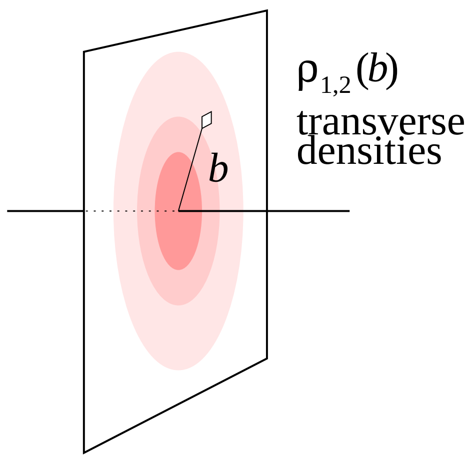
High–t form factors and short–range nucleon structure

C. Weiss (JLab), Hall A SBS Meeting, JLab, 4–Jun–13

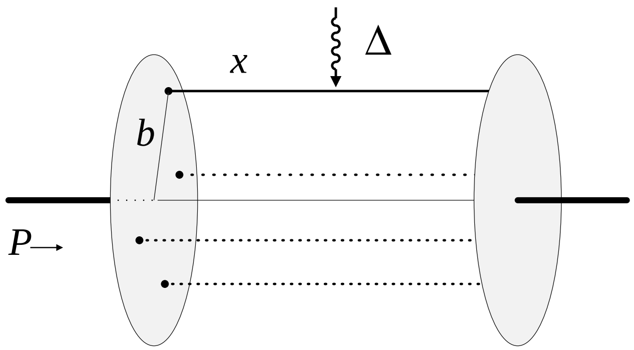


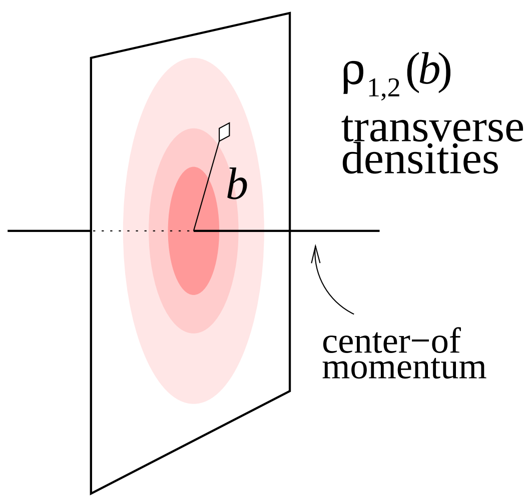
A) Physics interpretation of high–t elastic form factors: Model–indep., quantitative!
Transverse densities, configurations in WF

B) Connection with $x \to 1$ parton densities

- High–t form factors in QCD
  - Partonic/light–front description
  - Transverse densities
  - Small–size vs. end–point configurations
- Pion form factor
  - Transverse density from $e^+e^- \to \pi\pi$
  - Small–size configurations
  - Non–pert. interactions from dynamical χSB
- Nucleon form factors
  - Transverse densities
  - Small–size vs. end–point configurations?
  - Non–perturbative interactions?
  - Connection with large–x PDFs

Form factors: Parton picture





- Parton picture $P \to \infty$

  Hadron resolved in pointlike constituents with momentum fraction x_i, transv. position $\boldsymbol{r}_i$

  $\boldsymbol{\Delta}$ transverse, current cannot produce pairs

  Wave function description
  Subtle: Scale dependence, UV divergences, renormalization. . .

  Quantum–mechanical superposition: Configs with different particle number, spatial size

- Transverse charge/current density

$$F_{1,2}(t) \;=\; \int d^2b\; e^{i\boldsymbol{\Delta b}}\;\rho_{1,2}(b) \quad \text{2D Fourier}$$

$$\rho_{1,2}(b) = \sum_{\text{configs}} \int dx\; \psi^*(x, \boldsymbol{r}, ..)\psi(x, \boldsymbol{r}, ..)$$

