driven by Pomeron exchange (rightmost siongularity in the complex angular momentum plane)

Topology of diffractive final states

Non-diffractive | Single-diffractive | Double-diffractive | Double-Pomeron exchange





Diffractive factorisation-based approach to DDY

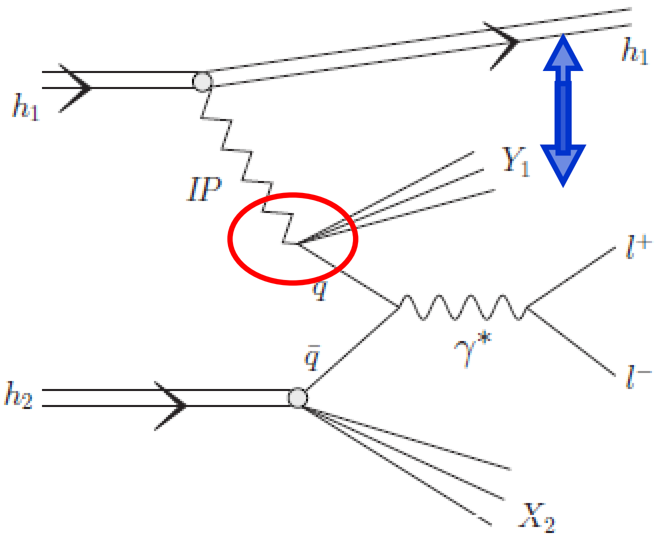
e.g. by A. Szczurek et al, Phys.Rev.D84:014005,2011

Ingelman-Schein mechanism → **QCD/Regge factorisation**

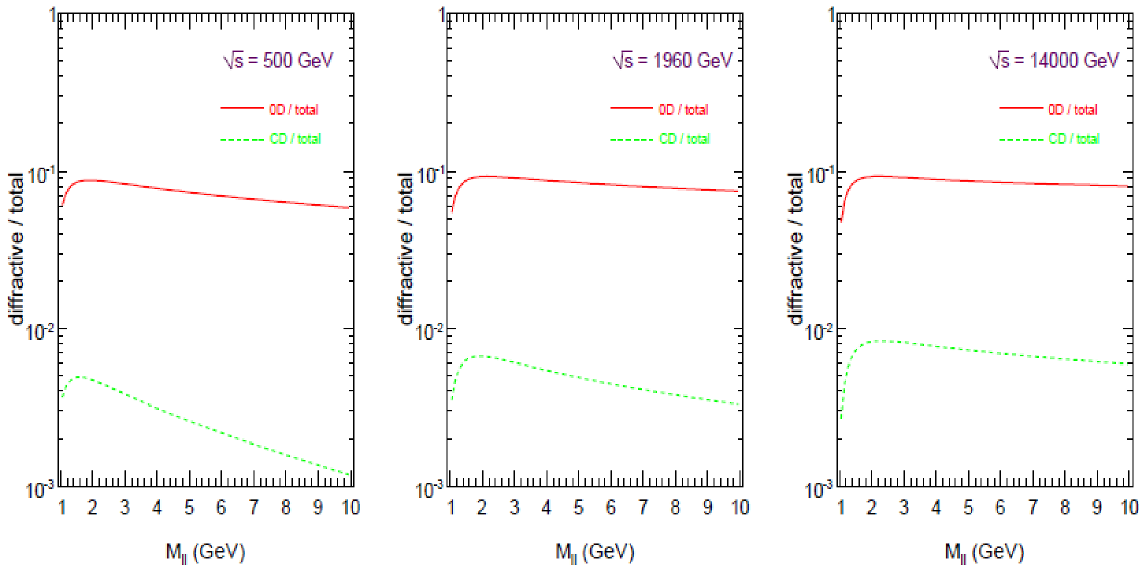
Diffractive quark density

$$q_f^D(x,\mu^2) = \int_x^1 \frac{dx_{\mathbb{P}}}{x_{\mathbb{P}}} f_{\mathbb{P}}(x_{\mathbb{P}}) q_{f/\mathbb{P}}\left(\frac{x}{x_{\mathbb{P}}},\mu^2\right)$$

