

Holographic description of elastic proton-proton scattering at LHC energies

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Based on:

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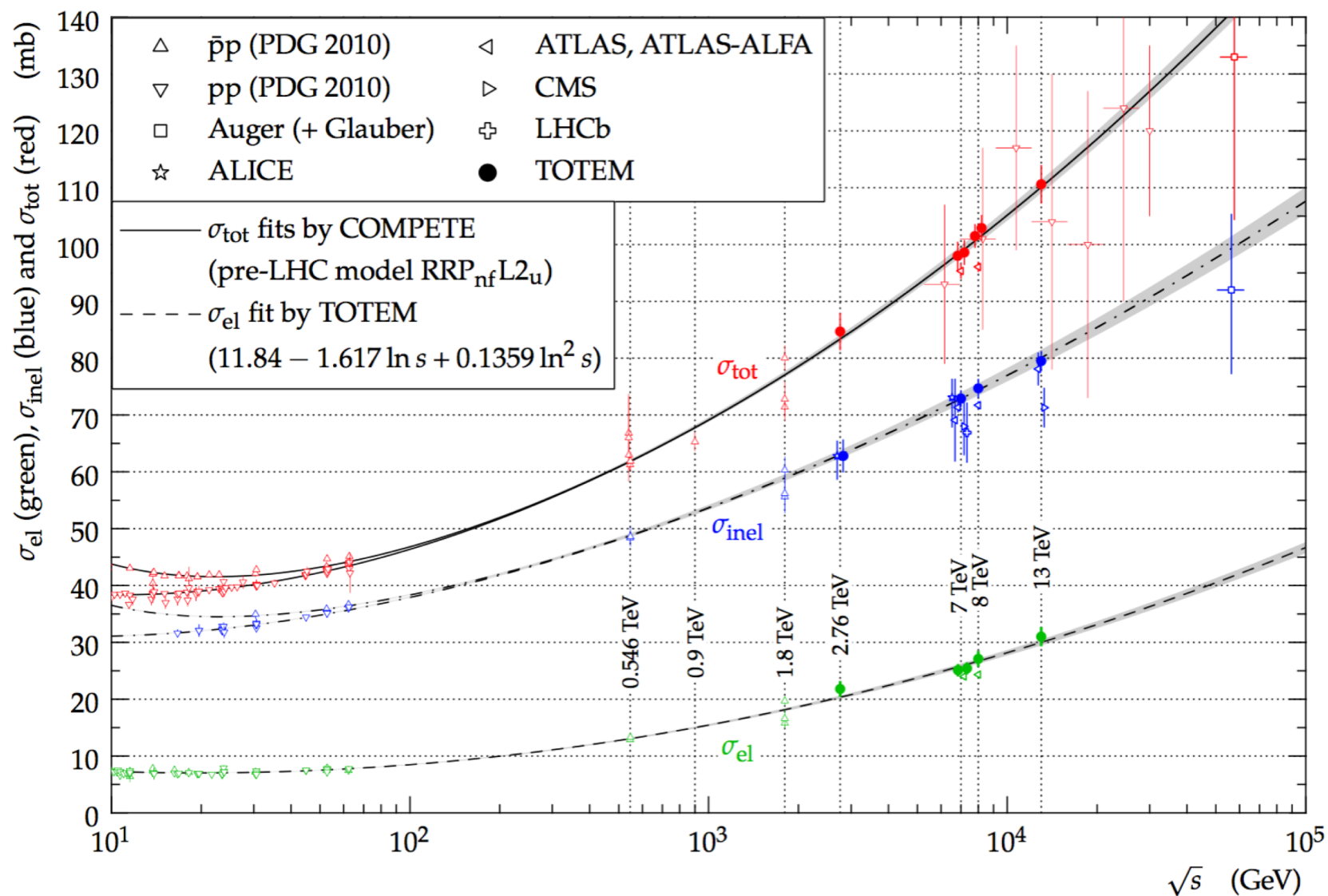
June 23, 2019 @ 湖南长沙, China

