BFKL, Dipols, λ-Fits and AWAKE-VHEeP

Motivation:

Confinement forces emerge from complicated gluon-gluon interaction, experimental studies of confinement are difficult because everything happens very quickly, 10^{-23} sec

However, at very high energies time dilatation slows down all physics processes what allows to describe complicated gluon structures from first principles

- BFKL resummation of all Feynman diagrams for gluon-gluon interaction
- highlight of AWAKE-VHEeP + …. physics studies

Henri Kowalski
x-Fitter Meeting, Krakow, 5th of March 2018

the talk is based on:

Decoupling of the leading contribution in the discrete BFKL analysis of high-precision HERA data

Eur. Phys. J. C (2017) 77:777

H. Kowalski, L. N. Lipatov, D. A. Ross, O. Schulz

✦Discrete spectrum of BFKL eigenstates

✦Analysis of HERA-F_2 ☛ BFKL-Ground State has to be saturated

✦Dipole Picture as a natural framework for analysis of saturated

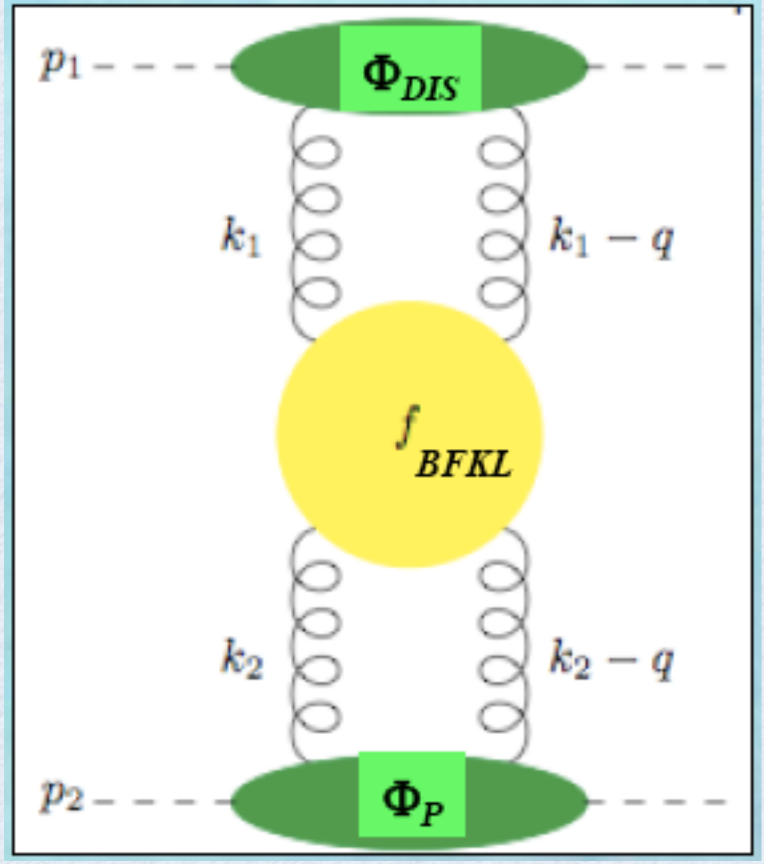
✦Ground State

λ-Fits with A. Luszczak

AWAKE-VHEeP project

The dynamics of Gluon Density at low x is determined by **the amplitude for the scattering of a gluon on a gluon**, described by the BFKL equation

$$\frac{\partial}{\partial \ln s}\mathcal{A}(s,\mathbf{k},\mathbf{k}') \;=\; \delta(k^2 - k'^2) + \int dq^2 \mathcal{K}(\mathbf{k},\mathbf{q})\mathcal{A}(s,\mathbf{q},\mathbf{k}')$$



solved by the Green function method, in terms of the eigenfunctions of the kernel

$$\int dk'^2 \mathcal{K}(\mathbf{k},\mathbf{k}') f_\omega(\mathbf{k}') \;=\; \omega f_\omega(\mathbf{k})$$

in LO, with fixed α_s

$$\begin{aligned} f_\omega(\mathrm{k}) &= \exp(i\nu \ln k^2)/k \\ \omega &= \alpha_s \chi_0(\nu) \end{aligned}$$

Green f. method - preserves the scaling (conformal) invariance of BFKL

⇒ most consistent solution of BFKL

a possible bridge to Pomeron-Graviton?

In LO with fixed α_s

BFKL predicts that F_2 is dominated by the leading trajectory $F_2 \sim (1/x)^{\omega}$

$\omega = 4\,\alpha_s \ln 2 \approx 0.5$

independent of Q^2

with NLO with resummation

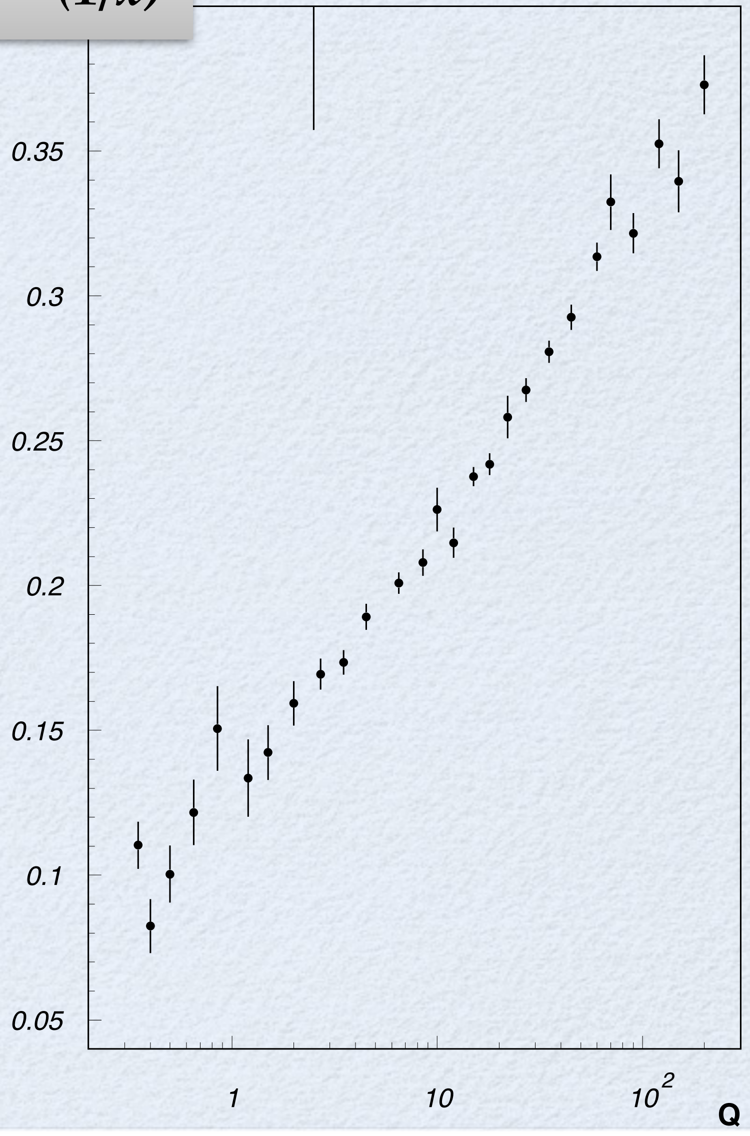
$\omega \approx 0.3$
also independent of Q^2