DY with gap and the leading proton

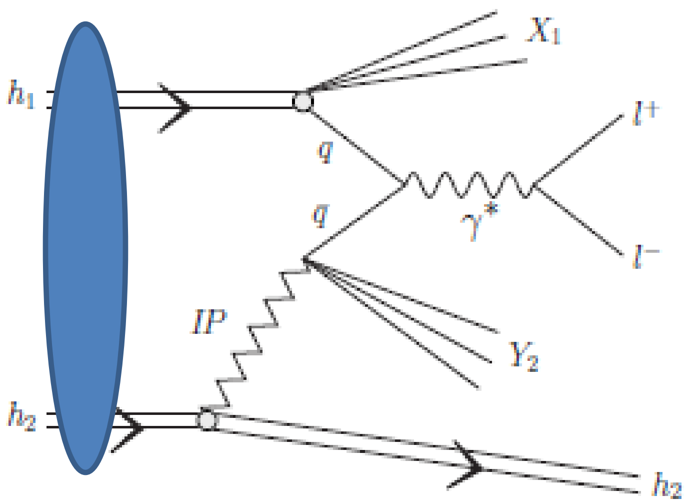


Raising with energy/dumping with scale!

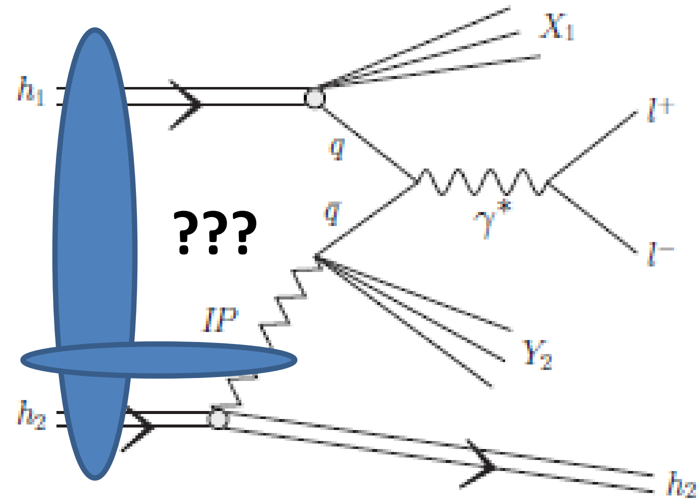


Regge factorization vs absorptive corrections

Eikonal part



“Enhanced” part breaks the factorisation!



without the factorisation breaking:

Diffractive Z,W / Inclusive Z,W **~ 30 %**

Noticeable growth with energy!

Gay-Ducati et al Phys. Rev. D75, 114013 (2007)

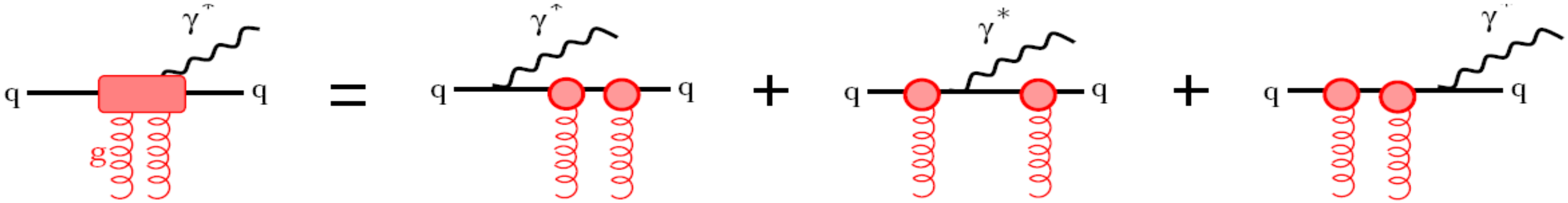
A. Szczurek et al, Phys.Rev.D84:014005,2011

with the factorisation breaking:

Effect is largely unknown! Different models…
Open issue…

What can the dipole approach offer us in this situation?

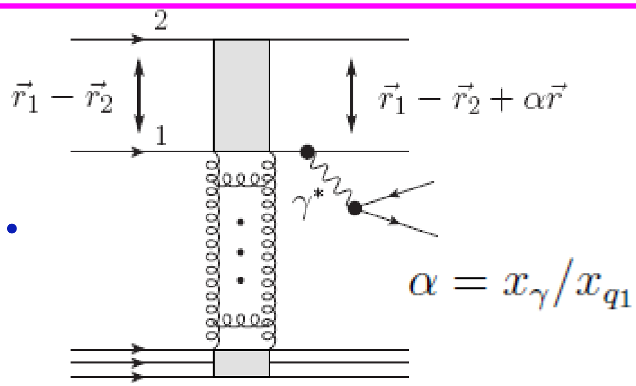
Is forward Drell-Yan off a quark or off a dipole?



the standard DY contribution from Abelian Bremsstrahlung off a quark disappears!

