XL International Symposium on Multiparticle Dynamics ISMD 2010
Antwerp, September 2010

Forward Physics and Cosmic Rays: Introduction

Convenors: M. Grothe, F. Hautmann and S. Ostapchenko

I. Introduction to 11 talks in Forward Physics and Cosmic Rays session:

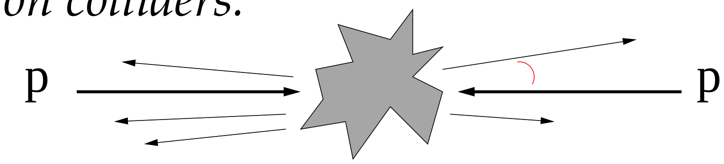
- LHC experimental results [5]
- Auger [1]
- HERA [1]
- Theory [4]

$\diamondsuit$ With the advent of the LHC, forward physics becomes largely a new field both from theory and experiment standpoints.

$\Downarrow$

II. Introduction to key themes from forward-region phenomenology

Particle production in the forward region at hadron colliders:



small polar angles, i.e. large rapidities

♢ Historically:

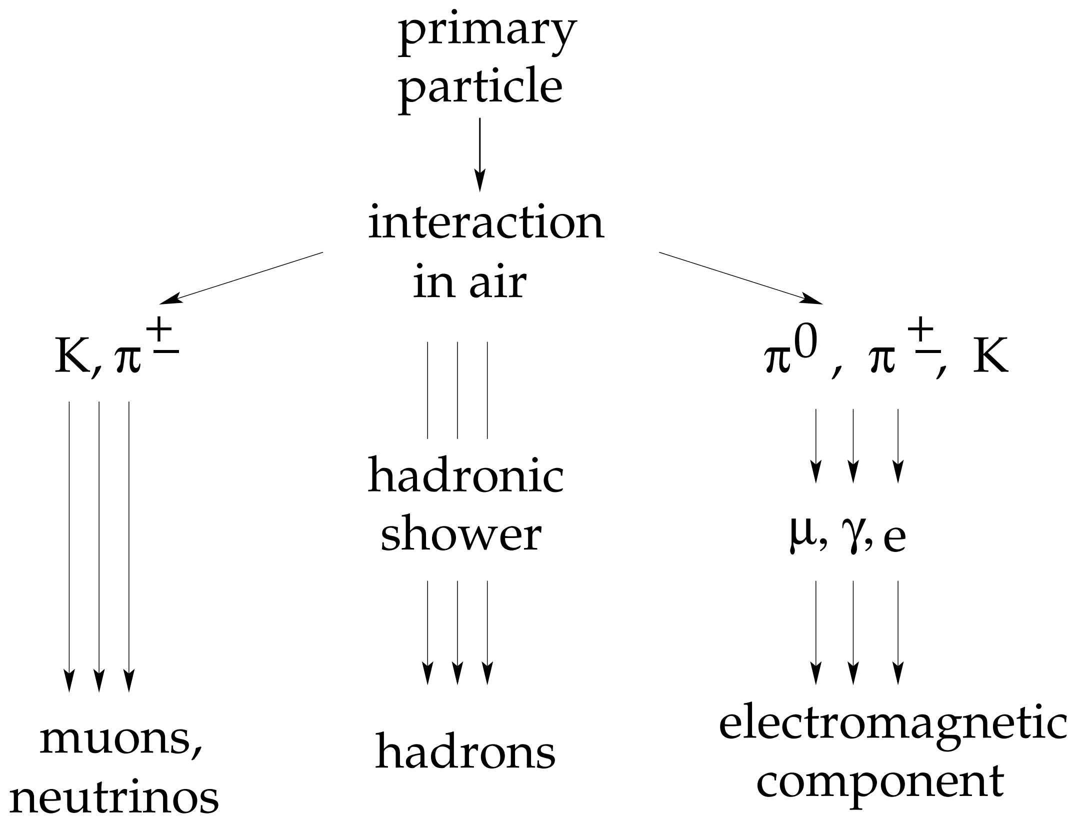
- fairly specialized subject: e.g., measurements of σ(total) and σ(elastic)
- dominated by soft, small-p_T processes

♢ At the LHC:

- forward processes involve both soft and hard production
- phase space opening up for large $\sqrt{s}$ $\Rightarrow$ multiple-scale processes
- unprecedented coverage of large rapidities (calorimeters + proton taggers)

$\Rightarrow$
- forward high-p_T production
- central production of high p_T + forward protons

• Measurements of forward particle production (soft and hard)
at the LHC serve as input to
Monte Carlo models of high-energy showers in cosmic ray physics



• Fixed target collision in air with 10^{17} eV corresponds to pp interaction at LHC

LHC experimental results

$\diamondsuit$ $A)$ Forward physics via main detectors + forward calorimeters:

- Low-x physics via LHC-b [J. Anderson]
- Forward particle production + energy flow: CMS [S. Cerci]
- Forward particle production + energy flow: LHC-f [L. Bonechi]

$\diamondsuit$ $B)$ 'Vetoes on forward detectors':

- LHC Diffraction [S. Navin]

$\diamondsuit$ $C)$ Physics with near beam proton taggers:

- TOTEM

Future physics:

- High-luminosity diffraction and γ physics
- Central exclusive production and discovery physics

NOTE:

♠ Nearly all above topics imply new experimental areas:
prime start-up physics subjects

♠ Theoretical issues: LHC is to a large extent a QCD machine;
LHC forward physics is dominated by QCD at small x.

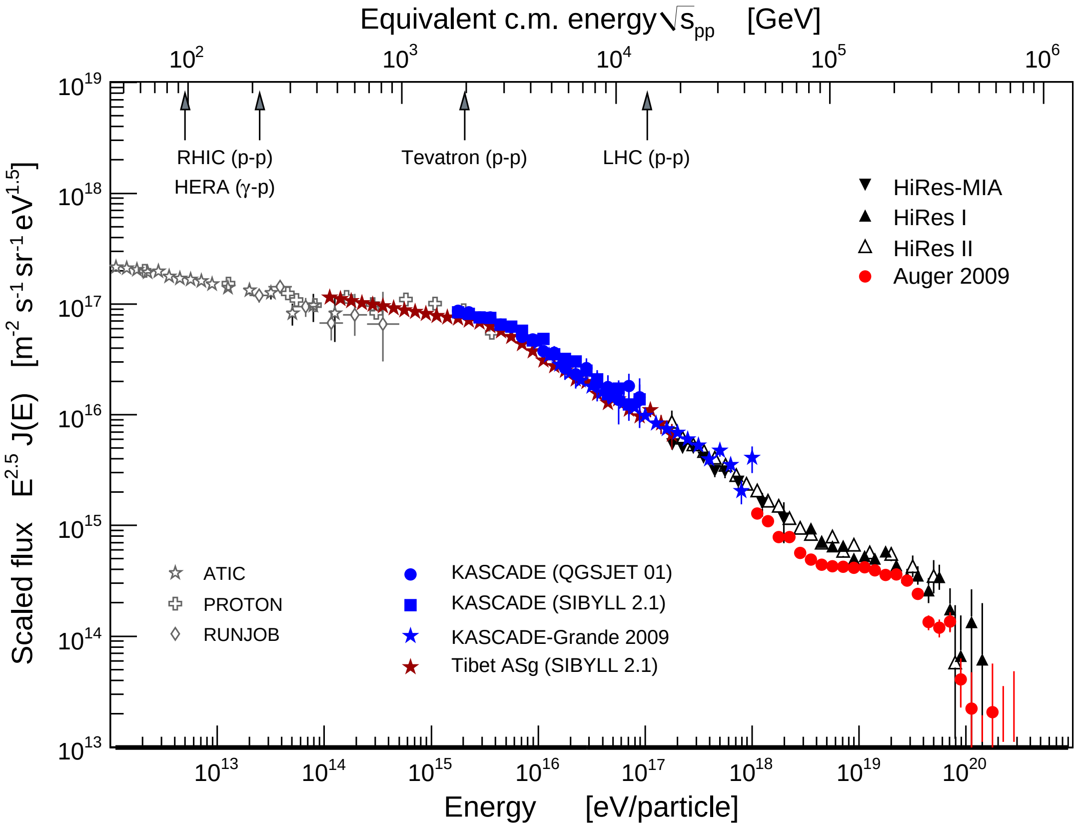
$\Downarrow$

- Factorization at small x
- Evolution / parton showering beyond collinear ordering
- High-density effects and parton saturation

♠ Phenomenology: How well do current Monte Carlo generators
simulate LHC final states in the forward region?