⇒

clear contradiction to HERA data

λ-Fit

$F_2 \propto (1/x)^{\lambda}$



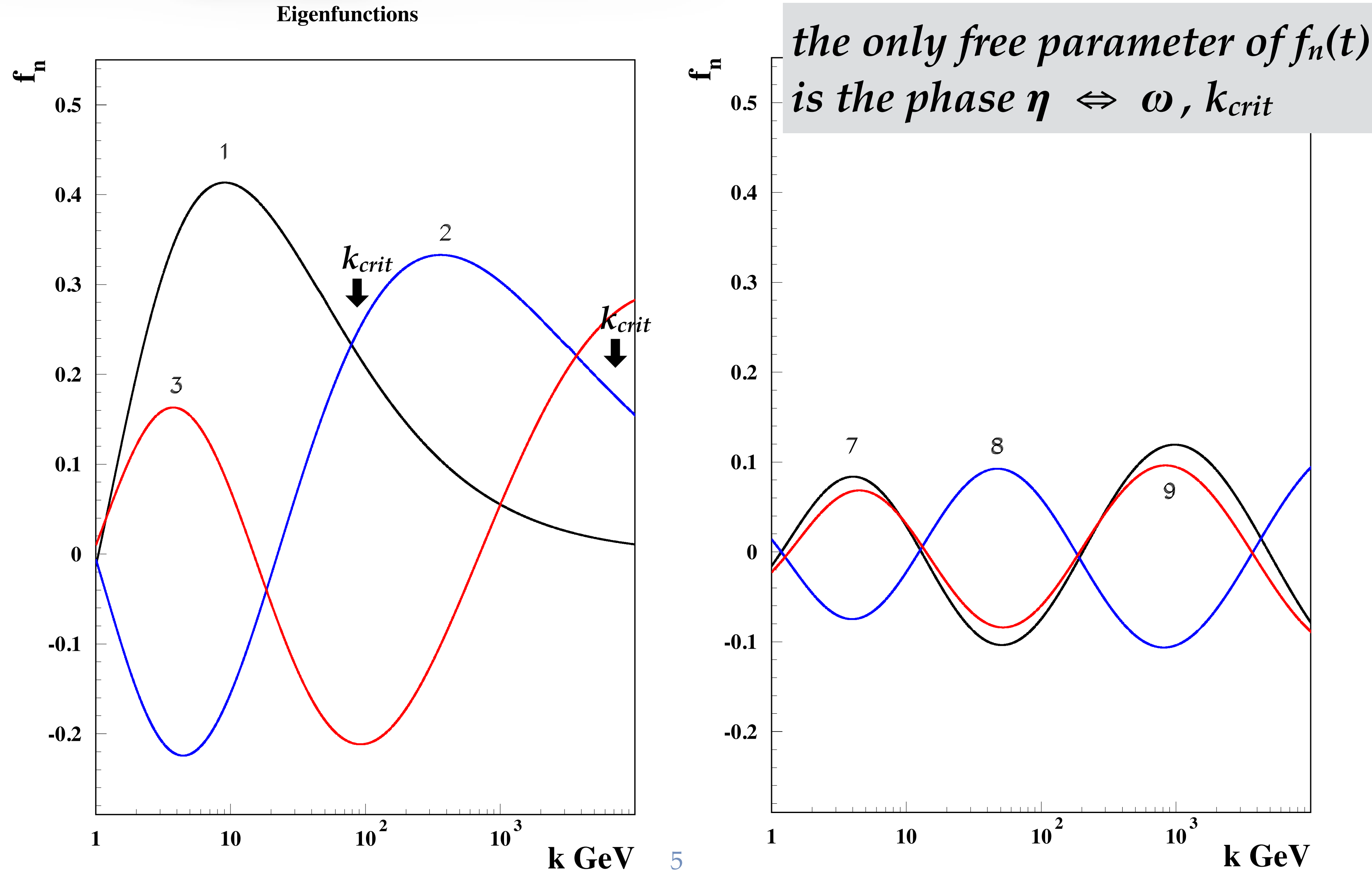
KLRO ⇒

with running α_s, the eigenfunctions of the BFKL Kernel are given by

$$f_{\omega_n}(t) \;=\; \sqrt{\frac{\pi}{\phi'(\omega_n)}}N_{\omega_n}(t)Ai(z(t)).$$

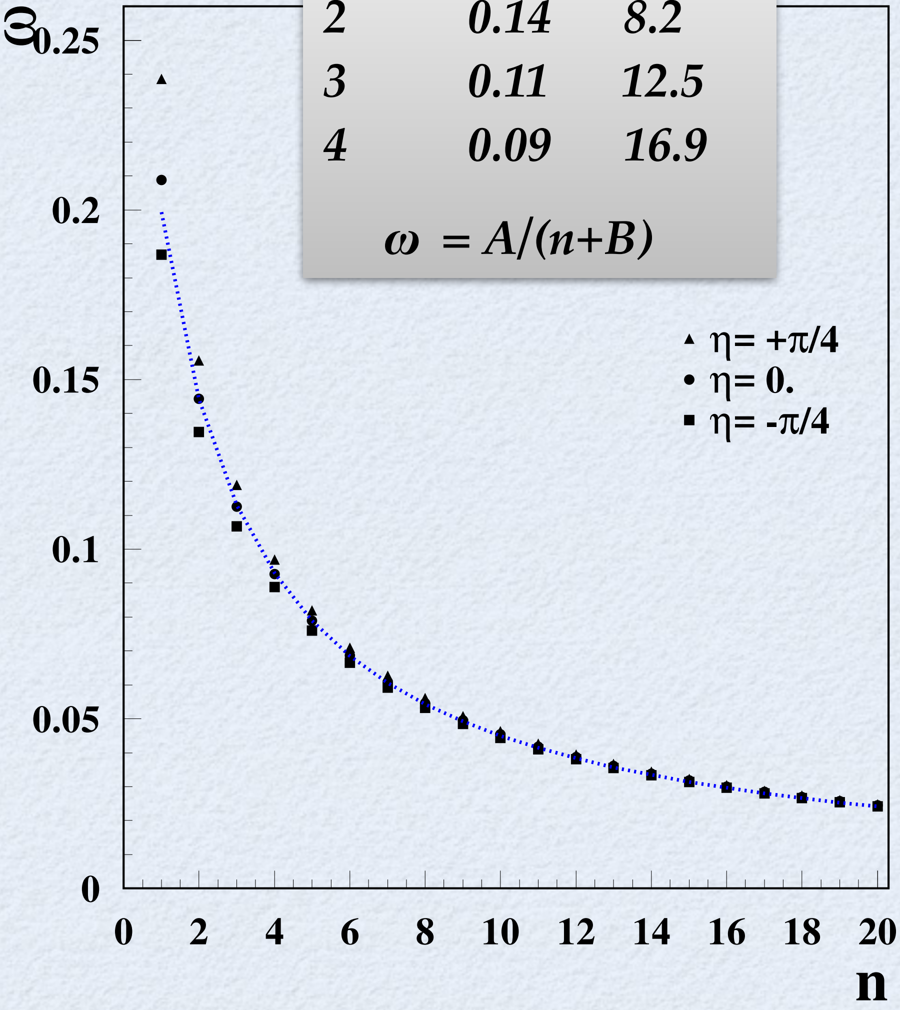
N_ω , z, ϕ are known functions of $t = \ln(k^2/\Lambda)$

the only free parameter of $f_n(t)$ is the phase $\eta \;\Leftrightarrow\; \omega$, k_{crit}

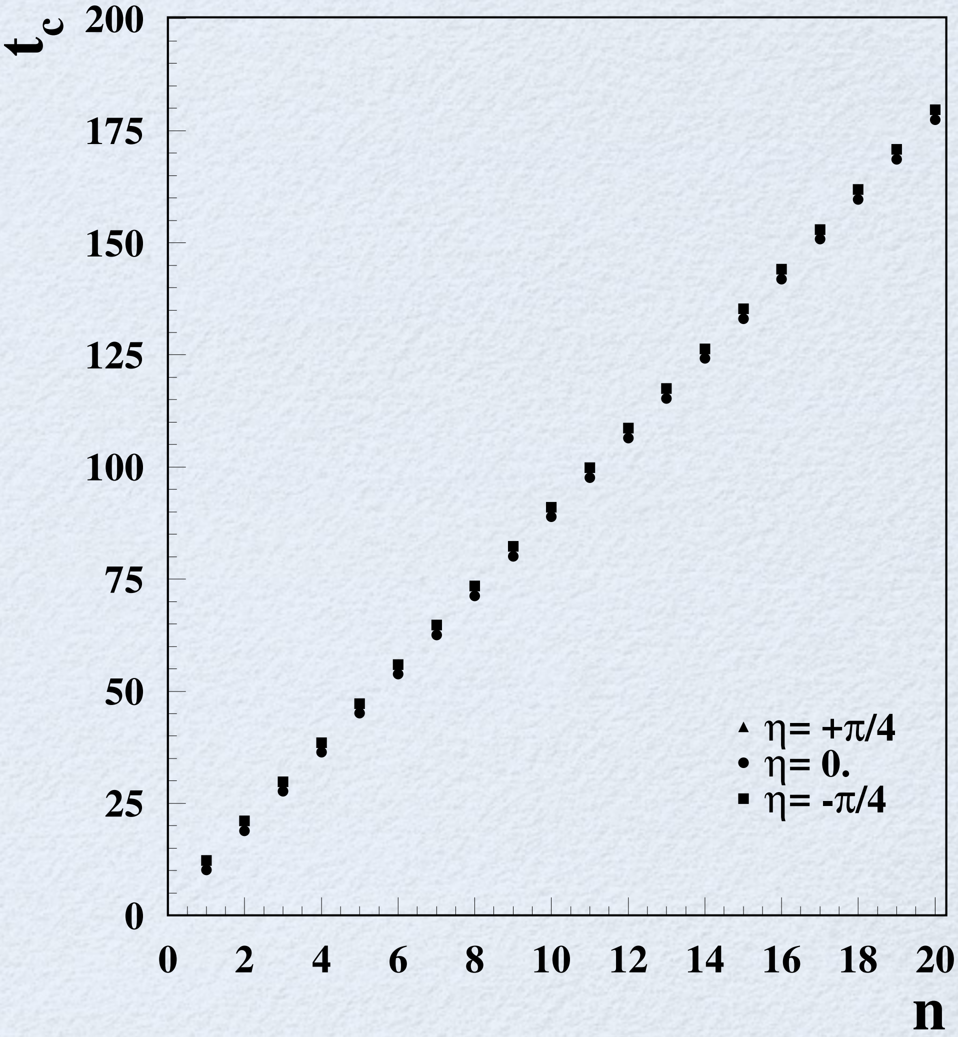


n	ω	$ln(k_{crit})$
1	0.2	3.8
2	0.14	8.2
3	0.11	12.5
4	0.09	16.9

$$\omega = A/(n+B)$$



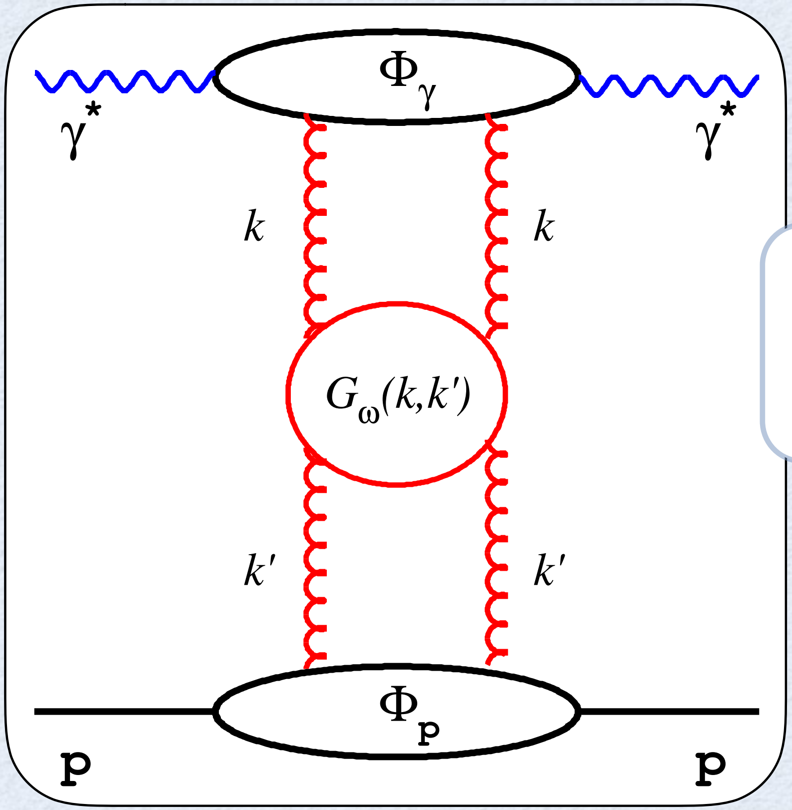
$$t_c = ln(k_{crit}^2 / \Lambda_{QCD})$$