Outline

1. Introduction
2. Model setup
3. Numerical results for proton-proton differential and total cross sections
4. Summary

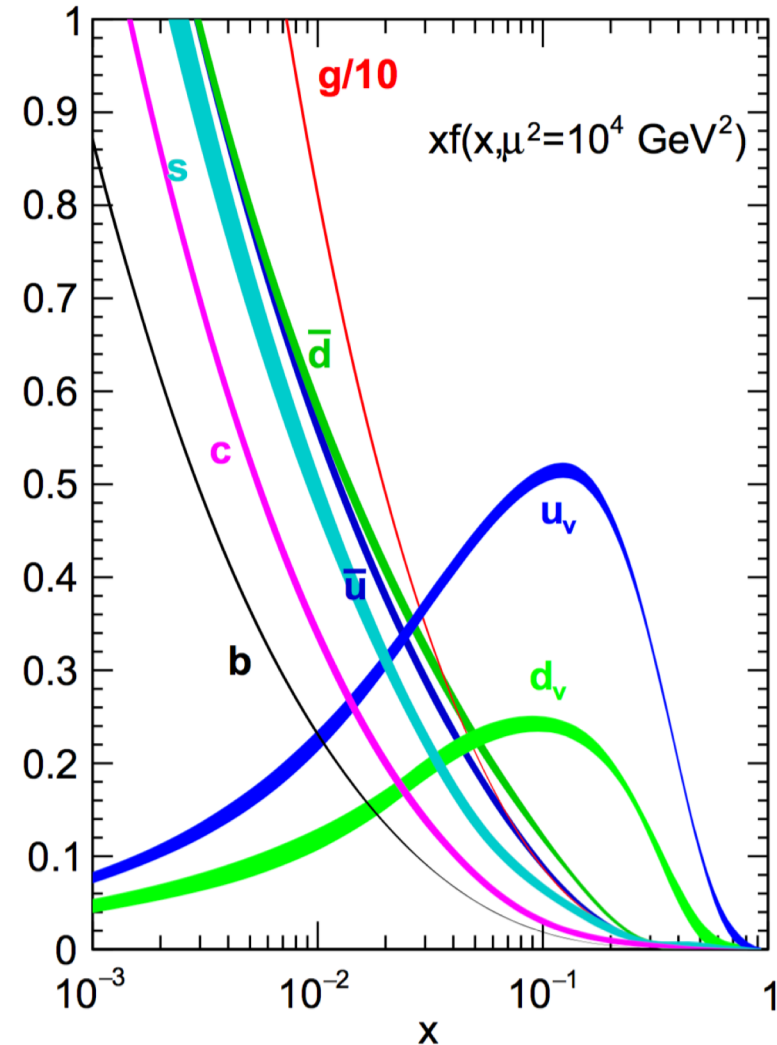
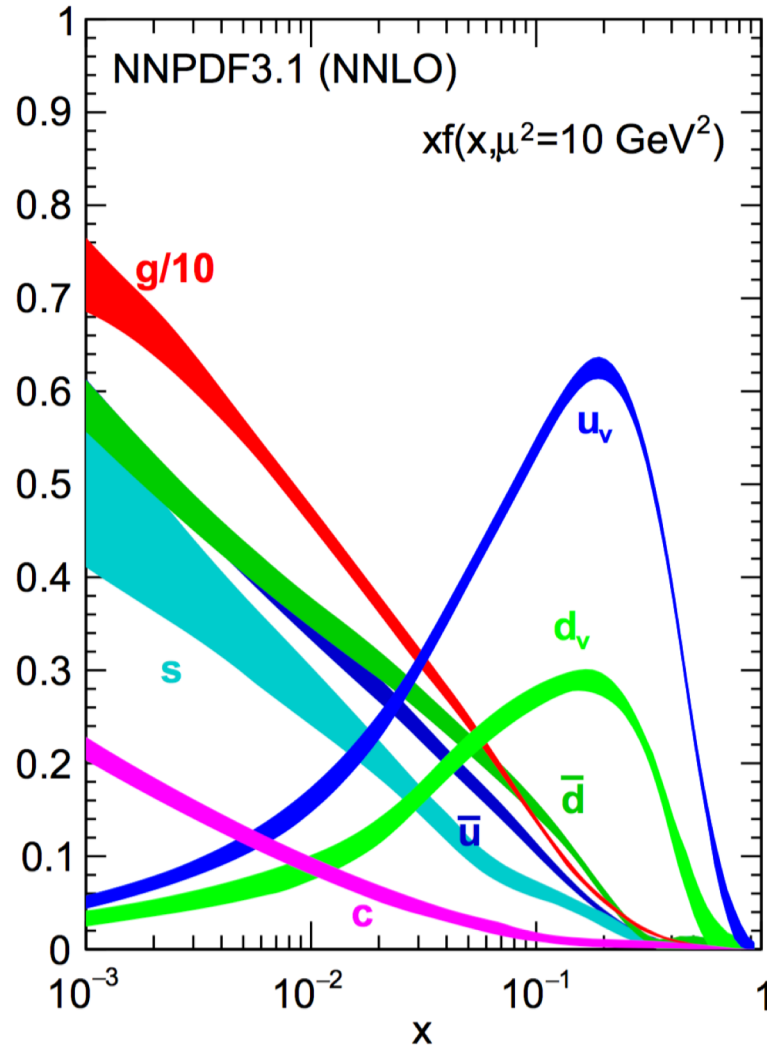
13TeV data from TOTEM

TOTEM Collaboration (2017)