Not only LHC physics...: The Cosmic Ray / Collider connection

[talk by G. Rodriguez]

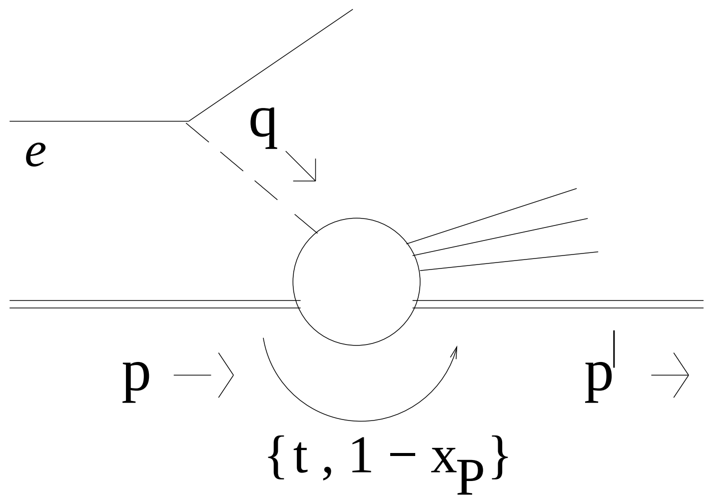


R. Engel, 2010

Inputs from HERA: Diffraction in DIS and photoproduction

[talk by R. Polifka]

- new diffractive fits with HERAII data
- diffractive jet photo- and lepto-production
- diffractive $F_L^{(D)}$



\+ further new results coming up from HERA analyses

OUTLINE

- Forward region $\Rightarrow$ multiple-scale, small-x physics

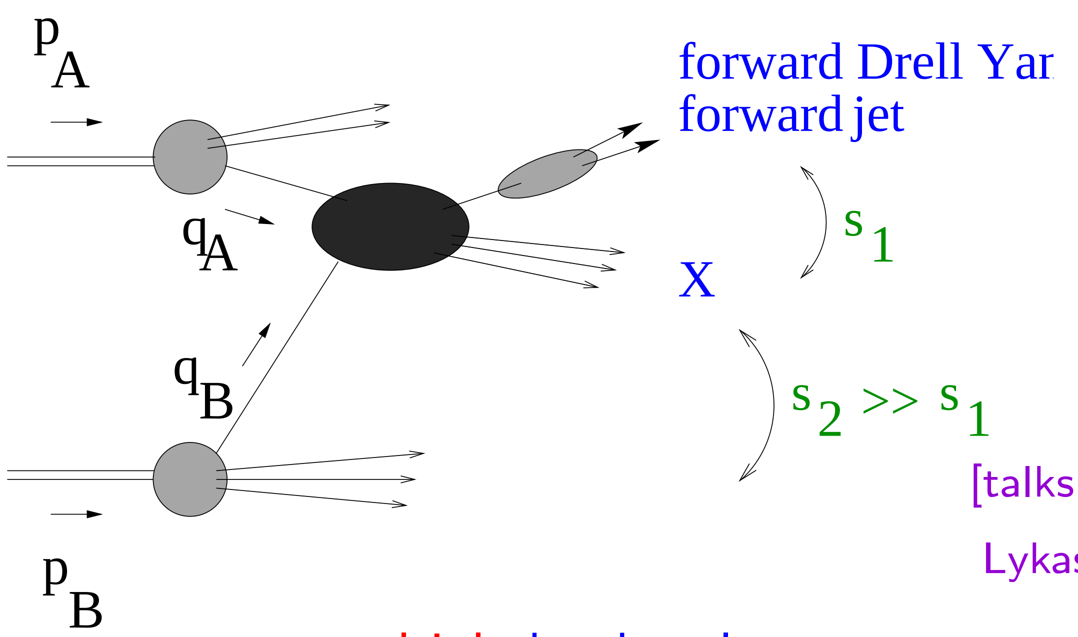
$\Rightarrow$ Evaluation of QCD theoretical predictions
in multi-scale regime:

- Perturbative QCD resummations?

- Corrections beyond single parton scattering?

- Theory tools to treat hard and soft interactions?

II. High-p_T production in the forward region



[talks by Anderson, Lykasov, Deak]

- multiple hard scales
- asymmetric parton kinematics $x_A \to 1, \; x_B \to 0$

♢ Are fixed-order QCD calculations reliable in the forward region?

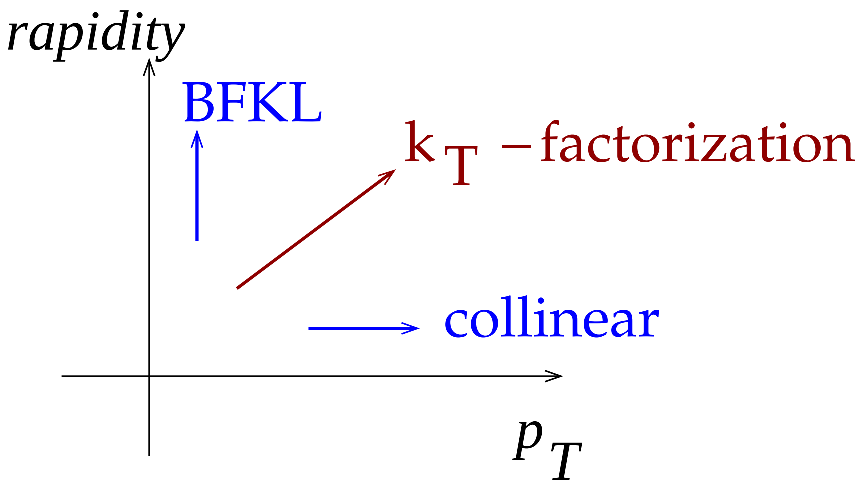
♢ Are perturbative QCD resummations to be performed?