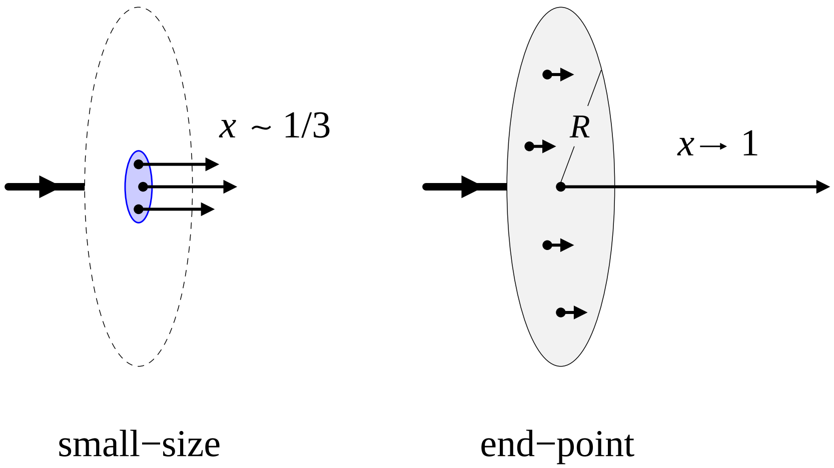
  Cumulative charge/current of constituents at transverse position b. Directly accessible from data!

- Selection of configurations

  Large $|t| \longleftrightarrow$ Small b Singularity?

  What configs generate density at small b?

Form factors: Configurations



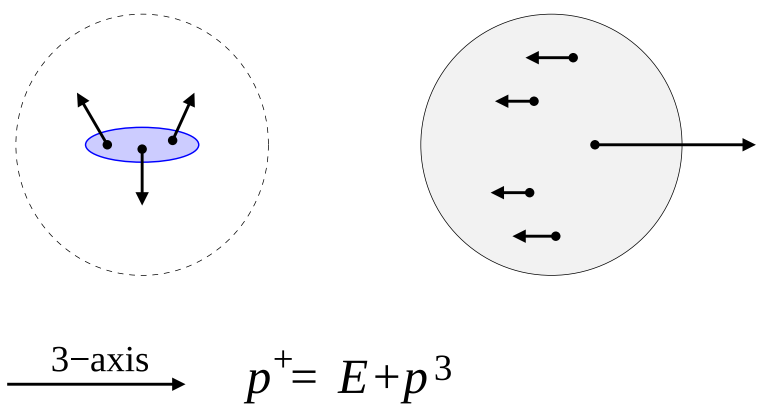
- Two types of configurations contribute to small–b density

$x \sim \frac{1}{3}$	size $\ll R$	small–size	mostly qqq
$x \to 1$	size $\sim R$	end–point	multiparticle, soft gluons

- Basic questions

  What is their relative importance?
  Probability of end–point configurations constrained by quark PDF at $x \to 1$

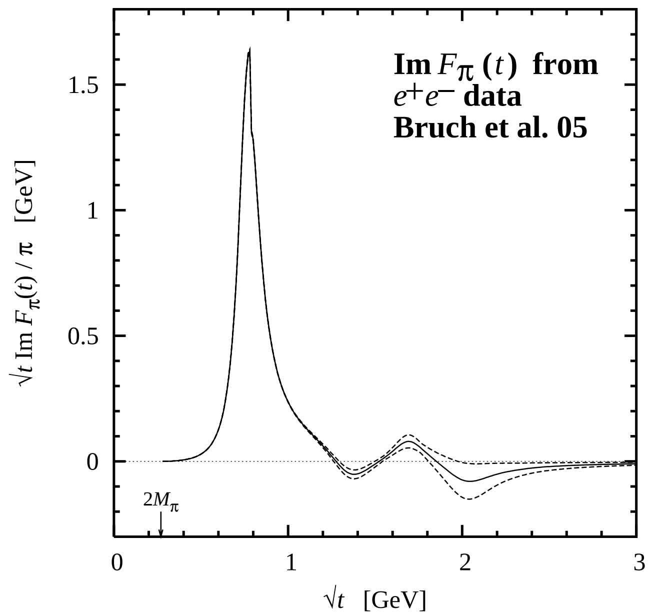
  How do they arise dynamically?
  Perturbative vs. non–perturbative interactions?