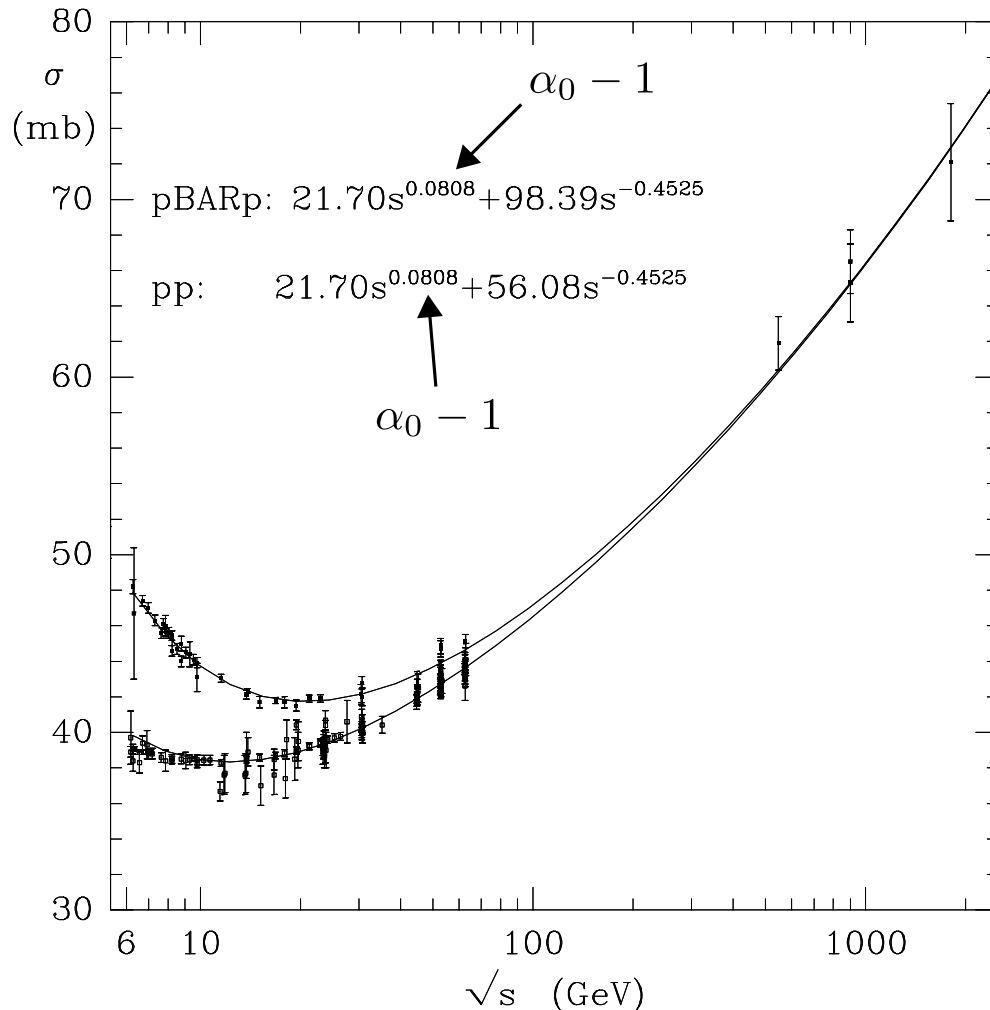
Proton parton distribution functions (PDFs)

NNPDF Collaboration (2017)



Total cross sections via Pomeron exchange

proton-(anti)proton total cross section

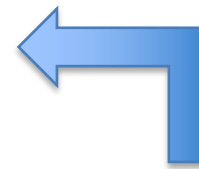


Donnachie-Landshoff (1992)

$$\sigma_{tot}(s) \sim s^{\alpha_0 - 1}$$



$\alpha_0 = 1.0808$
(soft Pomeron
intercept)

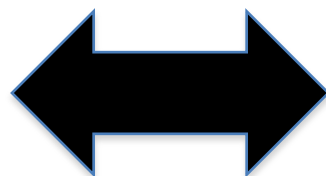


well describing the
experimental data

Holographic QCD

- Holographic QCD, which is constructed based on the AdS/CFT correspondence, has a potential to be a powerful tool for analysis on hadron physics.