Forward jet production as a multi-scale problem

- summation of high-energy logarithmic corrections long recognized to be necessary for reliable QCD predictions
  $\Rightarrow$ BFKL calculations

Mueller & Navelet, 1987; Del Duca et al., 1993; Stirling, 1994; Colferai et al., arXiv:1002.1365

- Large logarithmic corrections are present both in the hard scale and in the rapidity interval



$\longrightarrow$ Both kinds of log contributions can be summed consistently to all orders of perturbation theory via QCD factorization at fixed k_T

Forward jets:

- High-energy factorization at fixed transverse momentum

$$\frac{d\sigma}{dQ_t^2 d\varphi} = \sum_a \int \phi_{a/A} \otimes \frac{d\widehat{\sigma}}{dQ_t^2 d\varphi} \otimes \phi_{g^*/B}$$

▷ needed to resum consistently both logs of rapidity and logs of hard scale *Deak, Jung, Kutak & H, JHEP 09 (2009) 121*

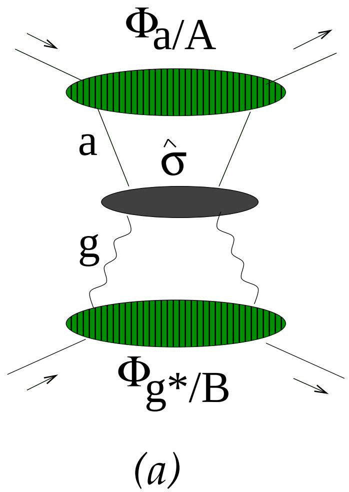


Figure 1: Factorized structure of the cross section.

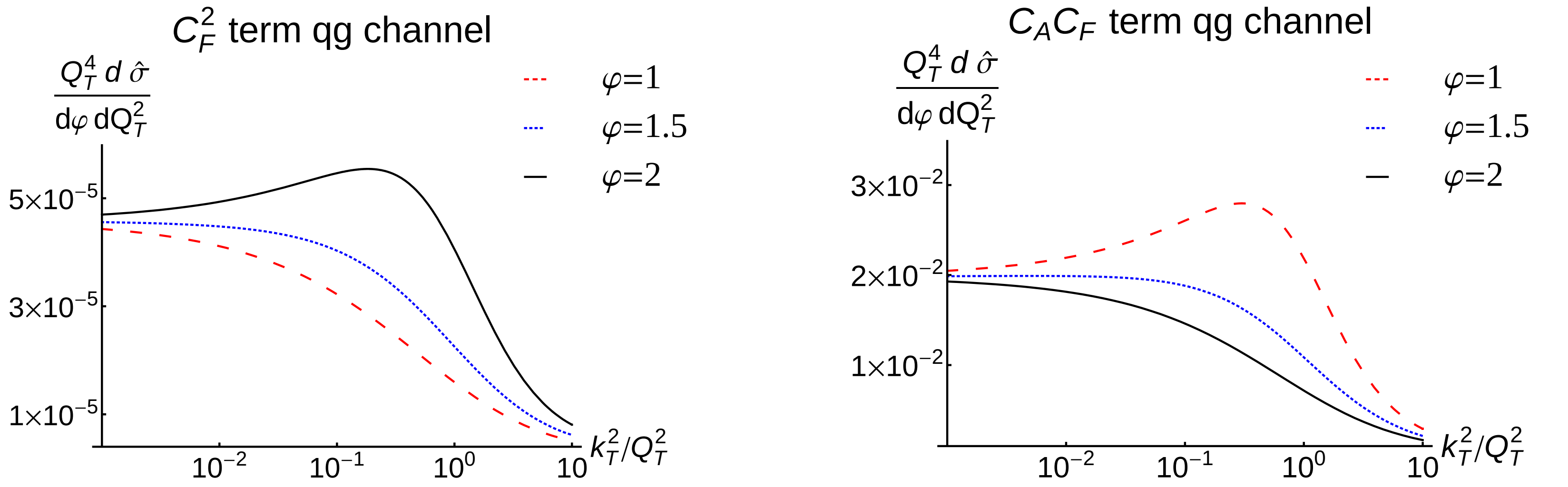
♢ ϕ_a near-collinear, large-x; ϕ_{g^*} $k_\perp$-dependent, small-x

♢ $\widehat{\sigma}$ off-shell continuation of hard-scattering matrix elements

FULLY EXCLUSIVE MATRIX ELEMENTS: BEHAVIOR AT LARGE $K_\perp$

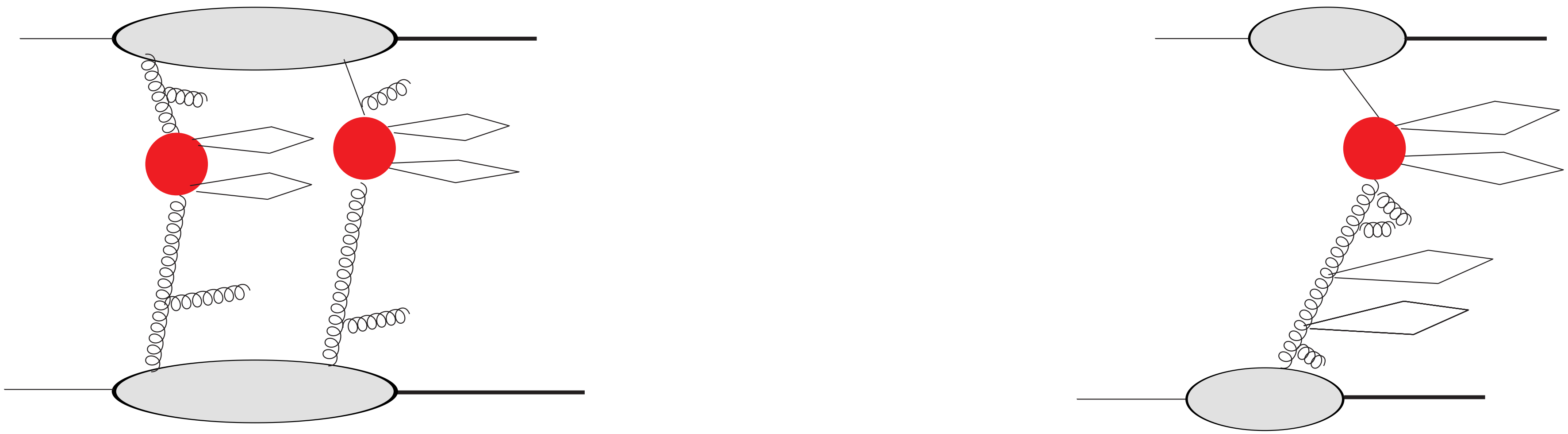
Q_t = final-state transverse energy (in terms of two leading jets p_t's)

k_t = transverse momentum carried away by extra jets



- dynamical cut-off at $k_t \sim Q_t$, set by higher-order radiative effects
  - non-negligible terms from finite k_t tail
- $C_F C_A$ contribution to qg dominates at high energies $s/Q_t^2 \gg 1$

Multiple parton interactions



Multi-jet production by (left) multiple parton chains; (right) single parton chain.

- modeled by shower Monte Carlo generators

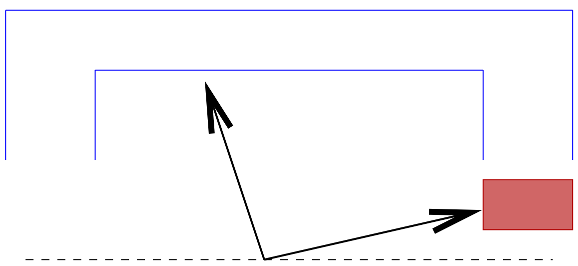
Sjöstrand & Skands, 2006; Gieseke et al., 2008

♢ Do multiple parton interactions become non-negligible in hard processes at forward rapidities?