Comparison with HERA data

Construct the Green Function and integrate it with the proton impact factor

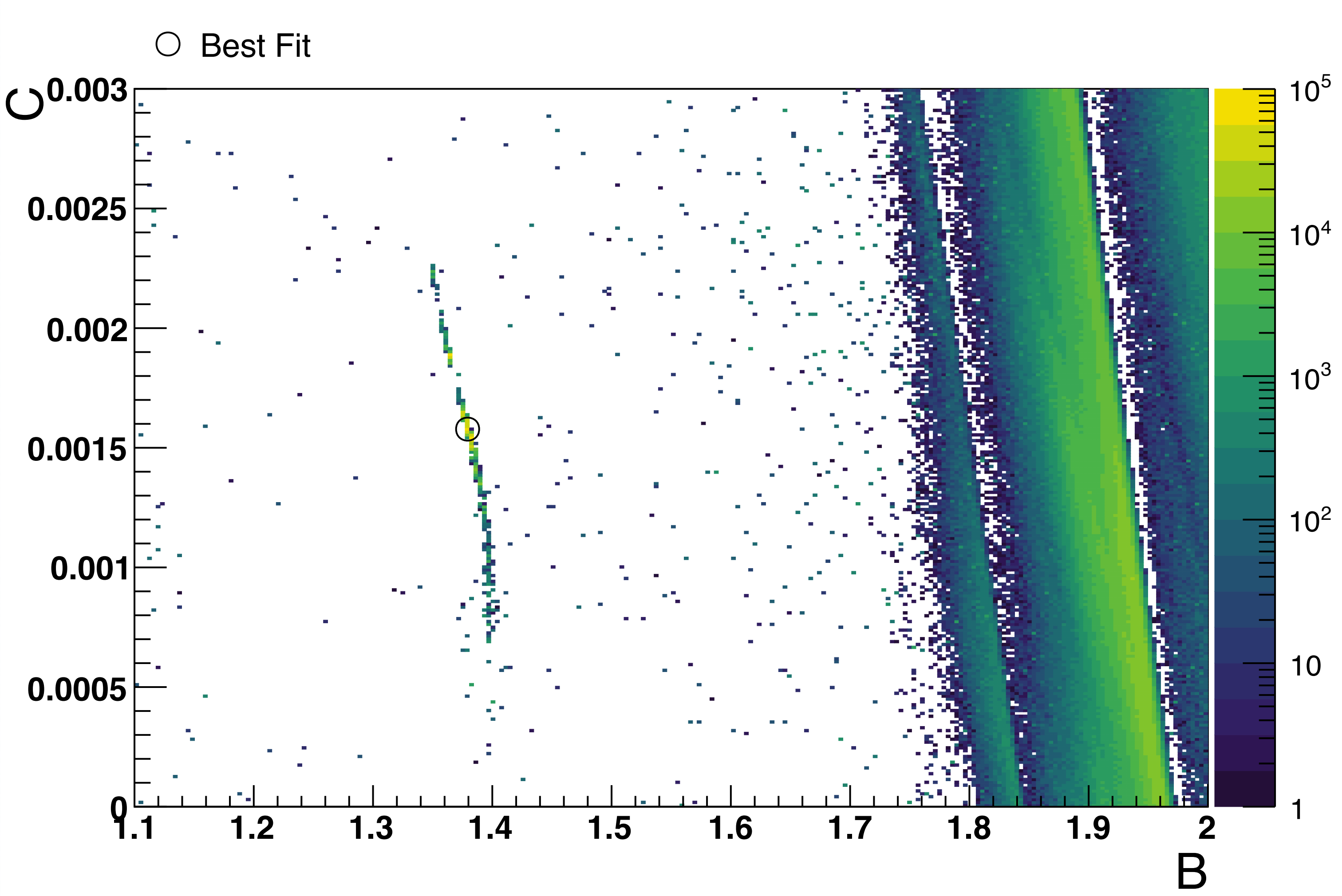
$$xg(x,k) \;=\; \int \frac{dk'}{k'} \Phi_p(k') \left(\frac{k'\,x}{k}\right)^{-\omega_n} k^2 \left(\sum_n f^*_{\omega_n}(k') f_{\omega_n}(k) + \int_{-\infty}^{0} d\omega x^{-\omega} f_{-|\omega|}(t) f_{-|\omega|}(t')\right)$$



Integrate the gluon density with the photon impact factor

$$F_2(x,Q^2) \;=\; \int_x^1 d\zeta \int \frac{dk}{k} \Phi_\gamma(\zeta,Q,k) xg\left(\frac{x}{\zeta},k\right)$$

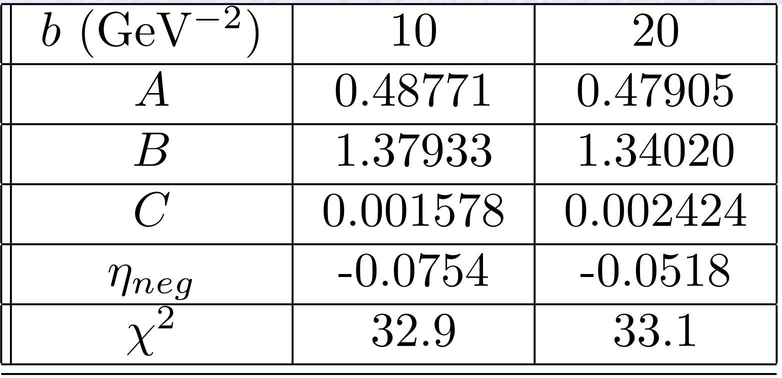
Markov-Chain MC
Bayesian Analysis Tool
probability density of the fit



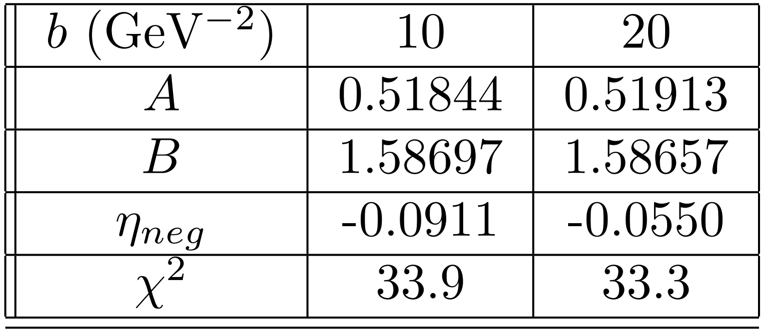
$$\Phi_p(\mathbf{k}) = A k^2 e^{-bk^2},$$

$Q^2 > 6$ GeV^2
$x < 0.001$

$N_p = 51$



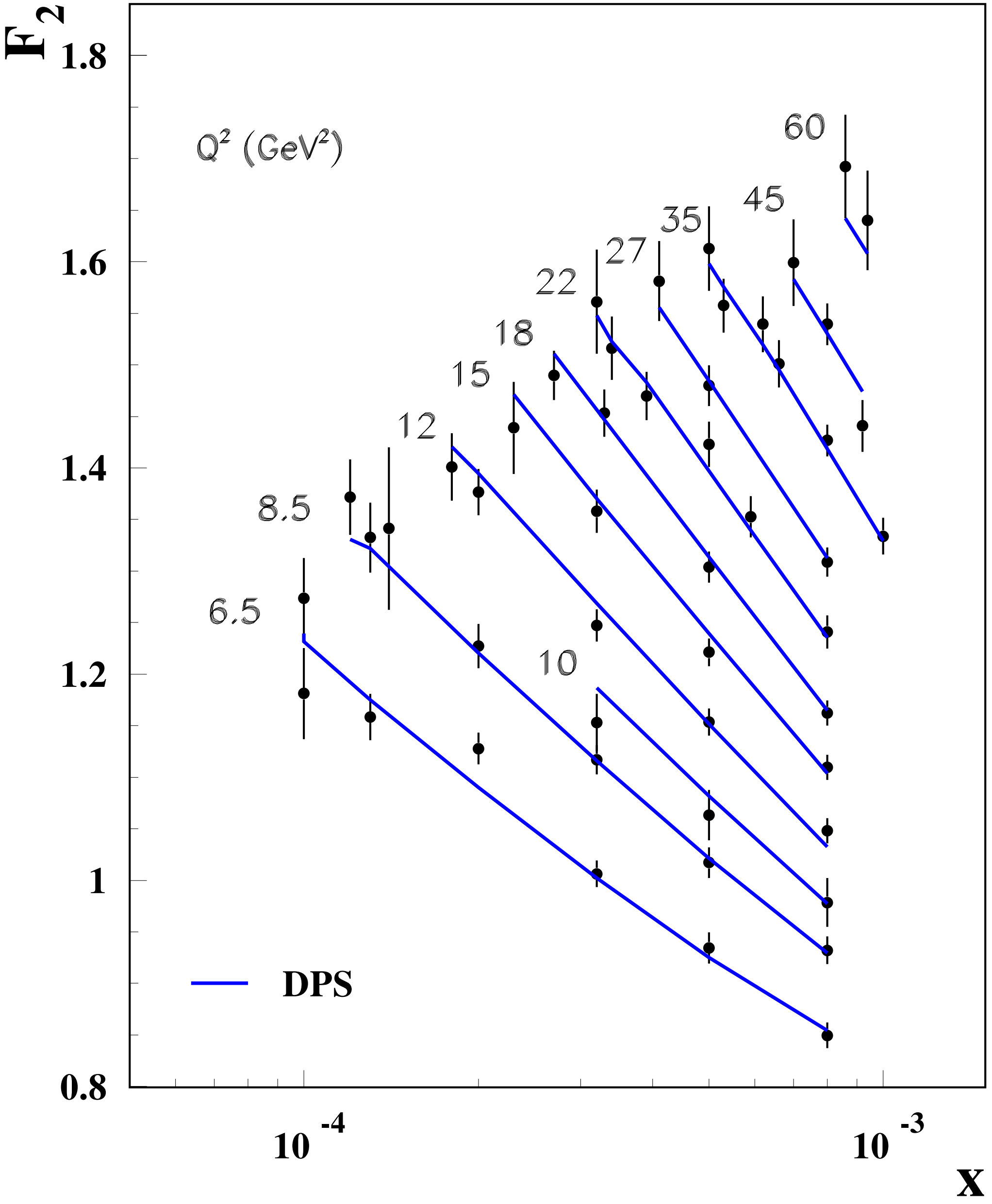
b (GeV^{-2})	10	20
A	0.48771	0.47905
B	1.37933	1.34020
C	0.001578	0.002424
η_{neg}	-0.0754	-0.0518
χ^2	32.9	33.1