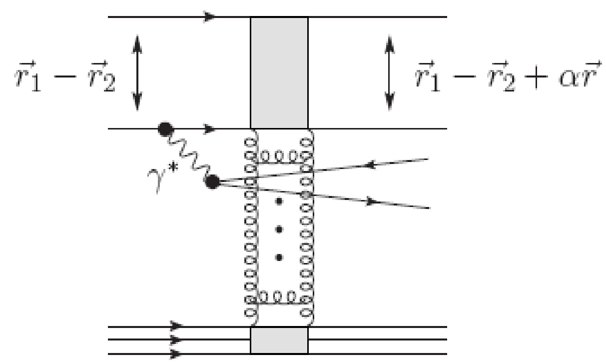
Landau-Pomeranchuk principle: **non-accelerated charge does not radiate!**

However…



$\sigma_{qq}(\vec{r}_1 - \vec{r}_2)$

+



$\sigma_{qq}(\vec{r}_1 - \vec{r}_2 + \alpha\vec{r})$

$\neq 0$

By optical theorem

$$\sigma_{\bar{q}q}(r_p) = \int d^2b \, 2\, \mathrm{Im} f_{el}(\vec{b}, \vec{r}_p)$$

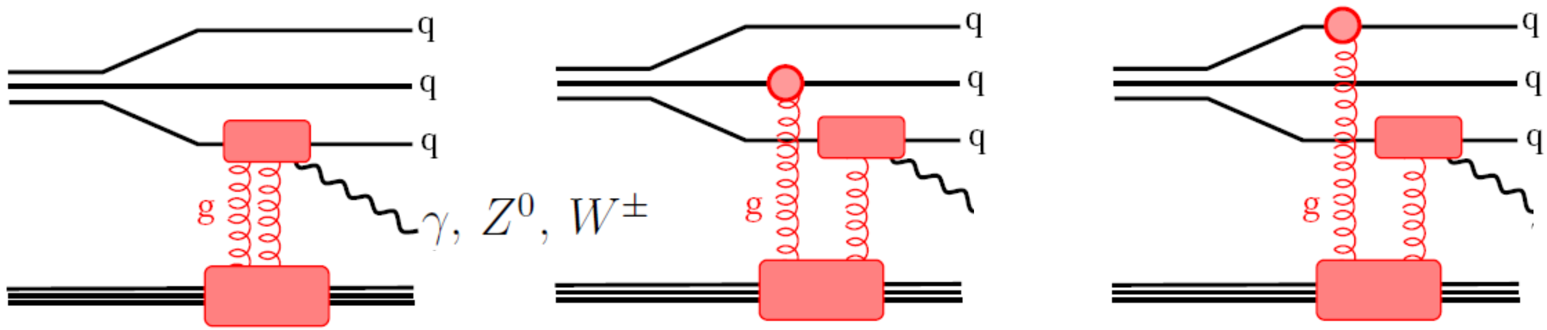
dipoles with different sizes interact differently!

Amplitude of DDY in the dipole-target scattering

$$M_{qq}^{(1)}(\vec{b}, \vec{r}_p, \vec{r}, \alpha) = -2ip_i^0 \sqrt{4\pi} \frac{\sqrt{1-\alpha}}{\alpha^2} \Psi^{\mu}_{\gamma^* q}(\alpha, \vec{r}) \left[2\mathrm{Im}\, f_{el}(\vec{b}, \vec{r}_p) - 2\mathrm{Im}\, f_{el}(\vec{b}, \vec{r}_p + \alpha\vec{r}) \right]$$

DY off a hadron: probing large distances in the proton

R. Pasechnik, B. Kopeliovich, Eur. Phys. J. C71: 1827, 2011
B. Kopeliovich, I. Potashnikova, I. Schmidt and A. Tarasov, Phys. Rev. D74: 114024, 2006



GBW dipole $\sigma(r) = \sigma_0 \left(1 - e^{-r^2/R_0^2}\right)$

Amplitude $\propto \sigma(\vec{R}) - \sigma(\vec{R} - \alpha\vec{r}) = \frac{2\alpha\,\sigma_0}{R_0^2(x_2)} e^{-R^2/R_0^2(x_2)} \left(\vec{r}\cdot\vec{R}\right) + O(r^2)$

Interplay between hard and soft scales

Diffractive DIS $\propto r^4$

…of the higher twist nature!

QCD factorization holds!

Diffractive gauge bosons production $\propto r^2$

…of the leading twist nature!

diffractive factorization is broken!