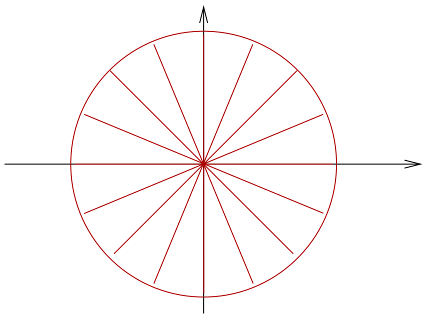
FORWARD-CENTRAL JET CORRELATIONS

- polar angles small but far enough from beam axis
  - measure correlations in azimuth, rapidity, p_T

$$p_\perp \gtrsim 20 \text{ GeV} \; , \; \Delta\eta \gtrsim 4 \div 6$$



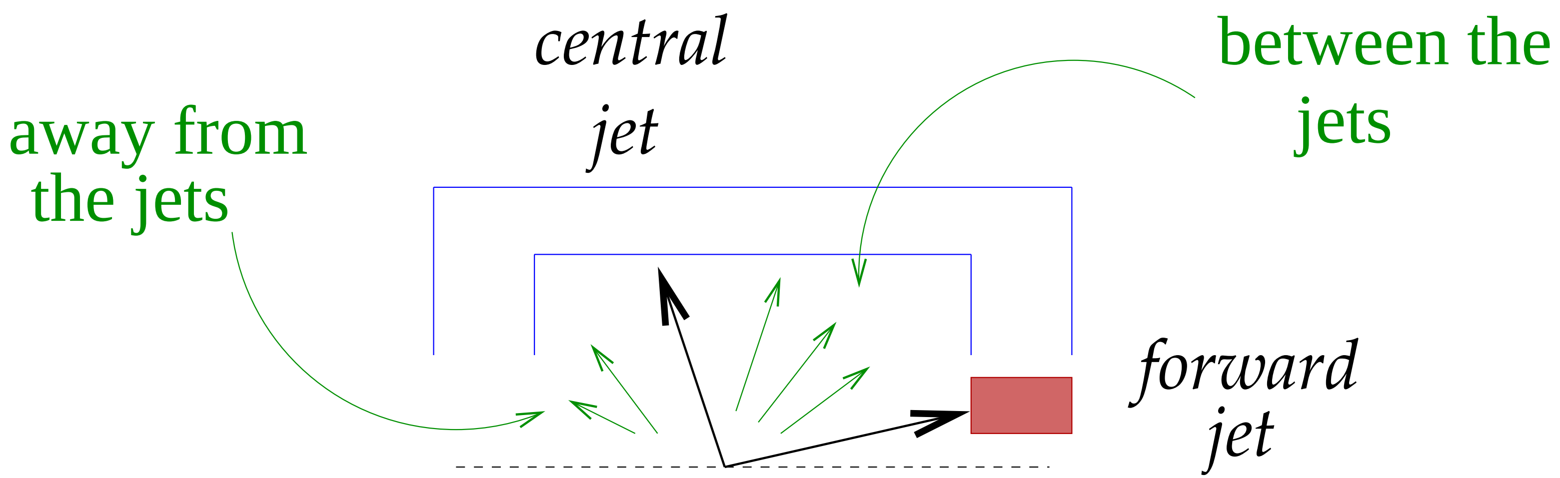
central $+$ forward detectors



azimuthal plane

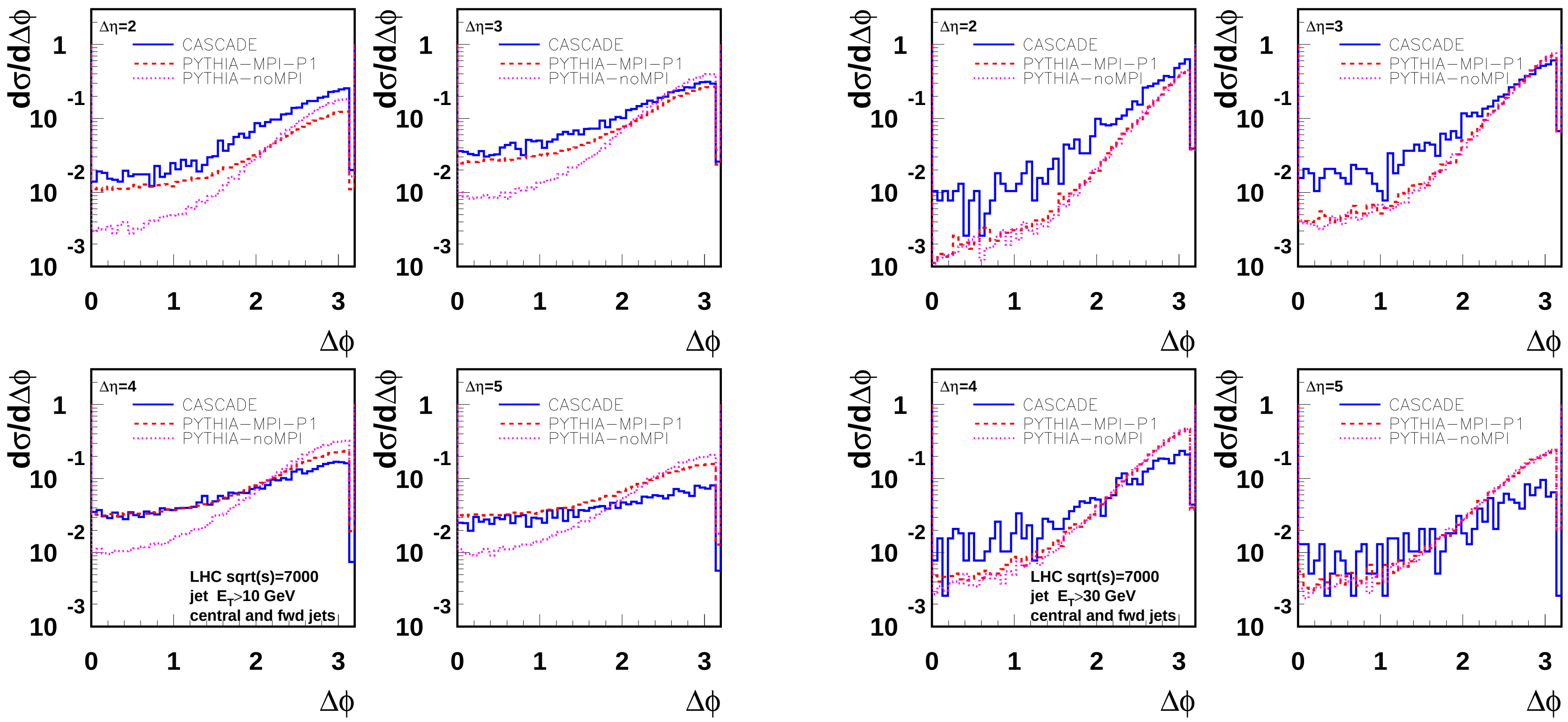
1 central + 1 forward jet:

particle and energy flow in the inter-jet and outside regions



Cross section as a function of the azimuthal difference $\Delta\phi$ between central and forward jet for different rapidity separations