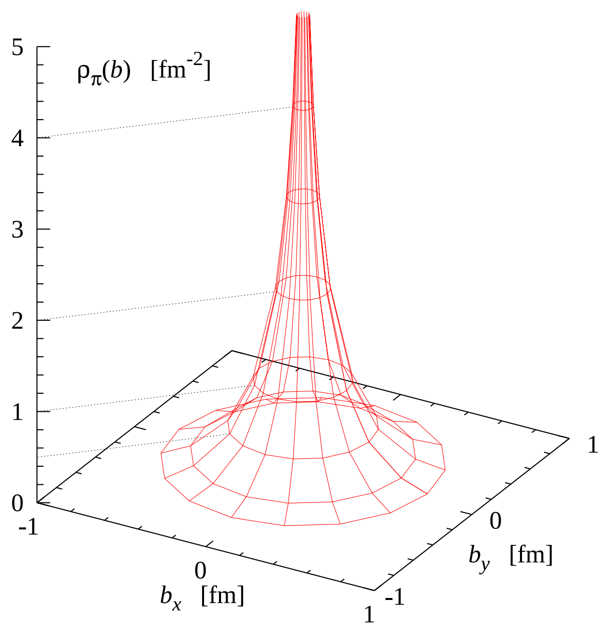


- Rest frame picture

  Can be rigorously discussed in light–front quantization
  Intuition from non–relativistic systems: Angular momentum, orbital motion, etc.

Pion: Transverse density





- Pion form factor $F_\pi(t)$

  Spacelike FF from electroproduction
  $ep \to e'\pi^+ n$ JLab Hall C 6/12 GeV

  Timelike FF from exclusive annihilation
  $e^+e^- \to \pi^+\pi^-$ CLEO, Belle, Babar, . . .

- Transverse density $\rho_\pi(b)$

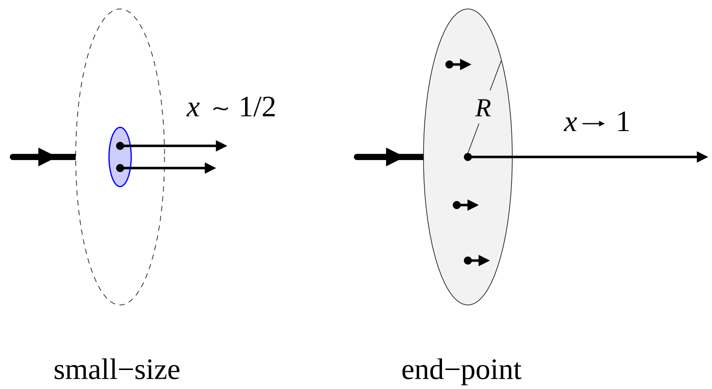
  Calculated from dispersion integral over timelike FF from e^+e^- data
  Miller, Strikman, CW 11

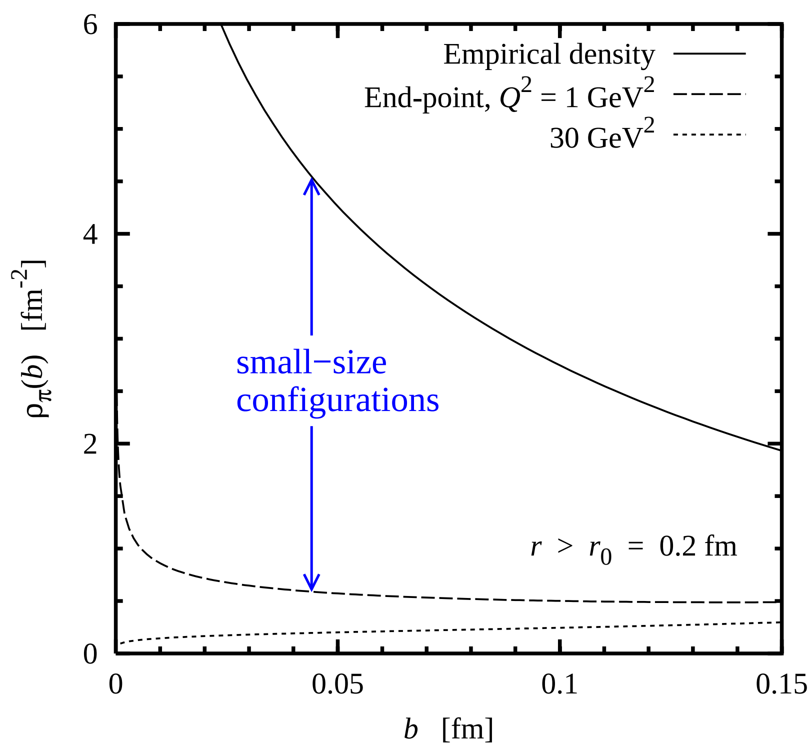
$$\rho_\pi(b) = \int_{4m_\pi^2}^{\infty} \frac{dt}{2\pi^2} K_0(\sqrt{t}b) \, \mathrm{Im}\, F_\pi(t)$$

  Model–independent, controlled accuracy

  High density at center $b \to 0$

Pion: Small–size configurations





- Is density in center due to small–size or end–point configurations?