type IIB
supergravity theory
on $S^5 \times \text{AdS}_5$



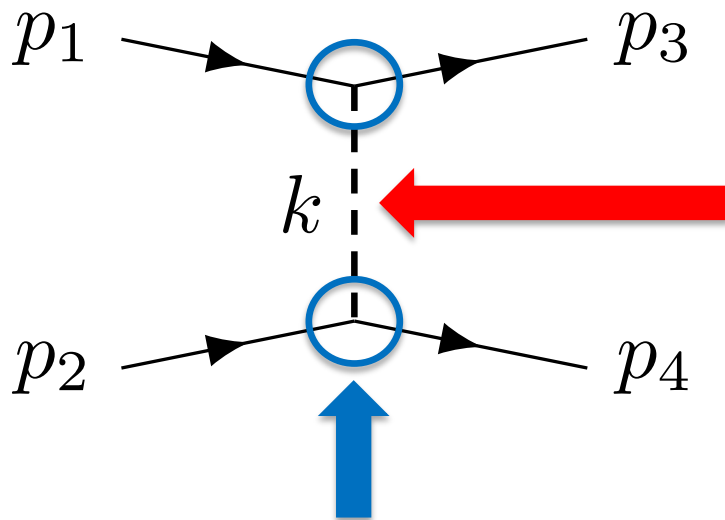
strong coupling 4D $N=4$
supersymmetric Yang-
Mills (SYM) theory

supergravity theory
(classical theory)
on AdS_5



usual 4D QCD
at strong coupling

Model setup



Domokos-Harvey-Mann (2009)

Reggeized spin-2
particle propagator

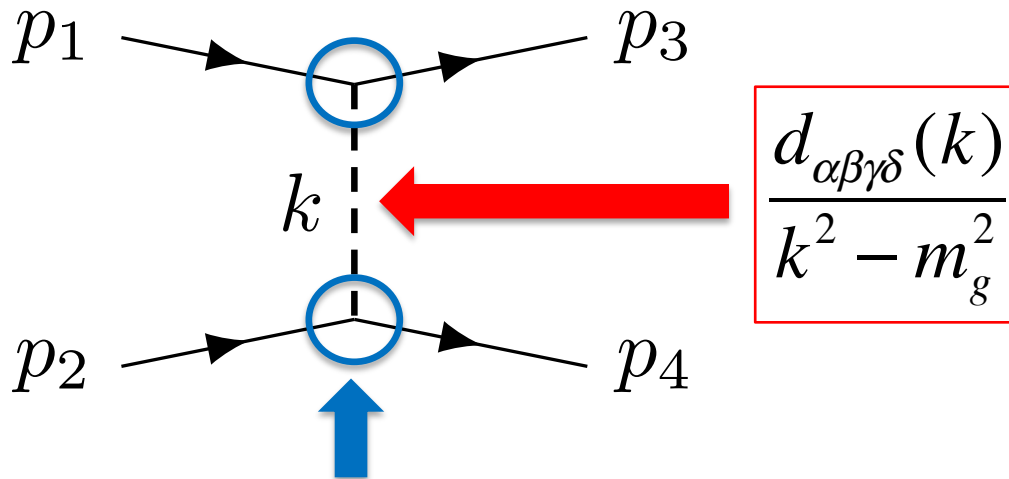
- 3 adjustable parameters are determined with data

Gravitational form factor

- Calculable with a bottom-up AdS/QCD model
- Model parameters are fixed by hadron properties

Applicable for other hadron-hadron scattering processes by replacing the form factors

Spin-2 glueball exchange



$$\langle p', s' | T_{\mu\nu}(0) | p, s \rangle = \bar{u}(p', s') \left[A(t) \frac{\gamma_\alpha P_\beta + \gamma_\beta P_\alpha}{2} + B(t) \frac{i(P_\alpha \sigma_{\beta\rho} + P_\beta \sigma_{\alpha\rho}) k^\rho}{4m_p} + C(t) \frac{(k_\alpha k_\beta - \eta_{\alpha\beta} k^2)}{m_p} \right] u(p, s)$$

Spin-2 glueball exchange

$$\mathcal{M}_g = \frac{\lambda^2 d_{\alpha\beta\gamma\delta}}{4(t - m_g^2)} \left[A(t)(\bar{u}_1 \gamma^\alpha u_3)(p_1 + p_3)^\beta + \frac{iB(t)}{2m_p}(p_1 + p_3)^\beta k_\rho (\bar{u}_1 \sigma^{\alpha\rho} u_3) + \frac{C(t)}{m_p}(\bar{u}_1 u_3)(k^\alpha k^\beta - \eta^{\alpha\beta} t) \right] \\ \times \left[A(t)(\bar{u}_2 \gamma^\gamma u_4)(p_2 + p_4)^\delta + \frac{iB(t)}{2m_p}(p_2 + p_4)^\delta k_\lambda (\bar{u}_2 \sigma^{\gamma\lambda} u_4) + \frac{C(t)}{m_p}(\bar{u}_2 u_4)(k^\gamma k^\delta - \eta^{\gamma\delta} t) \right]$$

where

$$d_{\alpha\beta\gamma\delta} = \frac{1}{2}(\eta_{\alpha\gamma}\eta_{\beta\delta} + \eta_{\alpha\delta}\eta_{\beta\gamma}) - \frac{1}{2m_g^2}(k_\alpha k_\delta \eta_{\beta\gamma} + k_\alpha k_\gamma \eta_{\beta\delta} + k_\beta k_\delta \eta_{\alpha\gamma} + k_\beta k_\gamma \eta_{\alpha\delta}) \\ + \frac{1}{24} \left[\left(\frac{k^2}{m_g^2} \right)^2 - 3 \left(\frac{k^2}{m_g^2} \right) - 6 \right] \eta_{\alpha\beta} \eta_{\gamma\delta} - \frac{k^2 - 3m_g^2}{6m_g^4} (k_\alpha k_\beta \eta_{\gamma\delta} + k_\gamma k_\delta \eta_{\alpha\beta}) + \frac{2k_\alpha k_\beta k_\gamma k_\delta}{3m_g^4}$$