b (GeV^{-2})	10	20
A	0.51844	0.51913
B	1.58697	1.58657
η_{neg}	-0.0911	-0.0550
χ^2	33.9	33.3

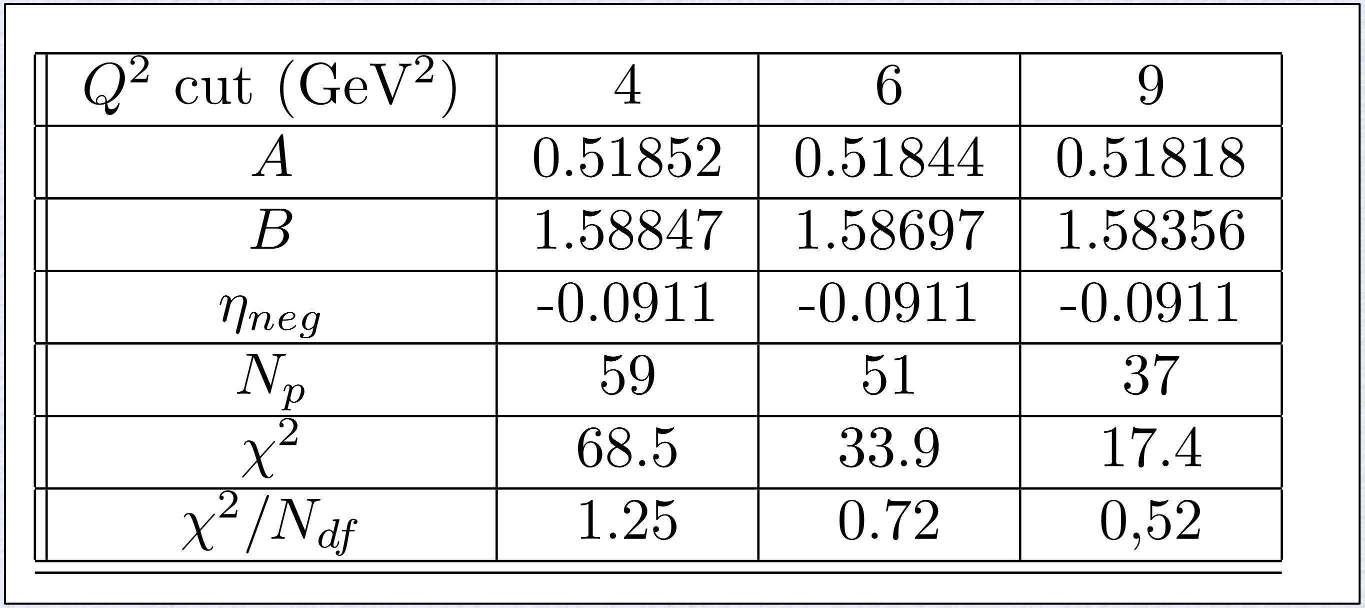
$\eta_1 = 0.0707$ $\eta_1 = 0.0503$

very low χ^2/N_{df} = 0,72
due to uncorrelated errors



Q^2 dependence

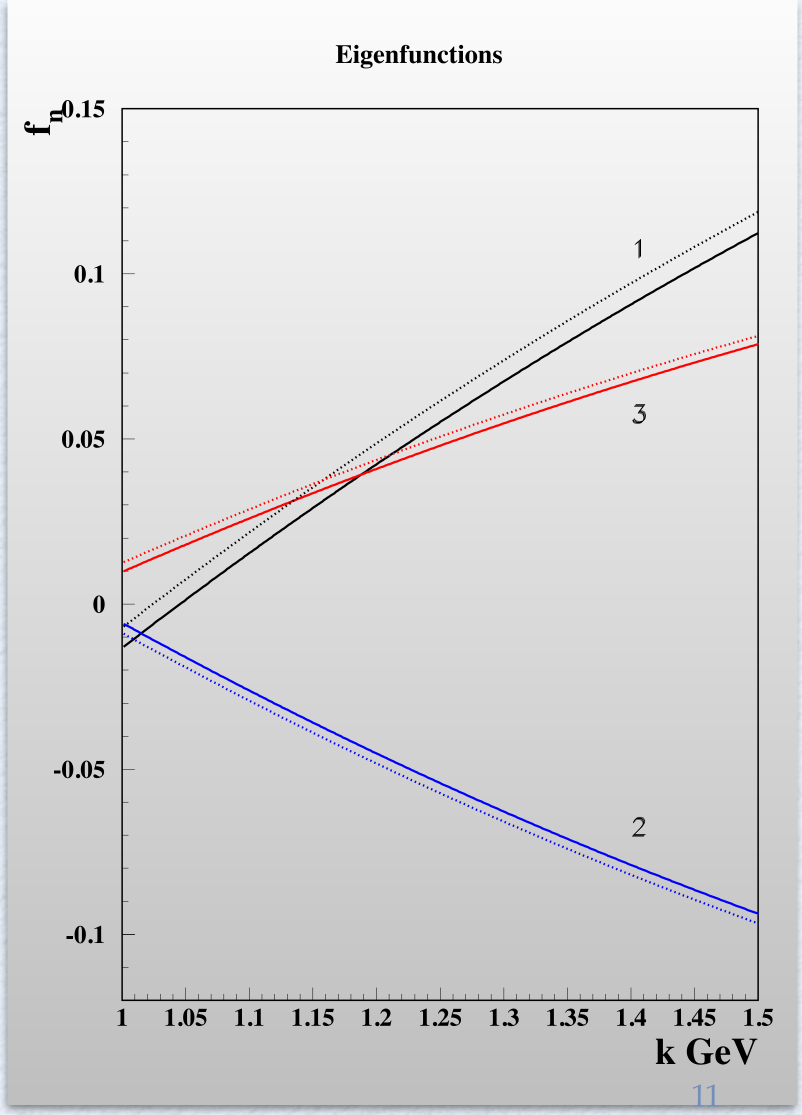
KMS photon form factor, computed beyond LO



Q^2 cut (GeV^2)	4	6	9
A	0.51852	0.51844	0.51818
B	1.58847	1.58697	1.58356
η_{neg}	-0.0911	-0.0911	-0.0911
N_p	59	51	37
χ^2	68.5	33.9	17.4
χ^2/N_{df}	1.25	0.72	0,52

Decoupling of the leading eigenfunction

the fit selected always a phase for which $\int \Phi_p(k)\, f_1(k)\, d(\ln k) \approx 0$