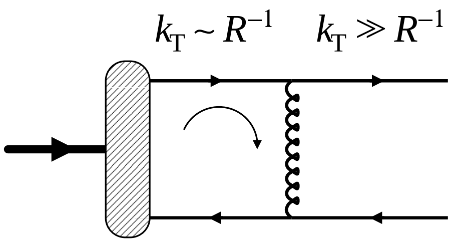
- Model–independent assessment
  Miller, Strikman, CW 10

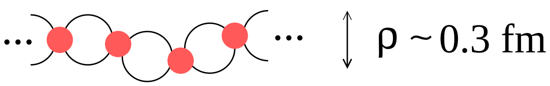
  Probability of end–point configs constrained by quark density in pion at $x \to 1$
  πA Drell–Yan data. PDF fits Glück, Reya, Schienbein 99.
  Subtle: Separate leading twist – higher twist in DY

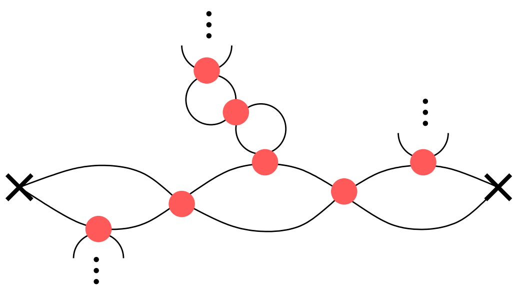
  Large–size configs account only for small part of empirical transverse density

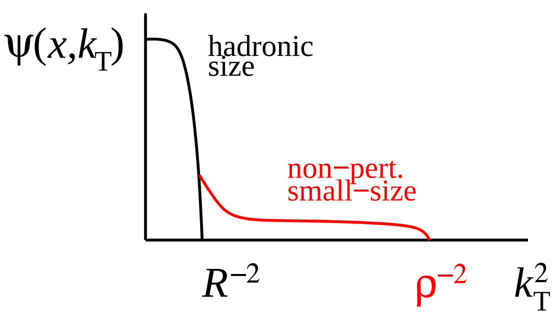
  Density in center of pion mostly from small–size configurations!

Pion: Dynamical origin of small–size configs









- Perturbative QCD interactions

  High–momentum component of wave function built up by pQCD interactions

  "Soft" wave function $k_T \sim R^{-1}$ as source

  $\Phi(x_i|\mu^2) = \int_{\mu^2} d^2 k_{Ti}\ \psi(x_i, \boldsymbol{k}_{Ti})$ distribution amplitude

  Responsible for leading $|t| \rightarrow \infty$ asymptotics of pion FF Efremov, Radyushkin 77+; Brodsky Lepage 80

- Dynamical chiral symmetry breaking

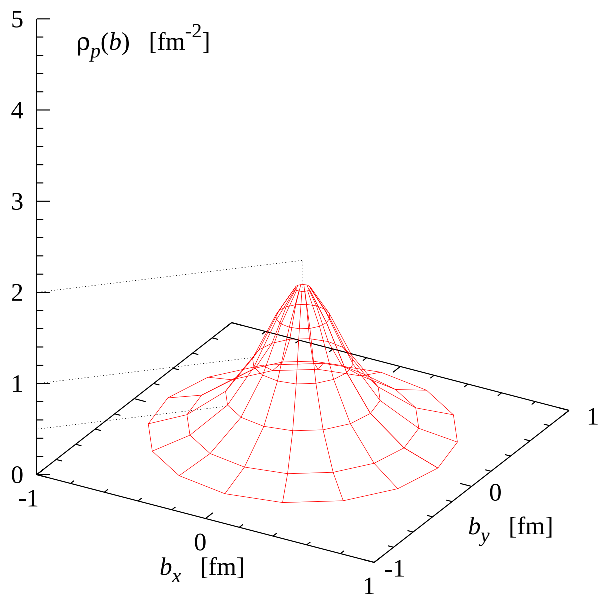
  Non–perturbative gluon fields of size $\rho \sim$ 0.3 fm flip quark chirality