$s \gg |t|$

$$\frac{d\sigma}{dt} = \frac{\lambda^4 s^2 A^4(t)}{16\pi(t - m_g^2)^2}$$

Needs to be Reggeized
to include the higher
spin states

Reggeized Spin-2 particle exchange

$$\frac{d\sigma}{dt} = \frac{\lambda^4 A^4(t) \Gamma^2[-\chi] \Gamma^2\left[1 - \frac{\alpha_c(t)}{2}\right]}{16\pi \Gamma^2\left[\frac{\alpha_c(t)}{2} - 1 - \chi\right]} \left(\frac{\alpha'_c s}{2}\right)^{2\alpha_c(t)-2}$$

$$\sigma_{tot} = \frac{\pi \lambda^2 \Gamma[-\chi]}{\Gamma\left[\frac{\alpha_c(0)}{2}\right] \Gamma\left[\frac{\alpha_c(0)}{2} - 1 - \chi\right]} \left(\frac{\alpha'_c s}{2}\right)^{\alpha_c(0)-1}$$

where

$$\alpha_c(x) = \alpha_c(0) + \alpha'_c x$$

$$\chi = \alpha_c(s) + \alpha_c(t) + \alpha_c(u) = 4\alpha'_c m^2 + 3\alpha_c(0)$$

3 parameters: $\lambda, \alpha_c(0), \alpha'_c$

to be determined with experimental data

Gravitational form factor

Abidin-Carlson (2009)

Matrix element of the energy momentum tensor in respect to spin 1/2 particle:

$$\langle p_2, s_2 | T^{\mu\nu}(0) | p_1, s_1 \rangle = u(p_2, s_2) \left(A(t) \gamma^{(\mu} p^{\nu)} + B(t) \frac{i p^{(\mu} \sigma^{\nu)\alpha} q_\alpha}{2m} + C(t) \frac{q^\mu q^\nu - q^2 \eta^{\mu\nu}}{m} \right) u(p_1, s_1)$$

A bottom-up AdS/QCD model of the nucleon:

$$S_F = \int d^5x \sqrt{g} e^{-\kappa^2 z^2} \left(\frac{i}{2} \bar{\Psi} e_A^N \Gamma^A D_N \Psi - \frac{i}{2} (D_N \Psi)^\dagger \Gamma^0 e_A^N \Gamma^A \Psi - (M + \kappa^2 z^2) \bar{\Psi} \Psi \right)$$

5D AdS space:
$$ds^2 = g_{MN} dx^M dx^N = \frac{1}{z^2} (\eta_{\mu\nu} dx^\mu dx^\nu - dz^2)$$

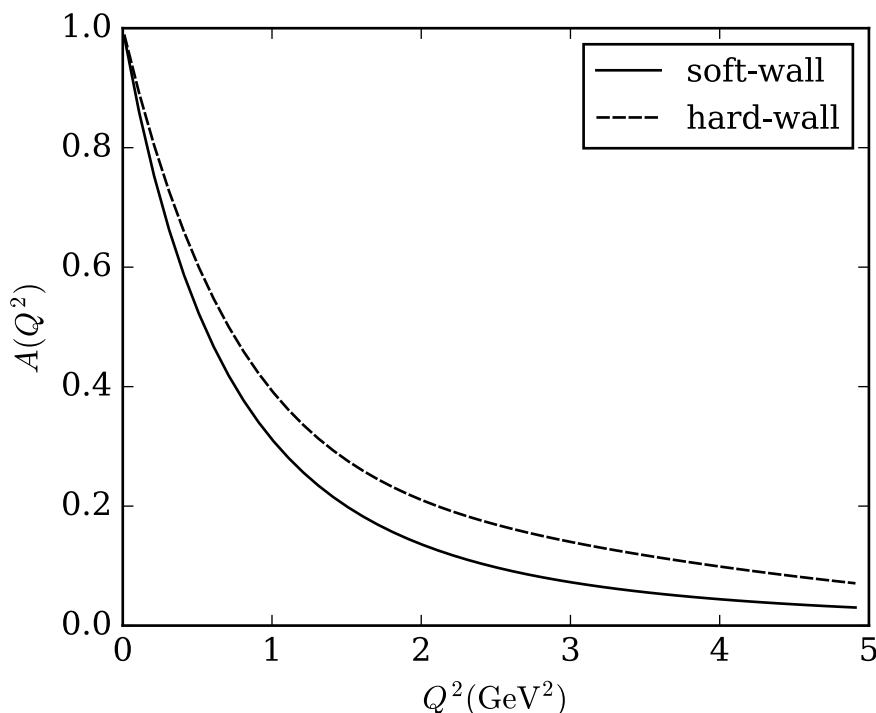
Introduce the metric perturbation, $\eta_{\mu\nu} \rightarrow \eta_{\mu\nu} + h_{\mu\nu}$, in the 5D classical action, and pick up the $h\psi\psi$ terms.