Diffractive DDY: probing proton structure at large x

The general result:

$$\frac{d^5\sigma_{\lambda_G}(pp \to pG^* X)}{d^2q_\perp\, d\ln\alpha\, d^2\delta_\perp} = \frac{1}{(2\pi)^2}\frac{1}{64\pi^2}\sum_q \int d^2r_1 d^2r_2 d^2r_3\, d^2r d^2r'\, d^2b d^2b'\, dx_{q_1} dx_{q_2} dx_{q_3}$$
$$\times\, \Psi^{\lambda_G}_{V-A}(\vec{r},\alpha,M)\Psi^{\lambda_G *}_{V-A}(\vec{r}\,',\alpha,M)\,|\Psi_i(\vec{r}_1,\vec{r}_2,\vec{r}_3;x_{q_1},x_{q_2},x_{q_3})|^2$$
$$\times\, \Delta(\vec{r}_1,\vec{r}_2,\vec{r}_3;\vec{b};\vec{r},\alpha)\Delta(\vec{r}_1,\vec{r}_2,\vec{r}_3;\vec{b}\,';\vec{r}\,',\alpha)\, e^{i\vec{\delta}_\perp\cdot(\vec{b}-\vec{b}\,')}\, e^{i\vec{l}_\perp\cdot\alpha(\vec{r}-\vec{r}\,')}$$

$$\Delta = -2\mathrm{Im}\, f_{el}(\vec{b},\vec{r}_1-\vec{r}_2) + 2\mathrm{Im}\, f_{el}(\vec{b},\vec{r}_1-\vec{r}_2+\alpha\vec{r})$$
$$-2\mathrm{Im}\, f_{el}(\vec{b},\vec{r}_1-\vec{r}_3) + 2\mathrm{Im}\, f_{el}(\vec{b},\vec{r}_1-\vec{r}_3+\alpha\vec{r})$$

Soft parameterisation for the dipole amplitude in the eikonal form incorporates the gap survival at the amplitude level!

Proton wave function

$$|\Psi_i(\vec{r}_1,\vec{r}_2,\vec{r}_3;x_q,x_{q_2},x_{q_3})|^2 = \frac{3a^2}{\pi^2}e^{-a(r_1^2+r_2^2+r_3^2)}\rho(x_q,x_{q_2},x_{q_3})$$
$$\times\, \delta(\vec{r}_1+\vec{r}_2+\vec{r}_3)\delta(1-x_q-x_{q_2}-x_{q_3})$$

$$a = \langle r_{ch}^2\rangle^{-1}$$

Valence quark distribution

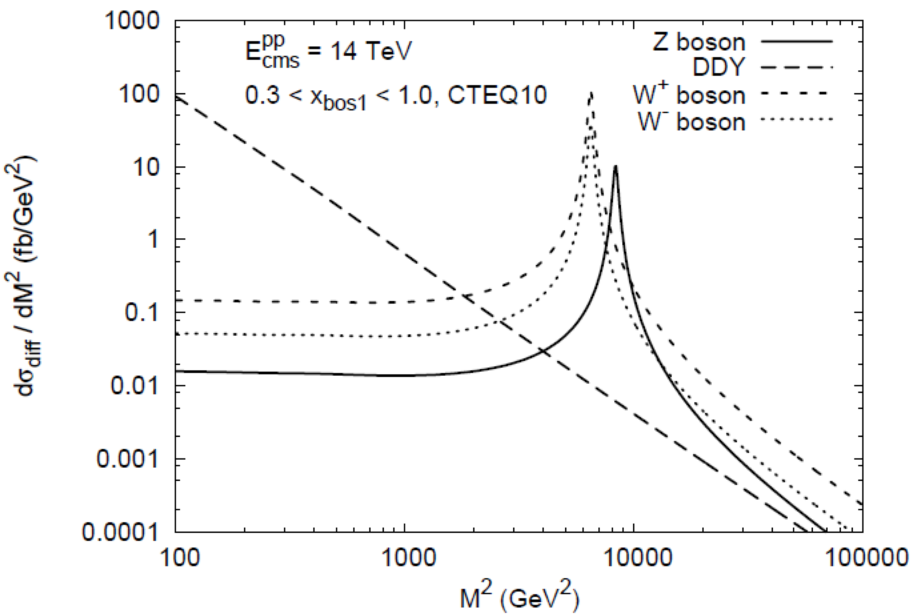
+ antiquarks!