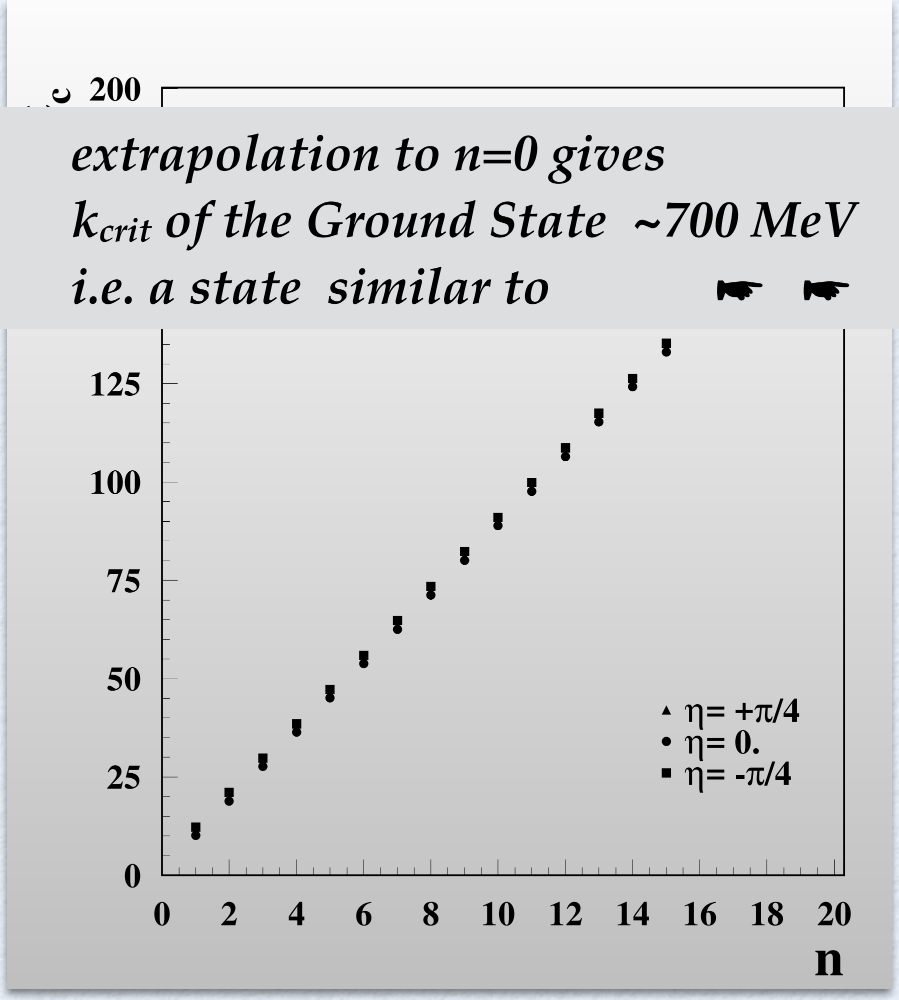


$\Phi_p(k) = Ak^2 \exp(-bk^2)$

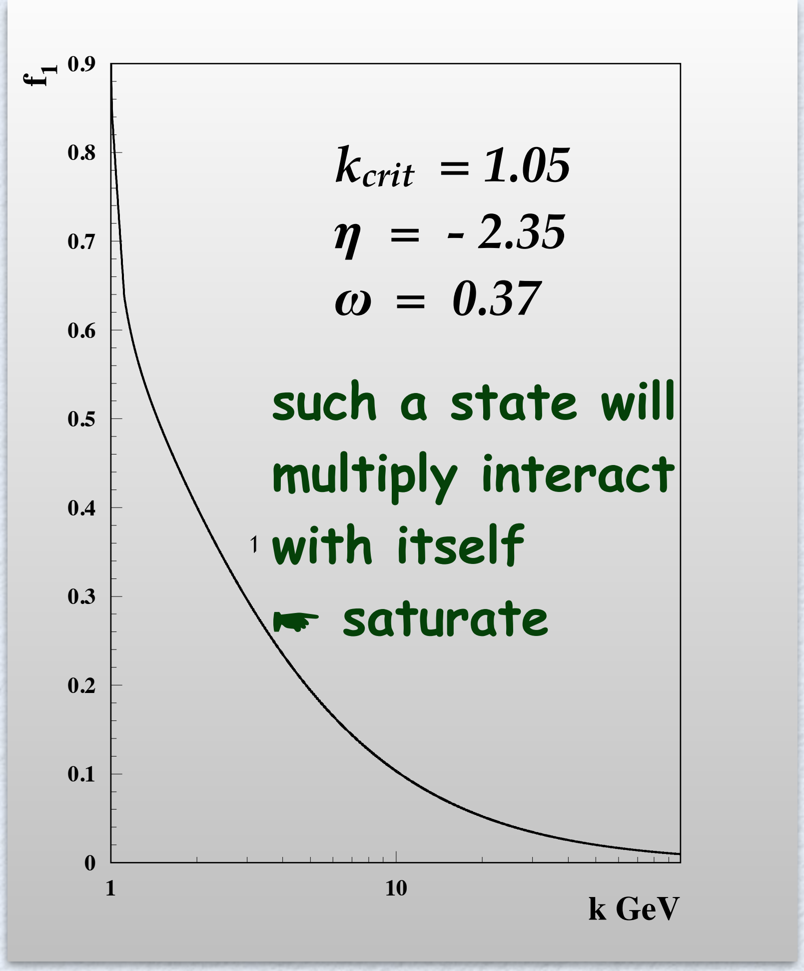
$\underline{\qquad}$ $b = 10\ GeV^{-2}$

…….. $b = 20\ GeV^{-2}$

$\Rightarrow f_1(t)$ **cannot be the Ground State of BFKL**



extrapolation to n=0 gives
k_{crit} of the Ground State ~700 MeV
i.e. a state similar to ☛ ☛



k_{crit} = 1.05
η = - 2.35
ω = 0.37

such a state will
multiply interact
with itself
☛ saturate

→ Evaluate using Dipole Model

Dipole Model evaluation

$$\sigma_{T,L}^{\gamma^* p}(x,Q) = \sum_f \int d^2\vec{r} \int_0^1 \frac{dz}{4\pi} (\Psi^*\Psi)^f_{T,L}\, \sigma_{q\bar{q}}(x,r)$$

$$\frac{d\sigma_{q\bar{q}}}{d^2\vec{b}} = 2\left[1-\exp\left(-\frac{\pi^2}{2N_c} r^2 \alpha_S(\mu^2) x g(x,\mu^2) T(b)\right)\right].$$

use BFKL Gluon Density with

$$\mu^2 = k^2 = C/r^2 + \mu_0^2$$

Ground State has some similarity to GBW Ansatz

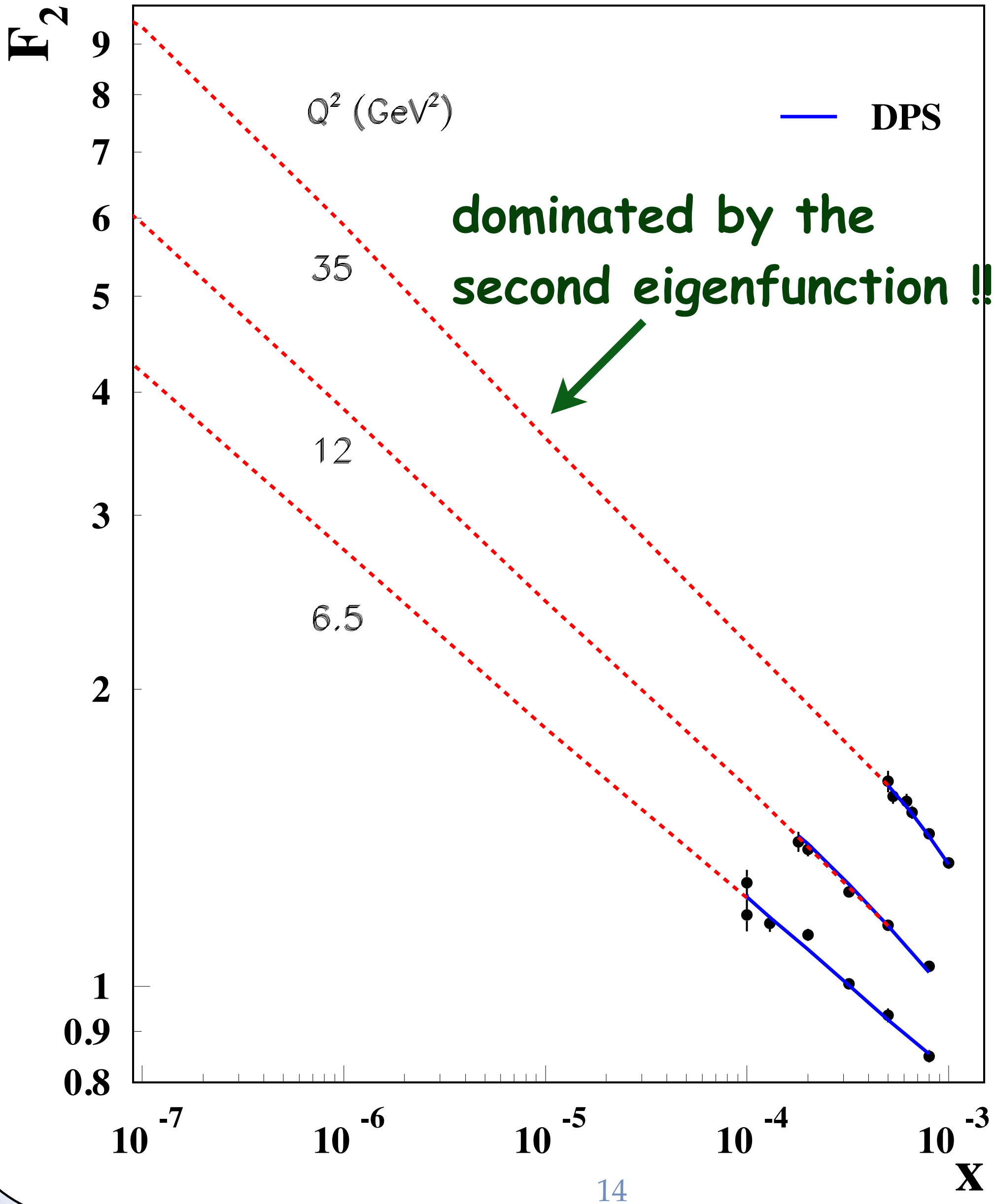
$$\sigma_{q\bar{q}}^{\mathrm{GBW}}(x,r) = \sigma_0 \left(1 - \mathrm{e}^{-r^2 Q_s^2(x)/4}\right)$$

$$Q_s^2(x) = (x_0/x)^{\lambda_{\mathrm{GBW}}}$$

~ exp(-1/r^2)