By comparing the Lorentz structure of them, one can obtain the form factors. (in this case, only A(t) remains)

Gravitational form factor

$$A(Q) = \int dz \frac{e^{-\kappa^2 z^2}}{2z^{2M}} H(Q, z) (\Psi_L^2(z) + \Psi_R^2(z))$$

$\Psi_{L,R}$: 5D wave functions describing a nucleon as a 5D Dirac fermion with chiral symmetry breaking



if $\kappa=0$ (hard-wall model), a sharp cutoff z_0 needs to be imposed in the large z (IR) region

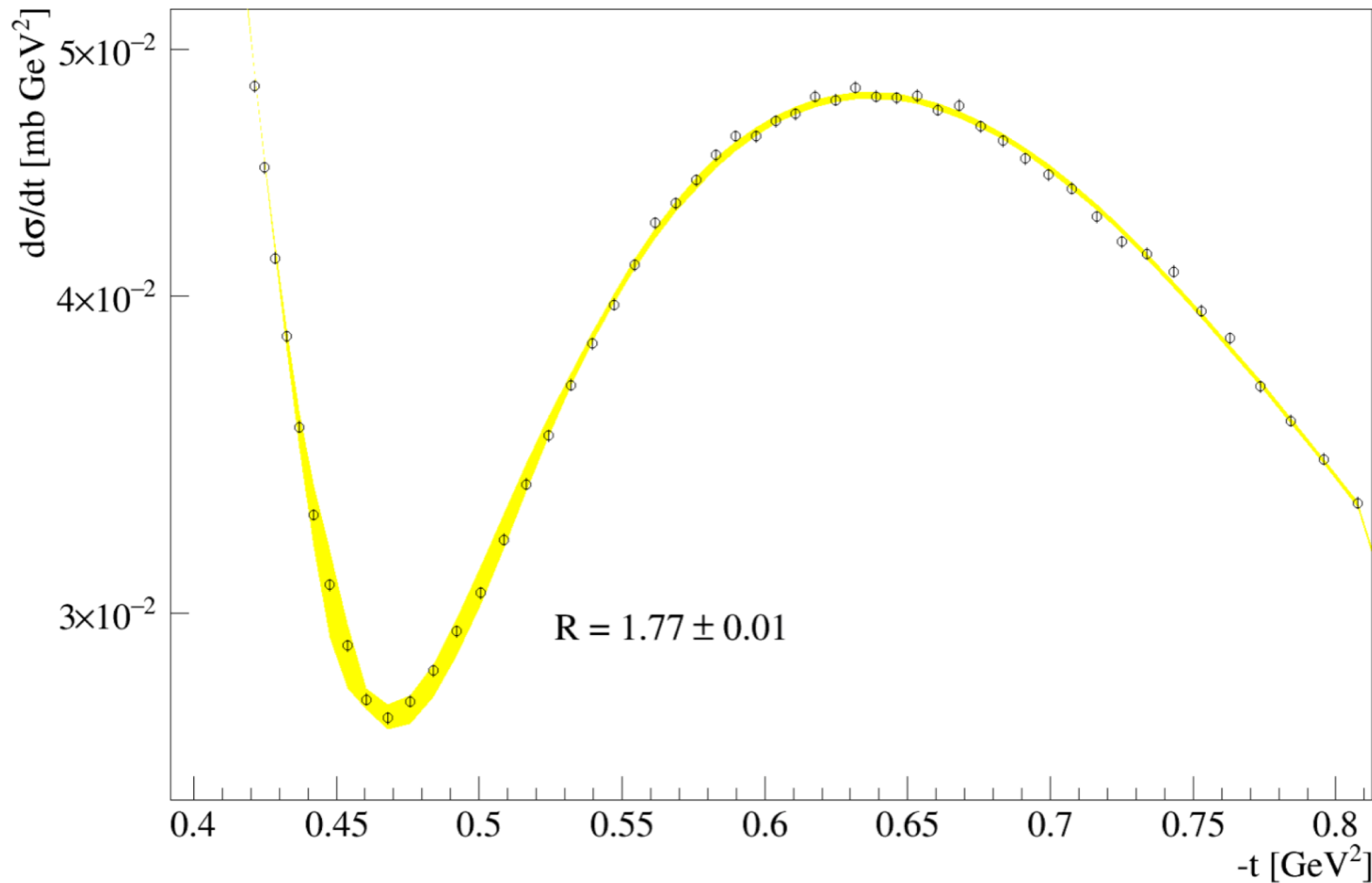
$$1/z_0 \sim \Lambda_{QCD}$$

Fitting with experimental data

- 3 adjustable parameters in total
- Considered experimental data are from:
 - UA4 collaboration (1984,1985)
 - E710 collaboration (1988,1989,1992)
 - CDF collaboration (1994)
 - TOTEM collaboration (2013,2016,2017,2018)
- Utilize data in kinematic range:
 - $546 \text{ GeV} < \sqrt{s} < 13 \text{ TeV}$
 - $0.01 \text{ GeV}^2 < |t| < 0.45 \text{ GeV}^2$

Diffractive minimum (dip)

TOTEM collaboration (2018)



Results of fits

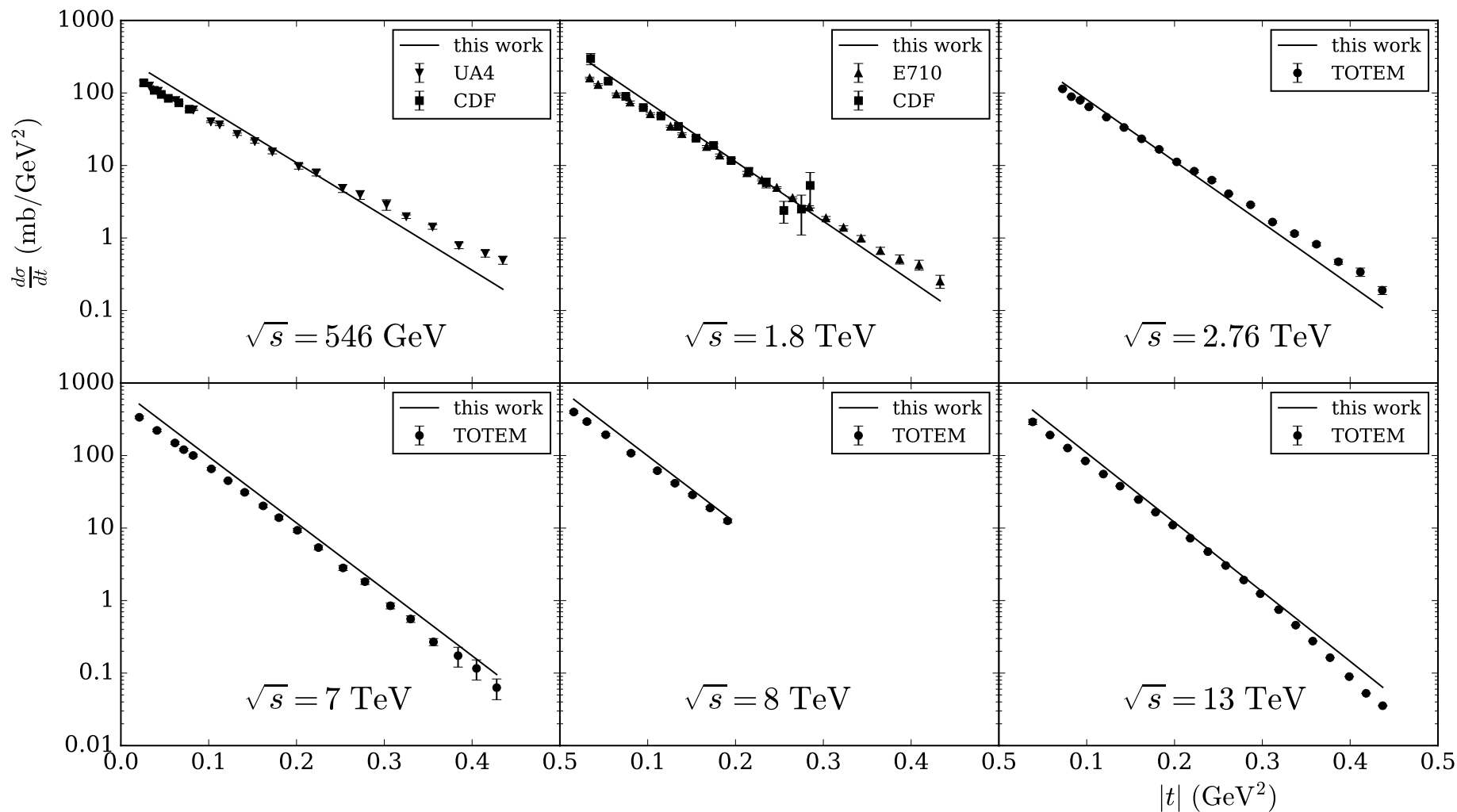
All data

Parameters	soft-wall	hard-wall
$\alpha_c(0)$	1.086 ± 0.002	1.087 ± 0.001
$\alpha'_c \text{ (GeV}^{-2}\text{)}$	0.395 ± 0.002	0.412 ± 0.002
$\lambda \text{ (GeV}^{-1}\text{)}$	8.95 ± 0.12	9.44 ± 0.13
$\chi^2/d.o.f.$	1.317	1.355