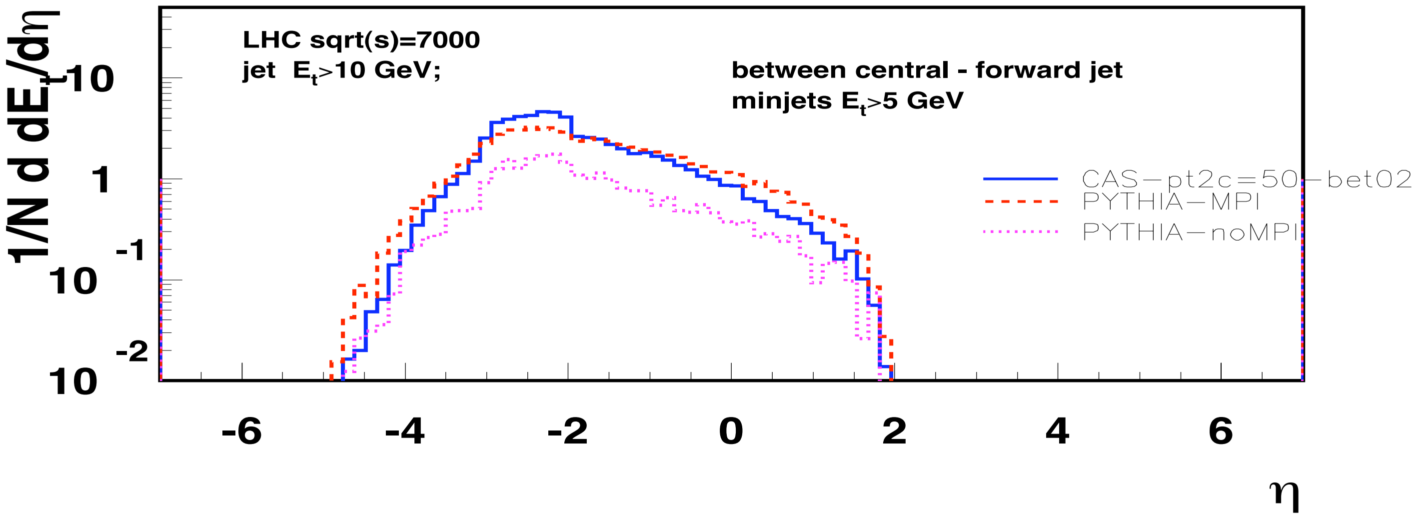
[Deak et al., in progress]

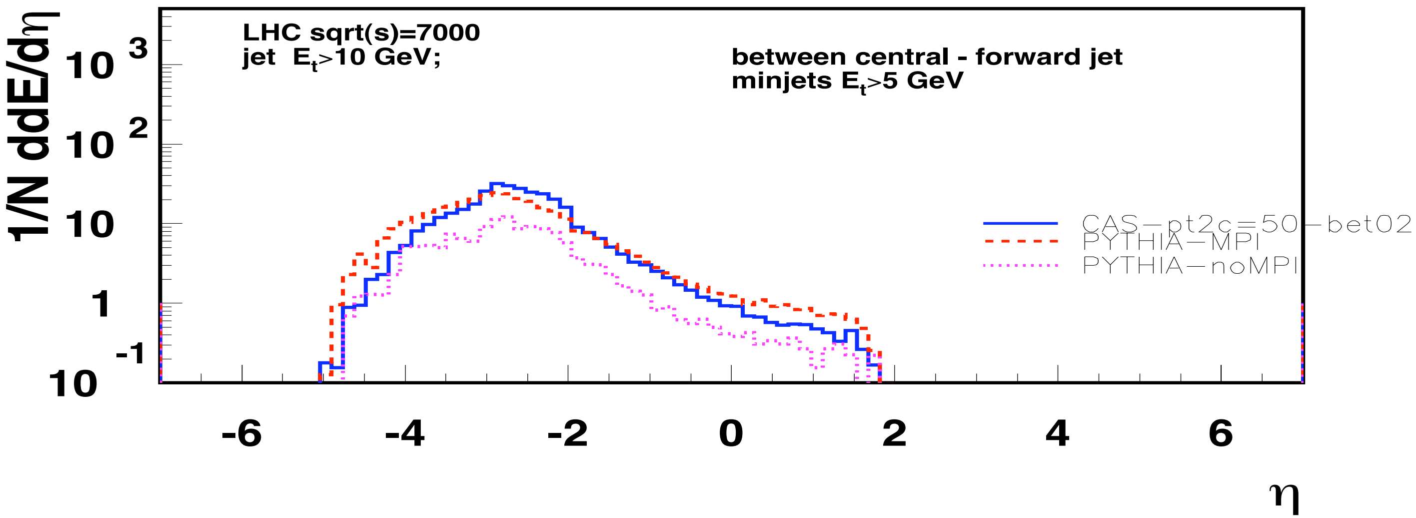


MC models: • CASCADE: non-collinear radiative corrections to single parton chain

• PYTHIA: multiple parton interactions, no corrections to collinear approximation

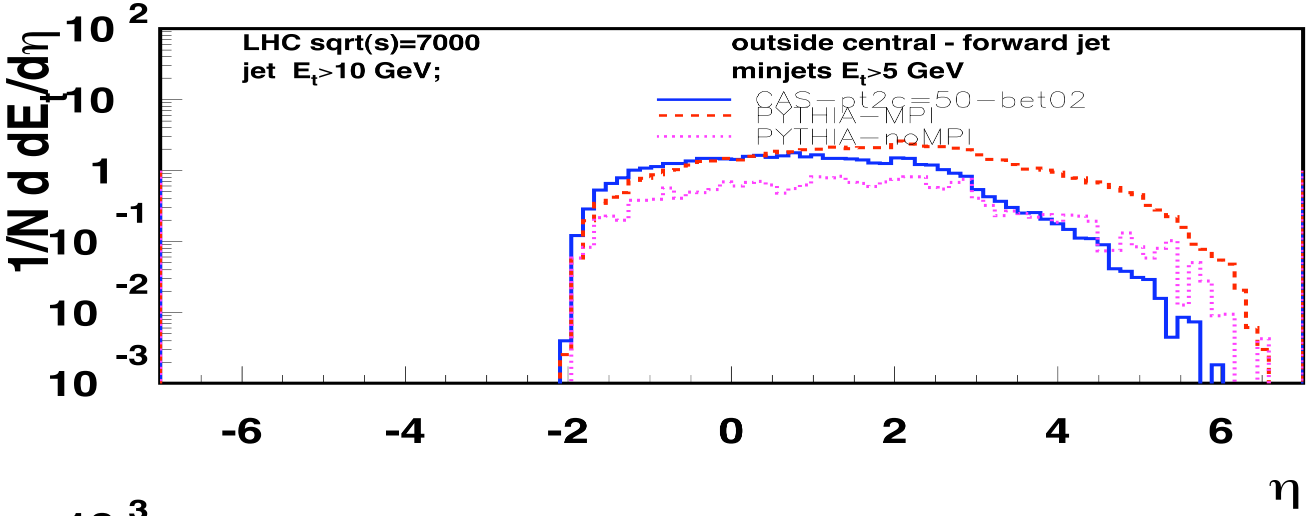
Transverse energy flow in the inter-jet region