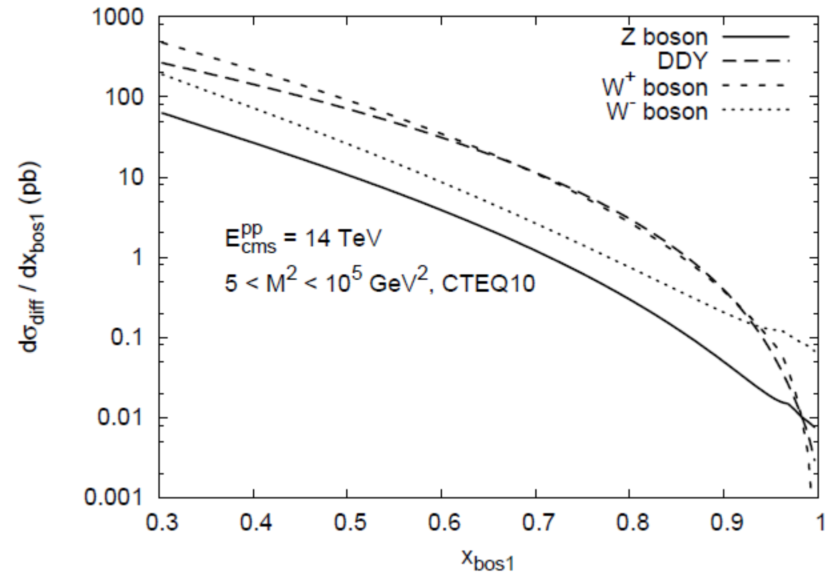
$$\int dx_{q_2} dx_{q_3}\, \delta(1-x_q-x_{q_2}-x_{q_3})\rho(x_q,x_{q_2},x_{q_3}) = \rho_q(x_q)$$

$$\sum_q Z_q^2[\rho_q(x_q)+\rho_{\bar{q}}(x_q)] = \frac{1}{x_q}F_2(x_q)$$

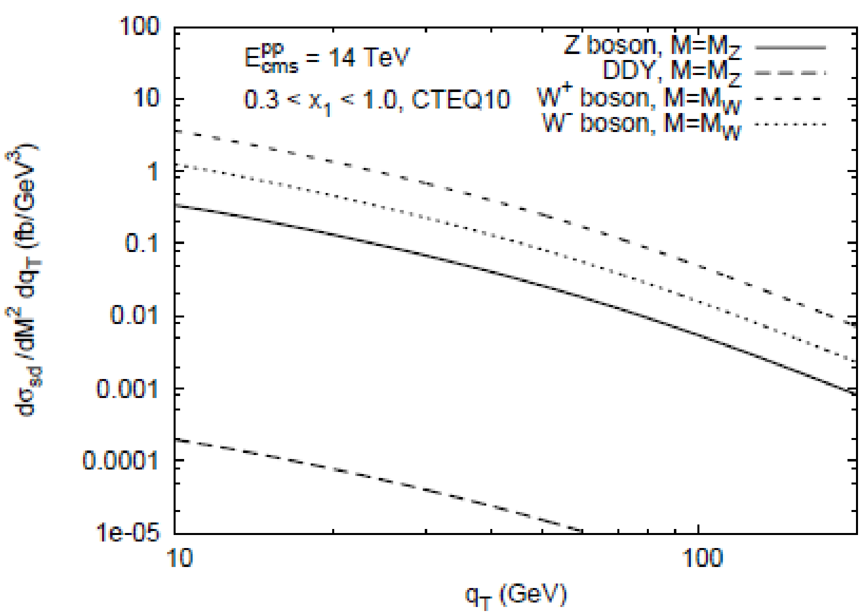
In DDY we get an immediate access to the proton structure function at large x!

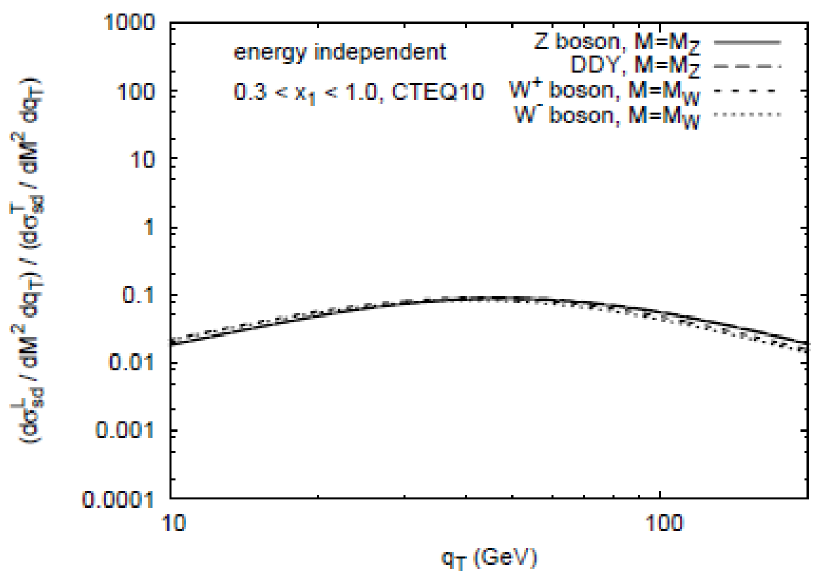
Diffractive DY production cross sections at the LHC