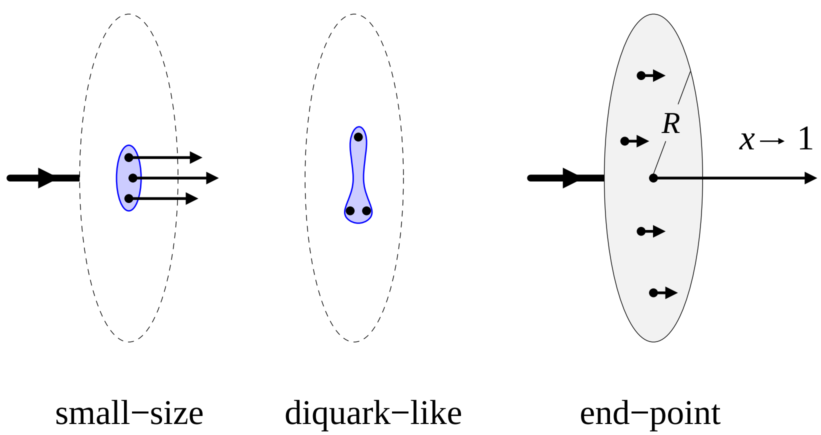
  $q\bar{q}$ condensate, dynamical mass generation
  Lattice QCD, instanton vacuum, Dyson–Schwinger eqs.

  Pion as collective excitation

  Non–perturbative small–size configurations in pion light–cone wave function, orbital angular momentum $L = 1$
  Schweitzer, Strikman CW 12

Nucleon: More complex system





- Transverse densities from FF data

  Errors estimated for $b \ll 1$fm
  Miller, Venkat 11. Incompleteness and experimental error

  Empirical proton density does not rise at $b \to 0$, contrast to pion

- Complex system, more possibilities

  Small–size qqq configurations require multiple or 3–body interactions

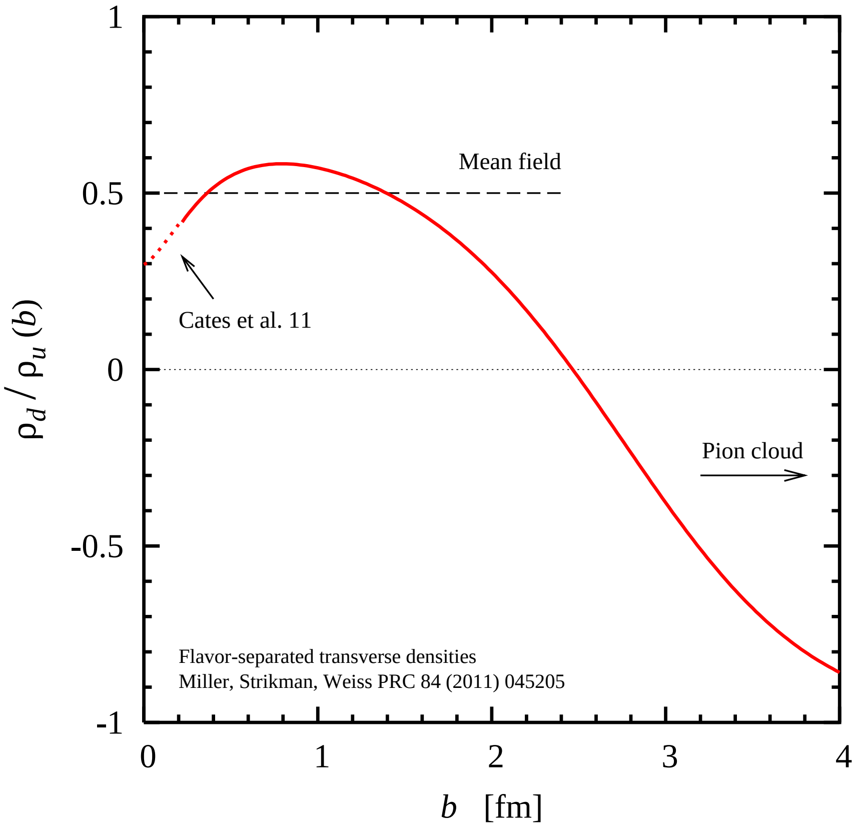
  Diquark–like configurations "between" small–size and end–point

  Mean–field picture successful at $x \sim 1/3$, cf. quark model, chiral soliton $N_c \to \infty$. End–point configs require dynamical correlations. . . what is their nature?