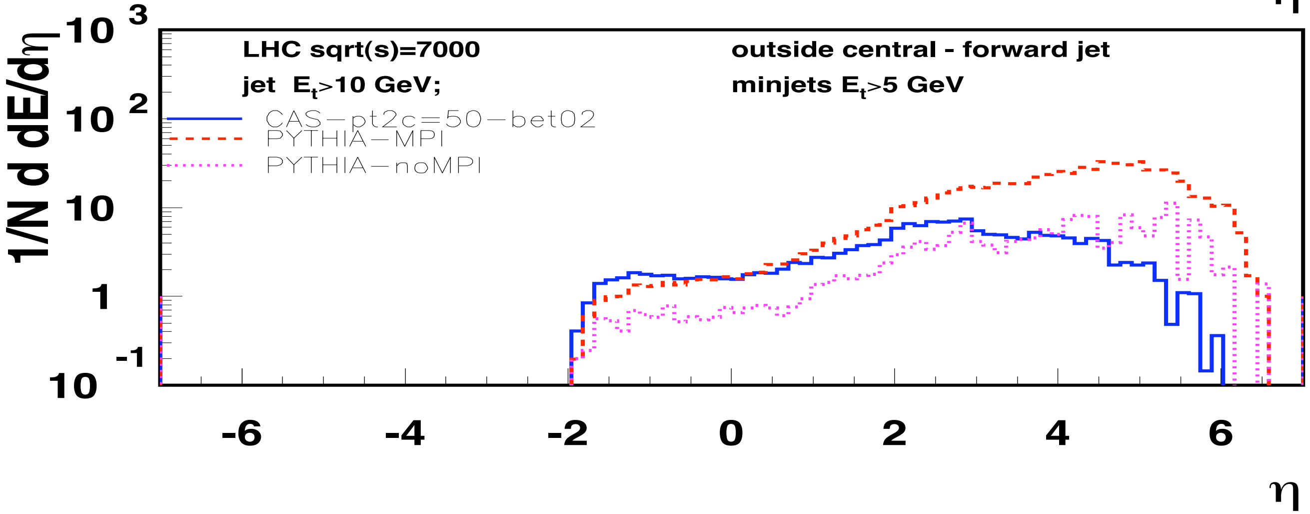




- higher mini-jet activity in the inter-jet region from corrections to collinear ordering

Transverse energy flow in the outside region





- at large (opposite) rapidities, full branching well approximated by collinear ordering
- higher energy flow only from multiple interactions

$\diamondsuit$ Energy flow due to minijets ($E_T > 5$ GeV) $\Rightarrow$

reduced IR sensitivity

$\Rightarrow$ 'tune' (semi-)hard interaction component

$\diamondsuit$ Particle spectra will serve similar purpose

$\diamondsuit$ Distribution in $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ also potentially useful ($\hookrightarrow$)

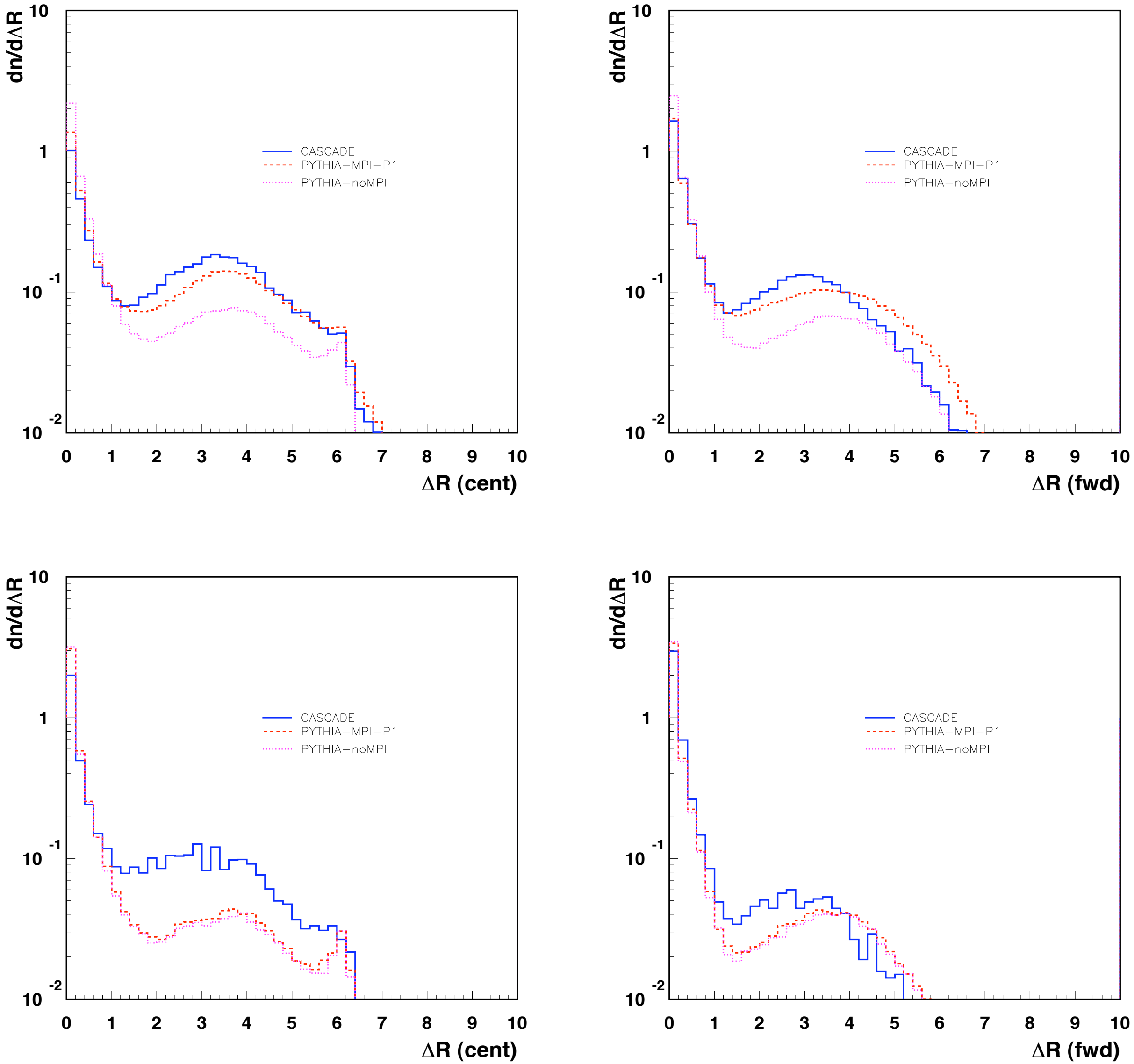


Figure 5: ΔR distribution of the central ($|\eta_c| < 2$, left) and forward jets ($3 < |\eta_f| < 5$, right) for $E_T > 10$ GeV (upper row) and $E_T > 30$ GeV (lower row). The prediction from the $k_\perp$ shower (Cascade) is shown with the solid blue line; the prediction from the collinear shower (Pythia) including multiple interactions and without multiple interactions is shown with the red and purple lines. $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$, where $\Delta\phi = \phi_{jet} - \phi_{part}$, $\Delta\eta = \eta_{jet} - \eta_{part}$

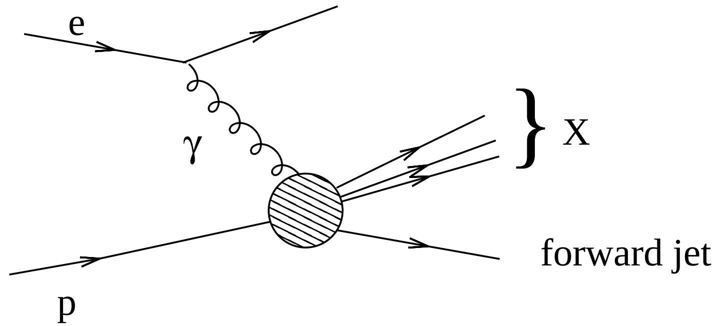
FURTHER QUESTIONS

♠ What are the implications of higher mini-jet activity in the between region for vector boson fusion search channels ?

♠ Could one include multi-parton interactions in a complete parton factorization picture?