Pasechnik et al'12





Diffractive vs inclusive Drell-Yan: probing small x physics

In **the hard limit**:

$$\frac{1}{2}\Big\{\sigma(\alpha r) + \sigma(\alpha r') - \sigma(\alpha|\vec{r} - \vec{r}\,'|)\Big\} \simeq \frac{\alpha^2 \bar{\sigma}_0}{\bar{R}_0^2(x)}\,(\vec{r}\cdot\vec{r}\,')$$

Inclusive production CS:

$$\frac{d^4\sigma_{\lambda_G}(pp \to G^* X)}{d^2q_\perp\, dx_{bos1}} = \frac{1}{(2\pi)^2}\frac{\bar{\sigma}_0}{\bar{R}_0^2(x)}\sum_q \int_{x_{bos1}}^1 d\alpha\left[\rho_q\Big(\frac{x_{bos1}}{\alpha}\Big) + \rho_{\bar{q}}\Big(\frac{x_{bos1}}{\alpha}\Big)\right]\times$$
$$\int d^2r d^2r'\,(\vec{r}\cdot\vec{r}\,')\,\Psi^{\lambda_G}_{V-A}(\vec{r},\alpha,M)\Psi^{\lambda_G *}_{V-A}(\vec{r}\,',\alpha,M)\,e^{i\vec{q}_\perp\cdot(\vec{r}-\vec{r}\,')}\,.$$

with naive GBW parametrization:

$$\bar{\sigma}_0 = 23.03\,\mathrm{mb}\,,\quad R_0 \equiv \bar{R}_0(x) = 0.4\,\mathrm{fm}\times(x/x_0)^{0.144}\,,\quad x_0 = 3.04\times 10^{-4}\,,$$

So, the diffraction-to-inclusive ratio:

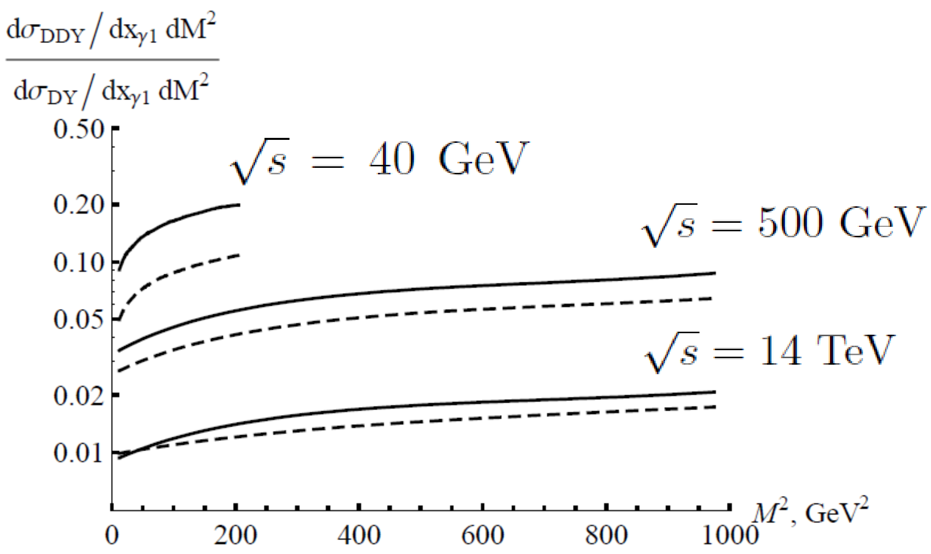
…does not depend on type of the boson!