- Spin and orbital angular momentum

  $Q^2 F_2/F_1$ suggests important role of orbital angular momentum
  Hall A 6 GeV 00/02. Belitsky, Ji, Yuan 03

Nucleon: End–point configurations



- Role of end–point configurations?

- Flavor–separated densities $\rho_{u,d}(b)$

  Large b from dispersion fit to FF data: Correct analytic structure essential in Fourier transform
  Belushkin, Hammer, Meissner 06

  Small $b < 0.3$ fm from new flavor–separated FF parametrization
  Cates, de Jager, Riordan, Wojtsekhowski 11

- Interpretation of ratio $\rho_d/\rho_u(b)$

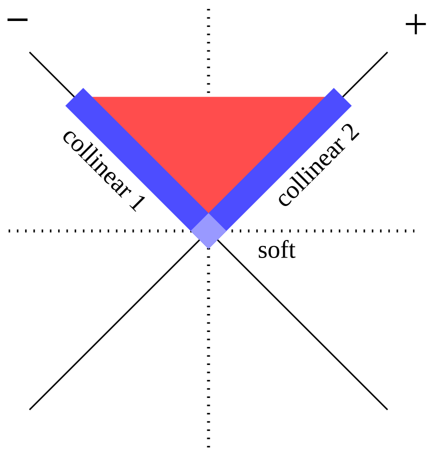
  $\rho_d/\rho_u \to -1$ for $b \gg 2$ fm:
  Pion cloud, rigorous chiral prediction
  Strikman, CW 10; Granados, CW 13

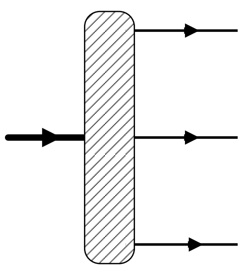
  $\rho_d/\rho_u \sim 1/2$ for $0.2 < b < 2$ fm:
  Mean field picture of valence quark bound state   Miller, Strikman, CW 11

  $\rho_d/\rho_u < 1/2$ for $b < 0.2$ fm:
  Consistent with end–point configs:
  $d(x)/u(x) \ll 1/2$ for $x \to 1$
  cf. PDF fits, particularly CJ Accardi et al. 13

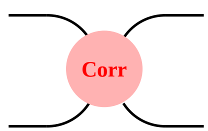
  Hint only, more quantitative analysis needed!

Nucleon: Theoretical approaches





"Mean field"



Correlation

- QCD light–cone sum rules
  Balitsky, Braun, Kolesnichenko 89; Braun et al. 02+

  pQCD–generated small–size configurations give leading asymptotic contribution
  Distribution amplitudes calculable in Lattice QCD

  End–point contributions reformulated as higher twist
  Can results be explained/reproduced in simple terms?

- Soft–collinear effective theory SCET
  Form factors: Kivel, Vanerhaeghen 10+, incl. two–photon exchange

  Process–driven classification of quark/gluon modes

  Soft spectator rescattering for $Q^2 \gg Q\Lambda \gg \Lambda^2$

- Light–front phenomenology   Suggestions only!

  Must include correlations in LCWF
  χSB interaction $\rho \sim$ 0.2 fm?

  Analyze jointly high–t FFs and large–x PDFs

  Include other high–t processes: WACS

Summary

- Physics interpretation of FFs based on partonic/light–front picture

  Transverse densities directly accessible from data

  Selection of configurations in wave function provides intuitive understanding

  Rigorous formulation: Scale dependence, renormalization $\rightarrow$ LC sum rules, SCET

- Small–size configurations in pion

  Seen in model–independent analysis

  Likely of non-perturbative origin: Dynamical χSB

- Nucleon complex

  Likely "mix" of configs, no single type dominant at $|t| \sim 10\,\mathrm{GeV}^2$

  Evidence for end–point configs in ratio $\rho_d/\rho_u(b)$ at small b

  Analyze high–t FFs together with large–x PDFs

  Other processes: WACS, high–t meson production