♠ Could one achieve a unified understanding of forward hard processes including DIS? $\longrightarrow$ prospects for future LHeC, EIC

- Note:



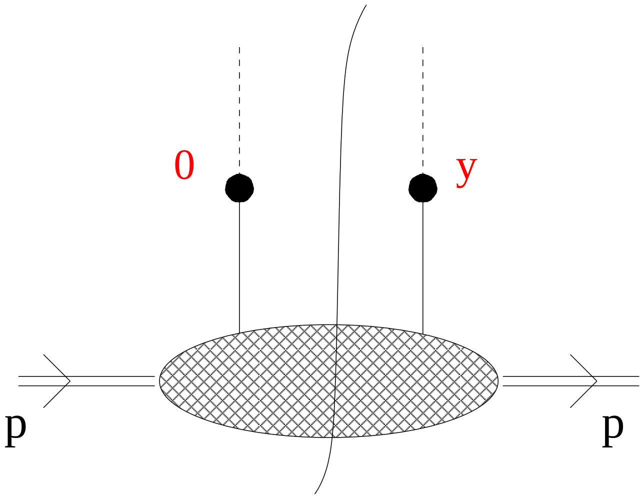
- neither PYTHIA Monte Carlo nor NLO calculations are able to describe forward jet HERA data

[A. Knutsson, LUNFD6-NFFL-7225-2007 (2007); L. Jönsson, AIP Conf. Proc. 828 (2006) 175]

A concept underlying several talks:

III. UNINTEGRATED (OR TRANSVERSE MOMENTUM DEPENDENT) PARTON DISTRIBUTIONS

- Gustafson [shower Monte Carlo]
- Enberg [uses of u-pdfs in diffraction]
- Deak [in High-p_T session]
- Cherednikov [theory developments]

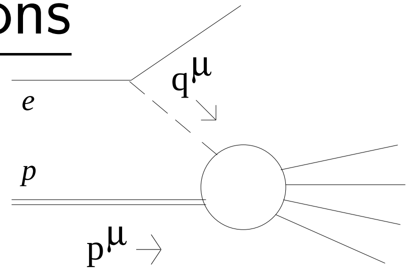


$p = (p^+ ,\ m^2 / 2 p^+ ,\ 0_\perp)$

$$\widetilde{f}(y) = \langle\ P \mid \overline{\widetilde{\psi}}(y)\ \gamma^+\ \widetilde{\psi}(0) \mid P\ \rangle \quad , \qquad y = (0, y^-, y_\perp)$$

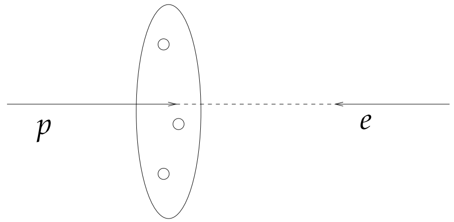
correlation of quark fields ('dressed' with gauge links) at distances y, $y_\perp \neq 0$

A) Single-scale hadron scattering. E.g., DIS structure functions



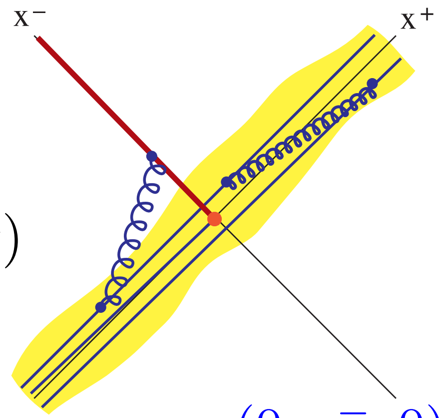
- necessarily sensitive to long timescales, BUT

σ can be written as $\sigma(Q,m) = C(Q, \text{parton momenta } > \mu) \otimes f(\text{parton momenta } < \mu, m)$



in "infinite-momentum" frame, $\delta t_{\text{scatter}} \ll \tau_{\text{parton}}$

$$\text{Pdf's}: \quad f(x,\mu) = \int \frac{dy^-}{2\pi}\, e^{-ixp^+y^-}\, \widetilde{f}(y)$$



$$\widetilde{f}(y) = \langle\, P \mid \overline{\psi}(y)\, V_y^\dagger(n)\, \gamma^+\, V_0(n)\, \psi(0) \mid P\,\rangle \quad , \qquad y = (0, y^-, 0)$$

$$V_y(n) = \mathcal{P}\exp\left(i g_s \int_0^\infty d\tau\ n\cdot A(y+\tau\, n)\right)$$

↖ correlation of parton fields at lightcone distances

◊ Renormalization group invariance ⇒

$$\frac{d}{d\ln\mu}\,\sigma = 0 \quad \Rightarrow \quad \frac{d}{d\ln\mu}\,\ln f = \gamma = -\frac{d}{d\ln\mu}\,\ln C$$

$\hookrightarrow$ DGLAP evolution equations [Altarelli-Parisi
Dokshitzer
Gribov-Lipatov]

$$f = f_0 \times \exp\int \frac{d\mu}{\mu}\,\gamma(\alpha_s(\mu))$$

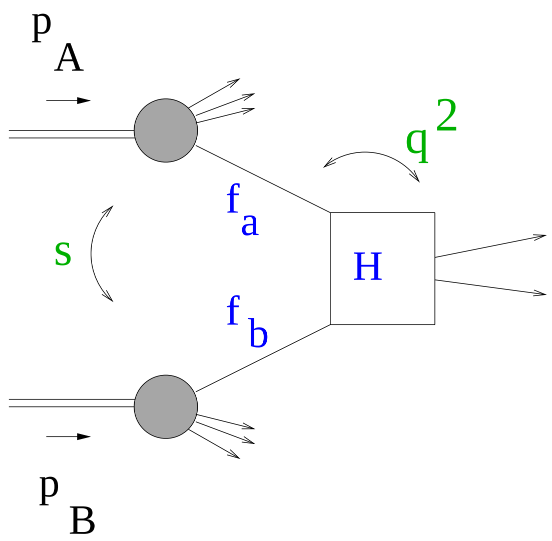
↗ resummation of $(\alpha_s \ln Q/\Lambda_{\rm QCD})^n$ to all orders in PT

Note: expansions $\gamma \simeq \gamma^{(LO)}\left(1 + b_1\alpha_s + b_2\alpha_s^2 + \ldots\right)$

$$C \simeq C^{(LO)}\left(1 + c_1\alpha_s + c_2\alpha_s^2 + \ldots\right)$$

give LO, NLO, NNLO, ... logarithmic corrections

B) Multiple-scale hard scattering at LHC energies



$$s \gg q_1^2 \gg \cdots q_n^2 \gg \Lambda$$

- more complex, potentially large corrections to all orders in α_s, $\sim \ln^k(q_i^2/q_j^2)$

$$e.g. \;\; \gamma \simeq \gamma^{(LO)} \left(1 + c_1 \alpha_s + \ldots + c_{n+m} \alpha_s^m (\alpha_s \; L)^n + \ldots\right) \; , \; L = \text{“large log”}$$

$\hookrightarrow$ yet summable by QCD techniques that

▷ generalize renormalization-group factorization

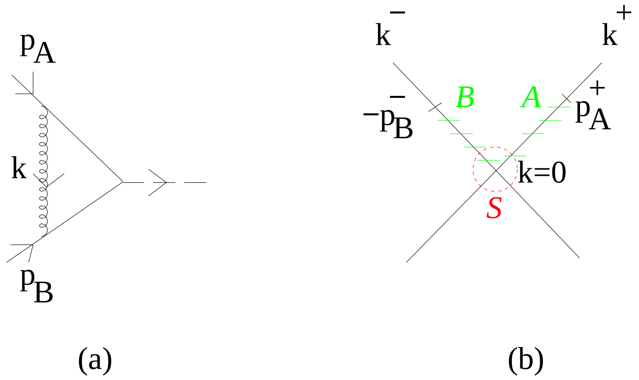
▷ extend parton correlation functions off the lightcone

$\Rightarrow$ unintegrated (or TMD) pdf's

Examples:

[see Cherednikov's talk]

- Sudakov form factor S:

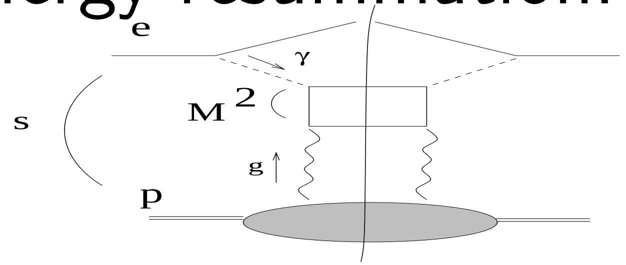


▷ entering Drell-Yan production, W-boson $p_\perp$ distribution, etc.