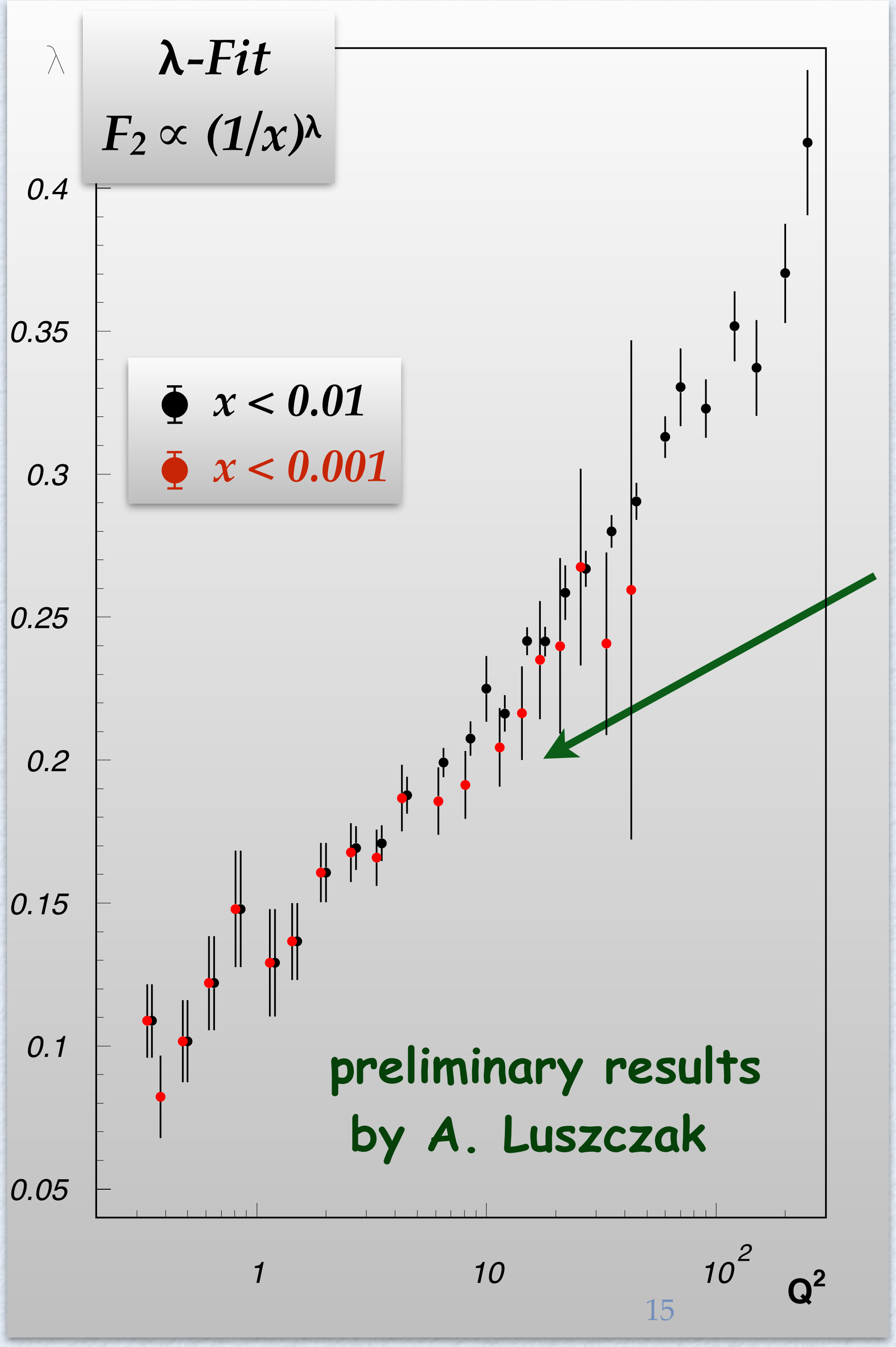
but exponentially suppressed at small r^2

Extrapolation of the BFKL fit to very low x



dominated by the second eigenfunction !!

VHEep or LHeC range



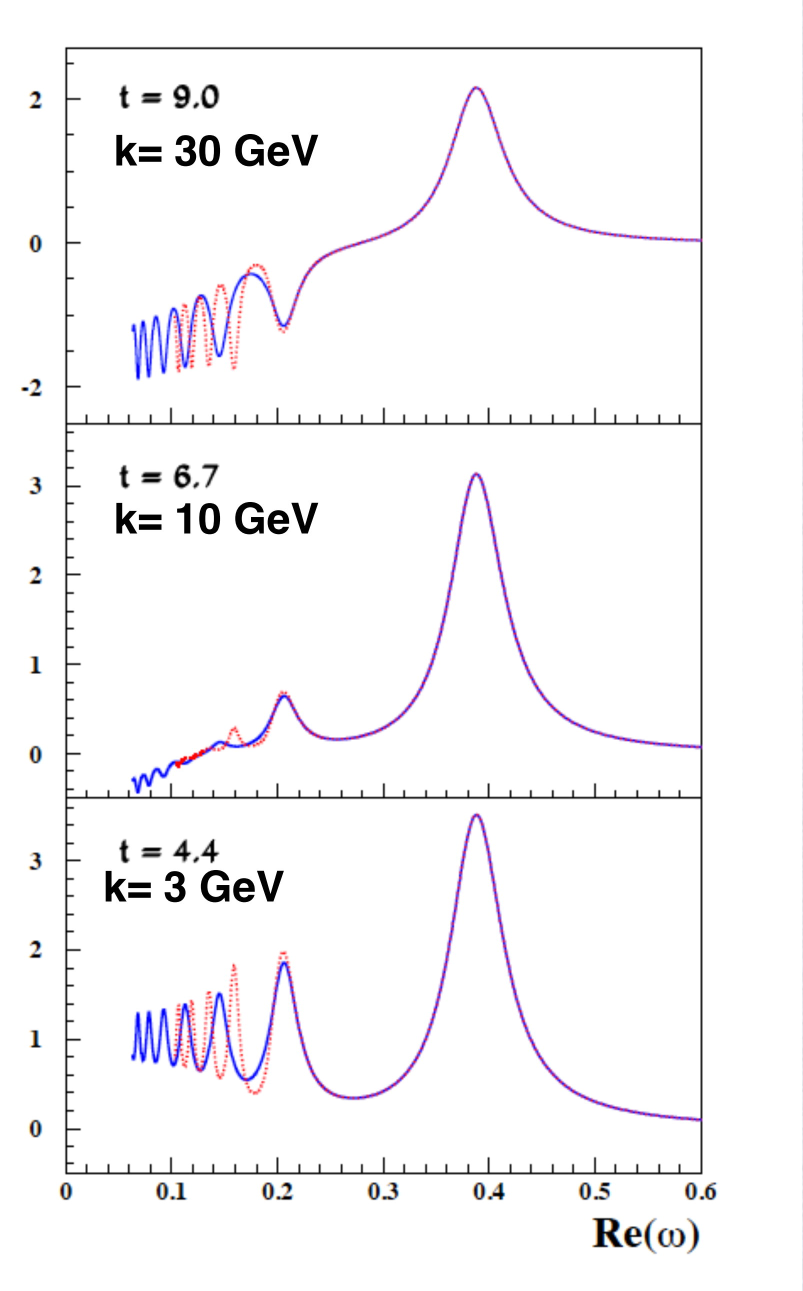
preliminary results
by A. Luszczak

can we see some signs of dominance of the second eigenfunction at HERA?

Effects of SuSy threshold at 3 TeV

$$\omega_n = \frac{0.96}{\pi\beta} \cdot \frac{1}{\eta + \mathbf{n} - 1/4}$$

$$\frac{\beta^{SM}}{\beta^{SUSY}} = \frac{7}{3}$$



Summary of Prospects for a very high energy eP and eA collider Workshop

Allen Caldwell
Max Planck Institute for Physics

Low-x Workshop
Bari, Italy

AWAKE

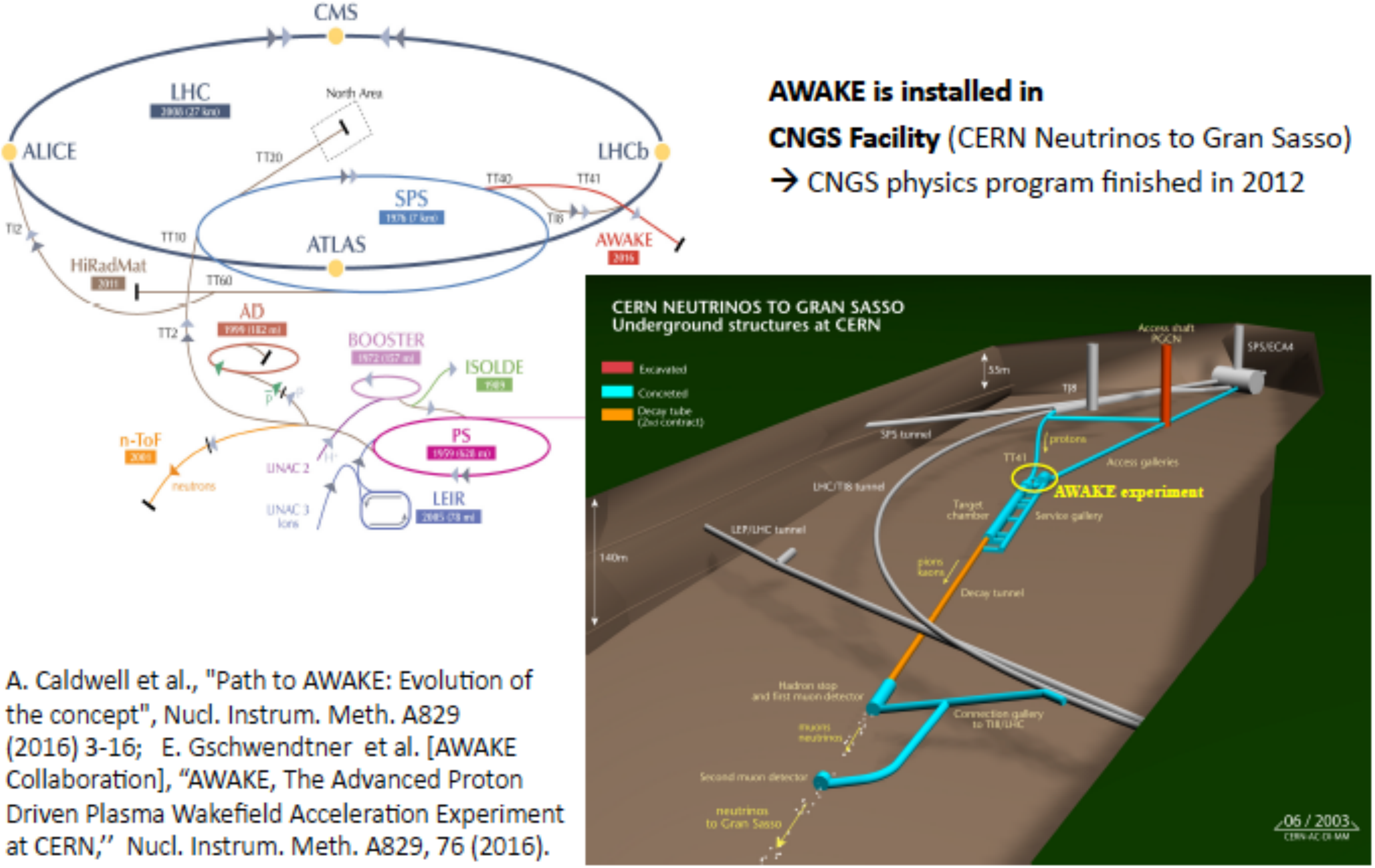
- AWAKE: Advanced Proton Driven Plasma Wakefield Acceleration Experiment
  - Use SPS proton beam as drive beam (Single bunch 3e11 protons at 400 GeV)
  - Inject electron beam as witness beam