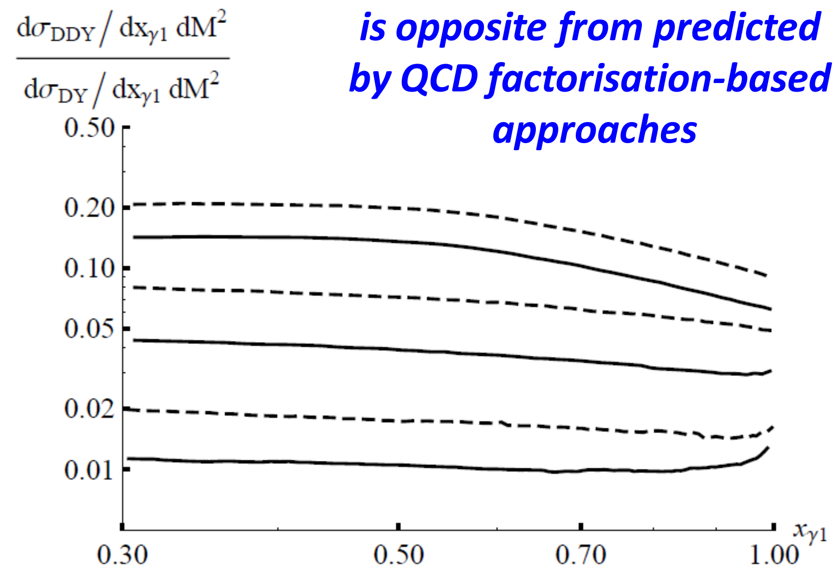
$$\boxed{\frac{d\sigma^{sd}_{\lambda_G}/d^2q_\perp\, dx_{bos1}\, dM^2}{d\sigma^{incl}_{\lambda_G}/d^2q_\perp dx_{bos1}\, dM^2} = \frac{a^2}{6\pi}\frac{\bar{R}_0^2(M_\perp^2/x_{bos1}s)}{B_{sd}(s)\,\bar{\sigma}_0}\frac{\sigma_0^2(s)}{R_0^4(s)}\frac{1}{A_2}\left[\frac{2}{(A_2-4A_1)^2} + \frac{A_2^2}{(A_2^2-4A_3^2)^2}\right]}$$

$$M_\perp^2 \equiv M^2 + |\vec{q}_\perp|^2 = x_{bos1}\,x\,s$$

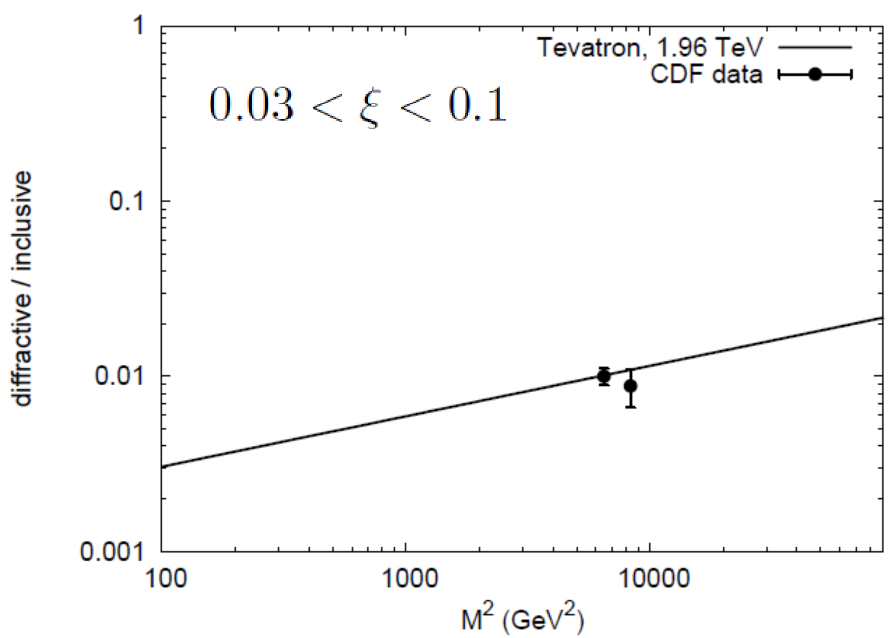
universal quantity for probing soft/multiple interactions and saturation physics at the LHC!

Diffractive vs inclusive DY: drops with energy!?





Energy/scale behavior is opposite from predicted by QCD factorisation-based approaches



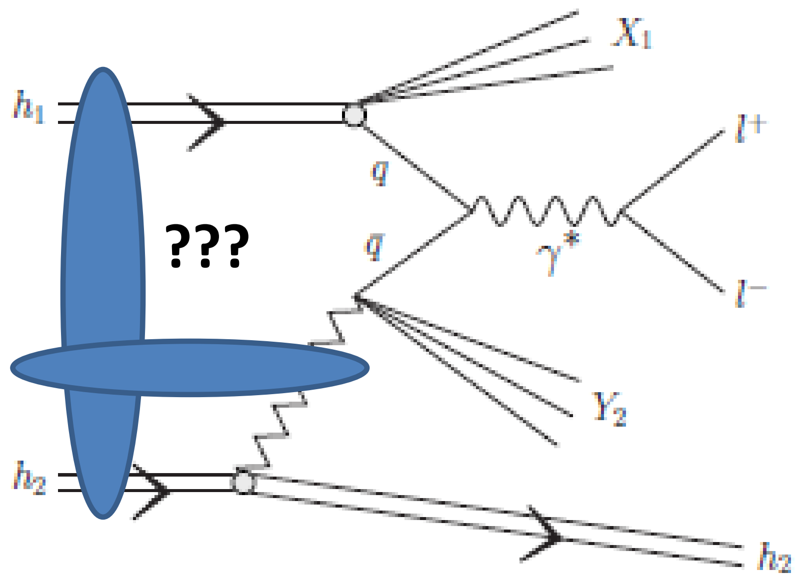
Pasechnik et al'12

Agrees well with the Tevatron data!