$\Rightarrow \partial S / \partial \eta = K \otimes S$ CSS evolution equations [Collins-Soper-Sterman]

$\nwarrow$ resums $\alpha_s^n \ln^m M/p_T$

- High-energy resummation: $s \gg M^2 \gg \Lambda^2_{\rm QCD}$



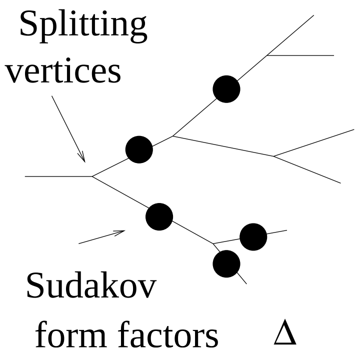
$\diamondsuit$ energy evolution: BFKL equation [Balitsky-Fadin-Kuraev-Lipatov]

$\hookrightarrow$ corrections down by $1/\ln s$ rather than $1/M$

IV. FROM QCD TO MONTE CARLO EVENT GENERATORS

- Factorizability of QCD x-sections $\longrightarrow$ probabilistic branching picture

$\diamondsuit$ $A)$ QCD evolution by "parton showering" methods:

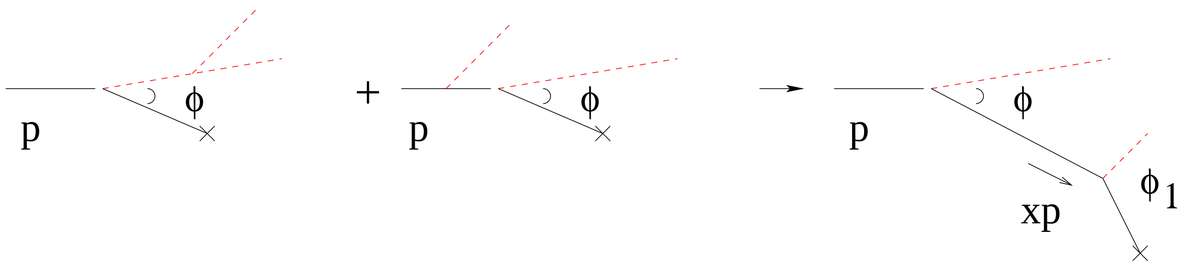


$$d\mathcal{P} = \int \frac{dq^2}{q^2} \int dz \; \alpha_S(q^2) \; P(z) \; \Delta(q^2, q_0^2)$$

$\hookrightarrow$ collinear, incoherent emission

$\diamondsuit$ $B)$ Soft emission $\longrightarrow$ interferences $\longrightarrow$ ordering in decay angles:

$\hookrightarrow$ gluon coherence for $x \sim 1$



$\diamondsuit$ $C)$ Gluon coherence for $x \ll 1 \Rightarrow$ corrections to angular ordering:

$\hookrightarrow$ MC based on $k_\perp$-dependent unintegrated pdfs and MEs

COHERENCE IN HIGH-ENERGY LIMIT

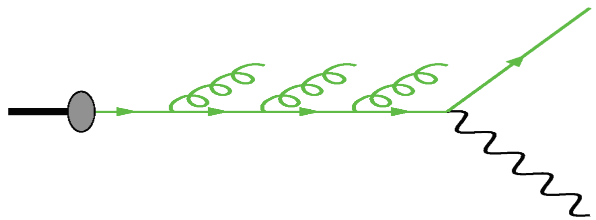
Soft vector-emission current from external legs $\rightarrow$

• leading IR singularities

[J.C. Taylor, 1980; Gribov-Low (QED)]

• fully appropriate in single-scale hard processes

Dokshitzer, Khoze, Mueller and Troian, RMP (1988); Webber, A. Rev. Nucl. Part. (1986)



multi-scale: $s = q_1^2 \gg \cdots \gg q_n^2 \gg \Lambda^2$
[e.g.: LHC final states with multi-jets]

$\Downarrow$

▷ internal emissions non-negligible

▷ current also factorizable at high-energy: *[Ciafaloni 1998; 1988]*

$$|M^{(n+1)}(k,p)|^2 = \left\{ [M^{(n)}(k+q,p)]^\dagger \, [\mathbf{J}^{(R)}]^2 \, M^{(n)}(k+q,p) - [M^{(n)}(k,p)]^\dagger \, [\mathbf{J}^{(V)}]^2 \, M^{(n)}(k,p) \right\} .$$

BUT... ▷

▷ ... • **J** depends on total transverse momentum transmitted

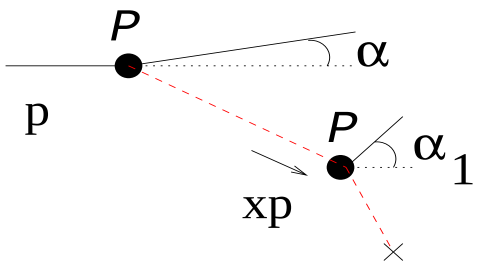
⇒ matrix elements and pdf at fixed $k_\perp$ ("unintegrated")

• virtual corrections not fully represented by Δ form factor

⇒ modified branching probability $P(z, k_\perp)$ as well

▷ $K_\perp$-DEPENDENT PARTON BRANCHING

$$\mathcal{G}(x, k_T, \mu) = \mathcal{G}_0(x, k_T, \mu) + \int \frac{dz}{z} \int \frac{dq^2}{q^2} \, \Theta(\mu - zq) \times \underbrace{\Delta(\mu, zq)}_{\text{Sudakov}} \; \underbrace{\mathcal{P}(z, q, k_T)}_{\text{unintegr. splitting}} \; \mathcal{G}(x/z, k_T + (1-z)q, q)$$



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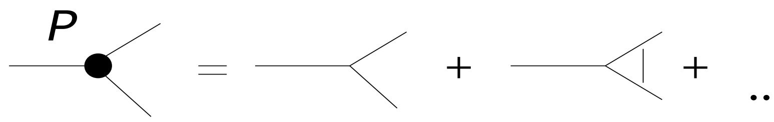

▷ CCFM evolution equation [talks by Deak,

▷ Monte Carlo implementations CASCADE, LDC, ... Gustafson]

♢ Unintegrated (TMD) pdf's are key ingredient for
different types of QCD resummations

♢ also relevant to fully take account of coherence effects
in parton showers at high energy

♢ possibly, more natural framework

to push theory towards soft p_T physics
and to treat diffraction

[talk by Enberg]

In summary...

♣ Exciting new results from the LHC

♣ Impact on cosmic rays physics $\longrightarrow$ Auger results

♣ Continuing stream of inputs from HERA

♣ Many new, challenging physics issues

... should make for an enjoyable session
and interesting times ahead!