- Proof-of-Principle Accelerator R&D experiment at CERN
  - First proton driven plasma wakefield experiment worldwide
  - First beam in 2016

- AWAKE Collaboration: 16 Institutes world-wide:

John Adams Institute for Accelerator Science,
Budker Institute of Nuclear Physics & Novosibirsk State University
CERN
Cockroft Institute
DESY
Heinrich Heine University, Düsseldorf
Instituto Superior Tecnico
Imperial College
Ludwig Maximilian University
Max Planck Institute for Physics
Max Planck Institute for Plasma Physics
Rutherford Appleton Laboratory
TRIUMF
University College London
Univesity of Oslo
University of Strathclyde

AWAKE at CERN



AWAKE is installed in

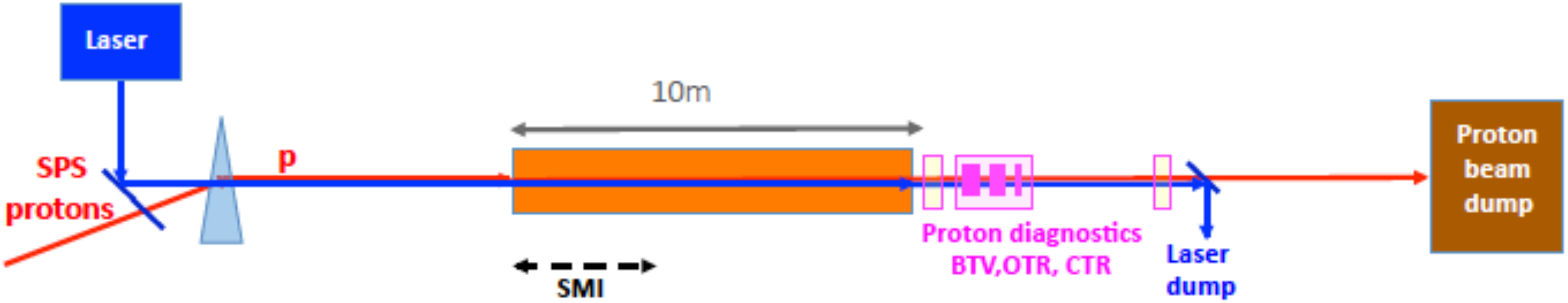
CNGS Facility (CERN Neutrinos to Gran Sasso)

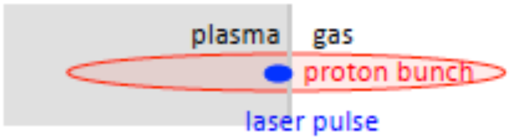
→ CNGS physics program finished in 2012

A. Caldwell et al., "Path to AWAKE: Evolution of the concept", Nucl. Instrum. Meth. A829 (2016) 3-16; E. Gschwendtner et al. [AWAKE Collaboration], "AWAKE, The Advanced Proton Driven Plasma Wakefield Acceleration Experiment at CERN," Nucl. Instrum. Meth. A829, 76 (2016).

AWAKE: Experimental Program

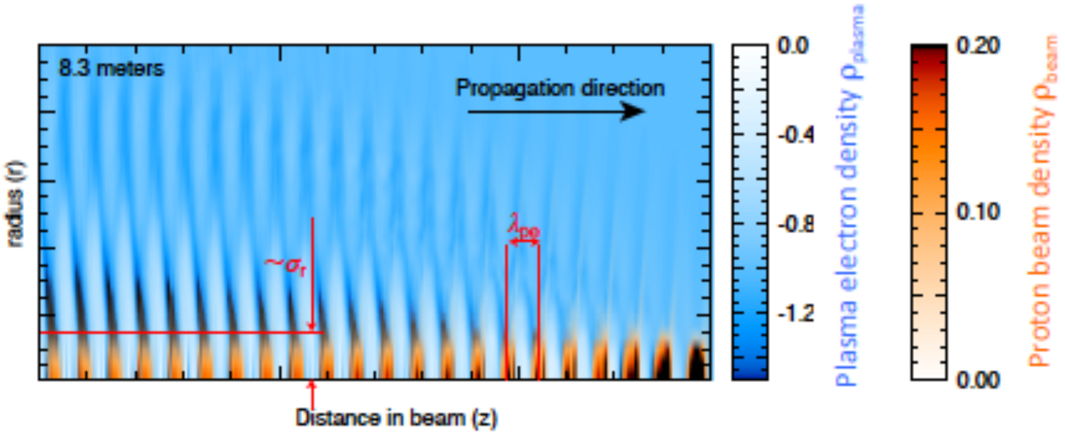
Phase 1: Understand **the physics of self-modulation instability.**





➔ Start with SMI studies December 2016!

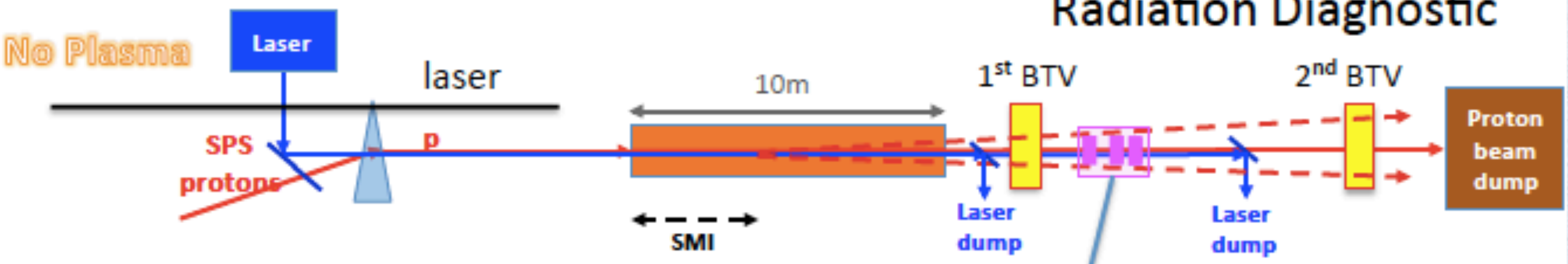
Self-modulated proton bunch resonantly driving plasma wakefields.



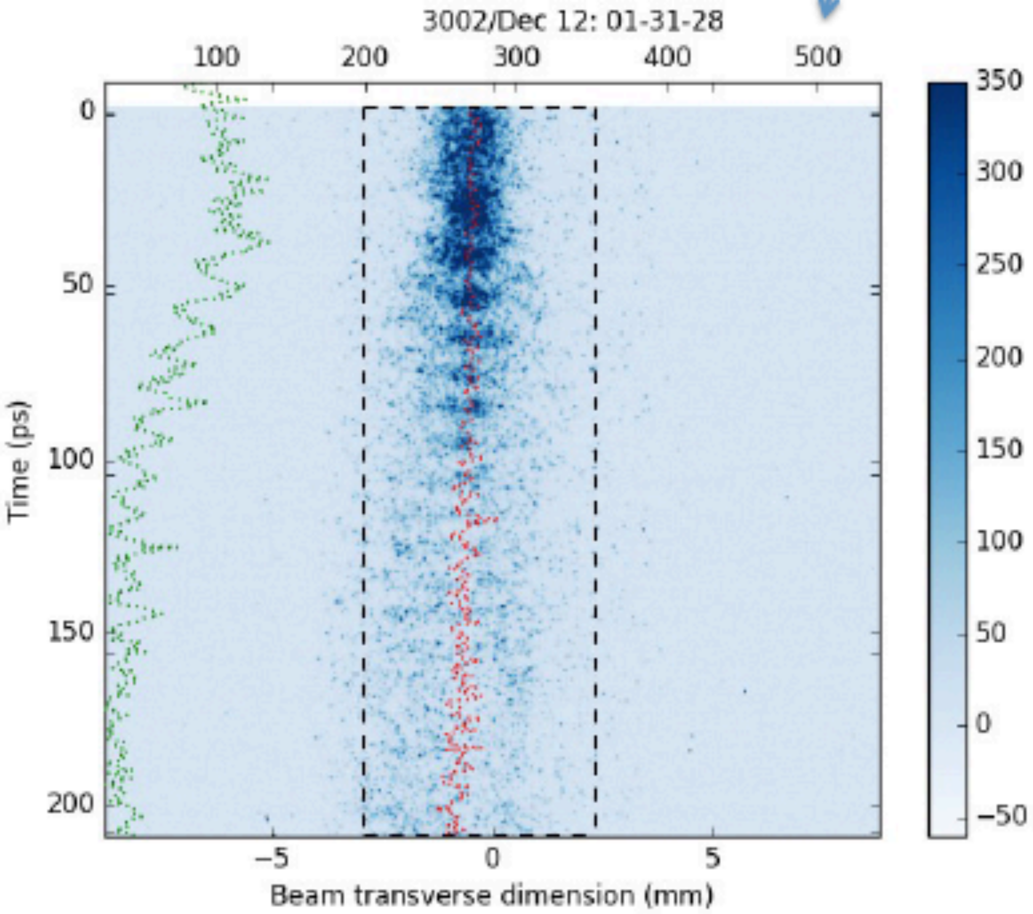
J. Vieira et al PoP 19063105 (2012)

Success !