A good probe for QCD diffractive mechanism and soft interactions!

Regge factorization breaking at the LHC

Absorptive effects destroy diffractive factorization in hadron-hadron scattering!



without the factorisation breaking:

Diffractive Z,W / Inclusive Z,W ~ 30 %

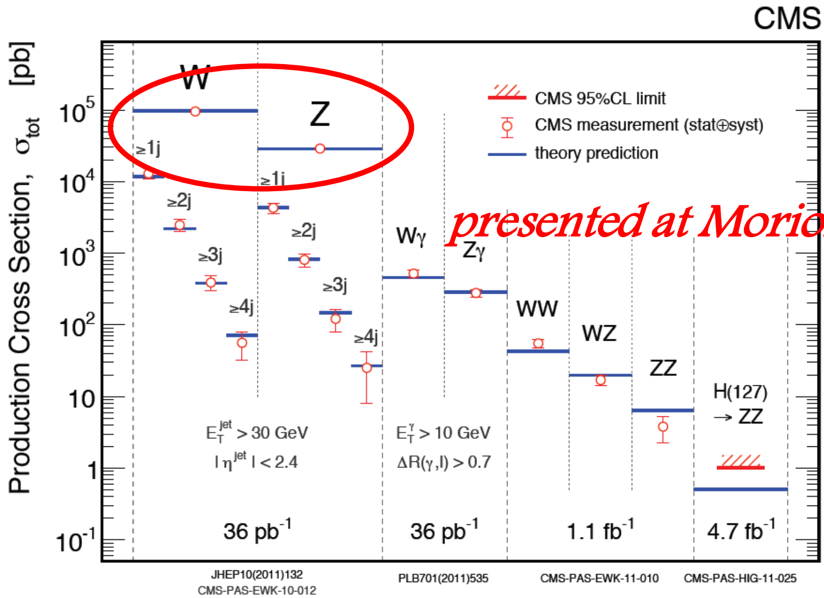
with the factorisation breaking:

$\boxed{\textbf{Diffractive Z,W / Inclusive Z,W} < 1\ \%}$

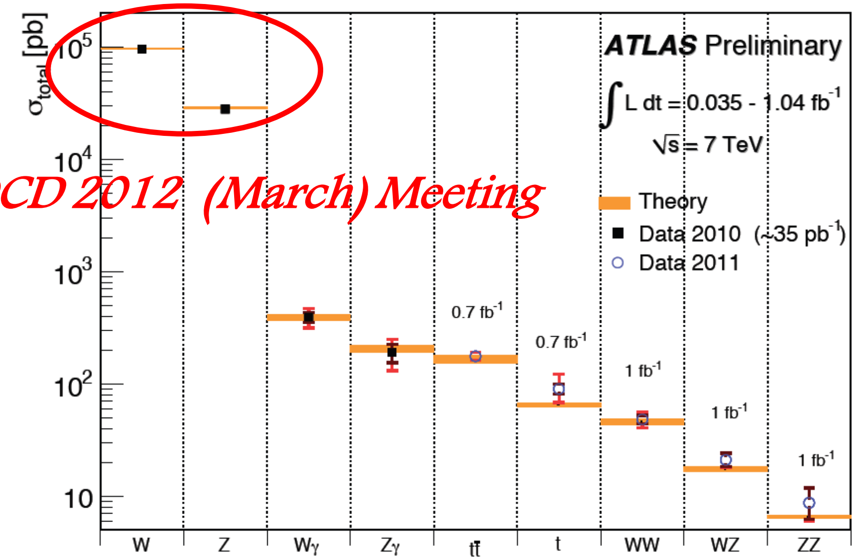
as predicted by the color dipole approach!

Summary and Outlook

The Standard Model works quite well so far!



presented at Moriond QCD 2012 (March) Meeting



- **Theoretical work in "cleaning up" of the QCD theory uncertainties (NLO, NNLO, resummation) in DY for the LHC is going very well!**
- **Existing LHC data allow to discriminate and constrain PDFs in much wider kinematics than ever before (much more to come)**
- **Forward (small-x and diffractive) Drell-Yan data from the LHC offers a lot of opportunities to constrain saturation physics at small-x and the proton structure function at large-x**