Optical Transition Radiation Diagnostic



Modulation visible in streak camera data

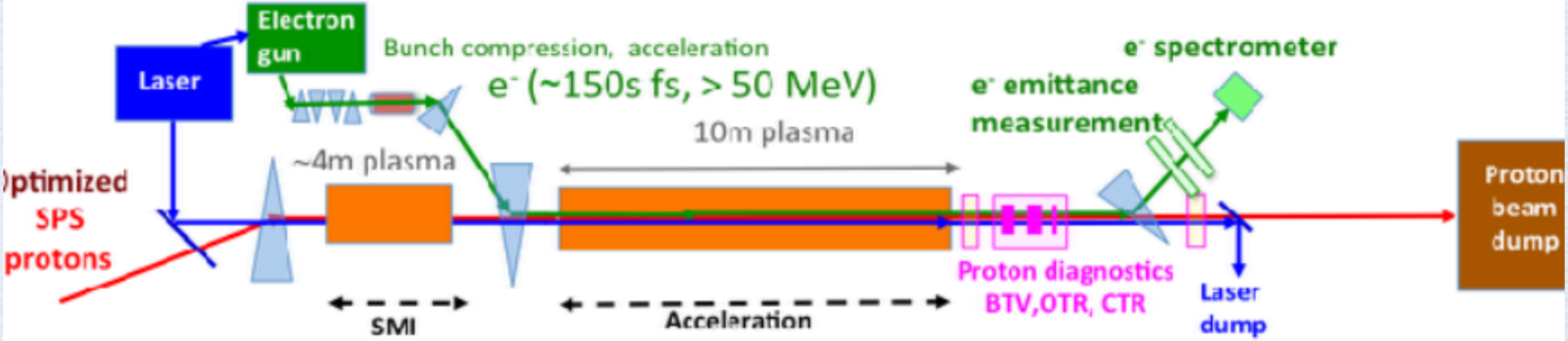


March 20, 2017

Run II

Goals:

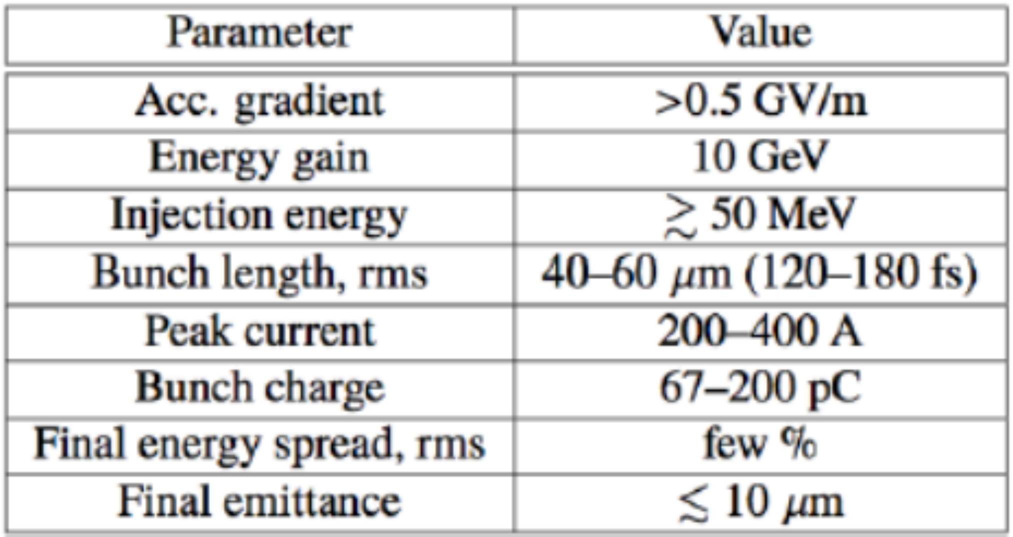
- stable acceleration of bunch of electrons with high gradients over long distances
- ‘good’ electron bunch emittance at plasma exit



Require:

- Compressed proton beam in SPS
- Short electron bunch with higher energy for loading wakefield
- Density step in plasma for freezing modulation
- Alternative plasma cell developments

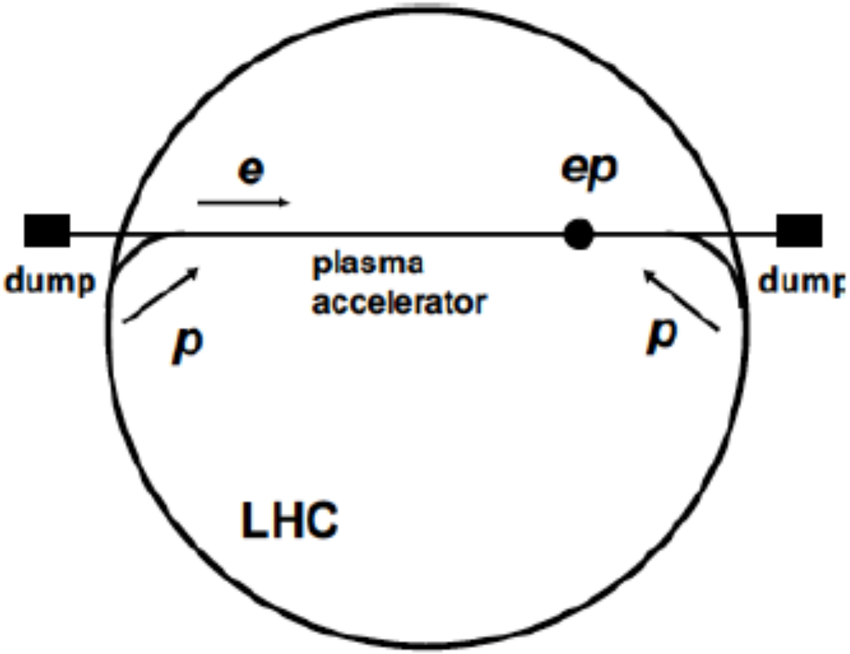
Preliminary Run 2 electron beam parameters



Parameter	Value
Acc. gradient	>0.5 GV/m
Energy gain	10 GeV
Injection energy	$\gtrsim$ 50 MeV
Bunch length, rms	40–60 μm (120–180 fs)
Peak current	200–400 A
Bunch charge	67–200 pC
Final energy spread, rms	few %
Final emittance	$\lesssim$ 10 μm

VHEeP

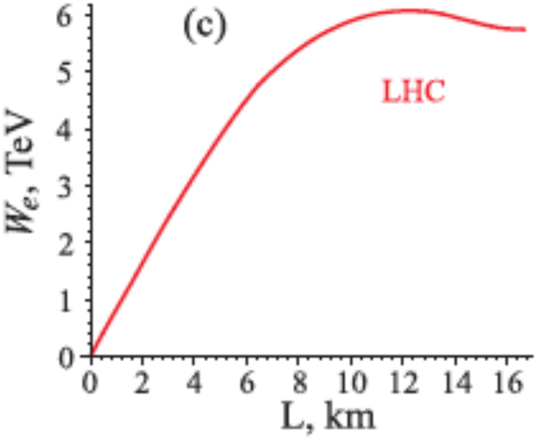
(Very High Energy electron-Proton collider)



One proton beam used for electron acceleration to then collide with other proton beam

Luminosity ~ $10^{28} - 10^{29}$ cm^{-2} s^{-1} gives ~ 1 pb−1 per year.

Electron energy from wakefield acceleration by LHC bunch



A. Caldwell, K. V. Lotov, Phys. Plasmas **18**, 13101 (2011)

Choose E_e = 3 TeV as a baseline for a new collider with E_p = 7 TeV yields √s = 9 TeV. Can vary.

- Centre-of-mass energy ~30 higher than HERA.
- Reach in (high) Q^2 and (low) Bjorken x extended by ~1000 compared to HERA.
- Opens new physics perspectives

VHEeP: A. Caldwell and M. Wing, Eur. Phys. J. C 76 (2016) 463

Particle Physics Perspectives

Consider:

- **Physics with a high energy electron beam**
  - E.g., search for dark photons

- **Physics with an electron-proton or electron-ion collider**
  - Low luminosity version of LHeC
  - Very high energy electron-proton, electron-ion collider

Are there fundamental particle physics topics for high energy but low luminosity colliders ?

I believe – yes ! Particle physicists will be interested in going to much higher energies, even if the luminosity is low.

In general – start investigating the particle physics potential of an AWAKE-like acceleration scheme. Contributions welcome !

Back up slides

contribution to gluon density from negative ω

$$\Delta_{\omega<0}\overline{g}(x,k) \;=\; \lim_{\omega_{min}\to-\infty}\int_{\omega_{min}}^{0} d\omega x^{-\omega}\int dt' f_{-|\omega|}(t) f_{-|\omega|}(t')\Phi_P(t'),$$

x = 10^{-3}
t = 12