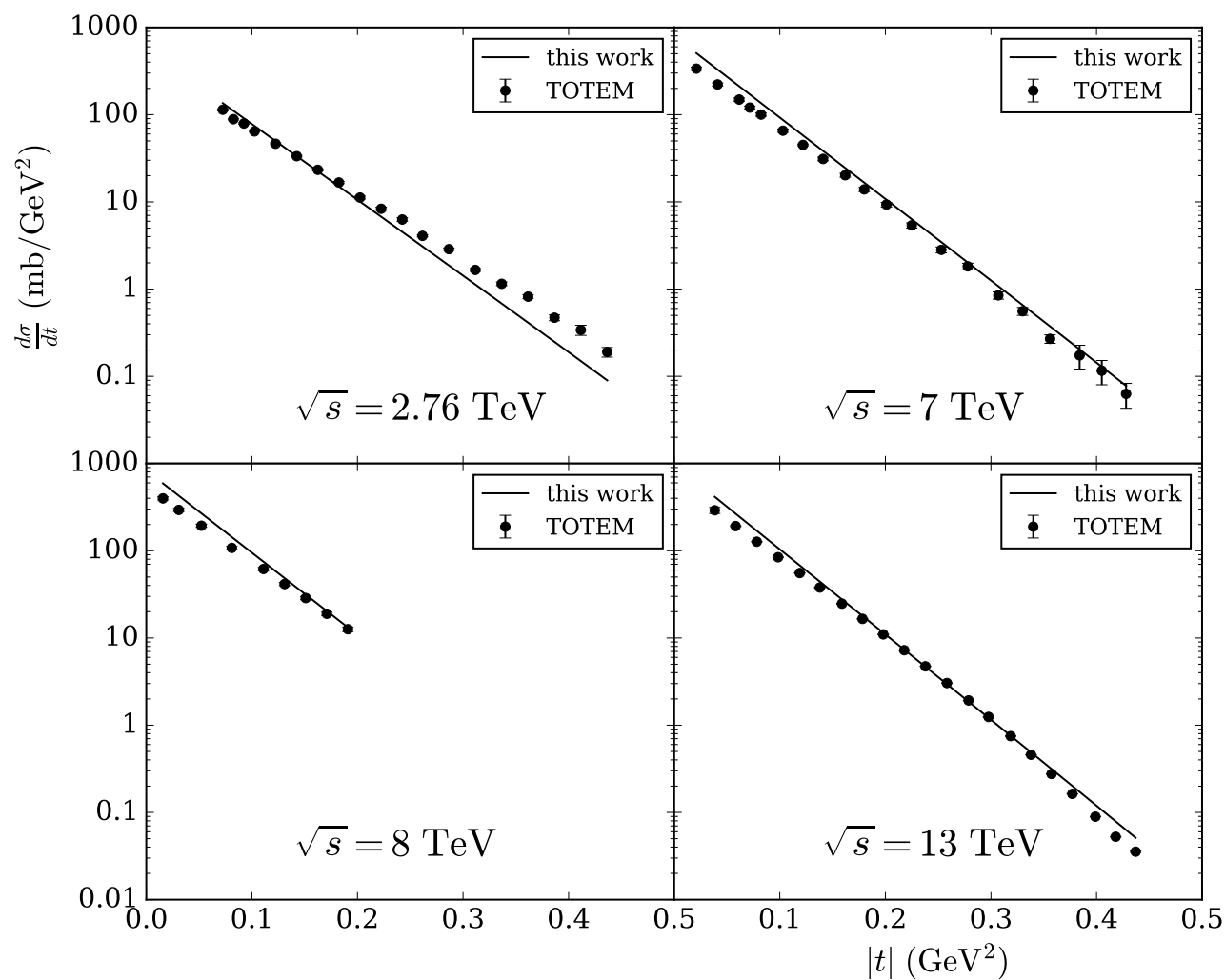
TOTEM data only

Parameters	soft-wall	hard-wall
$\alpha_c(0)$	1.086 ± 0.002	1.087 ± 0.001
$\alpha'_c \text{ (GeV}^{-2}\text{)}$	0.402 ± 0.002	0.416 ± 0.001
$\lambda \text{ (GeV}^{-1}\text{)}$	9.16 ± 0.13	9.60 ± 0.13
$\chi^2/d.o.f.$	1.248	1.279

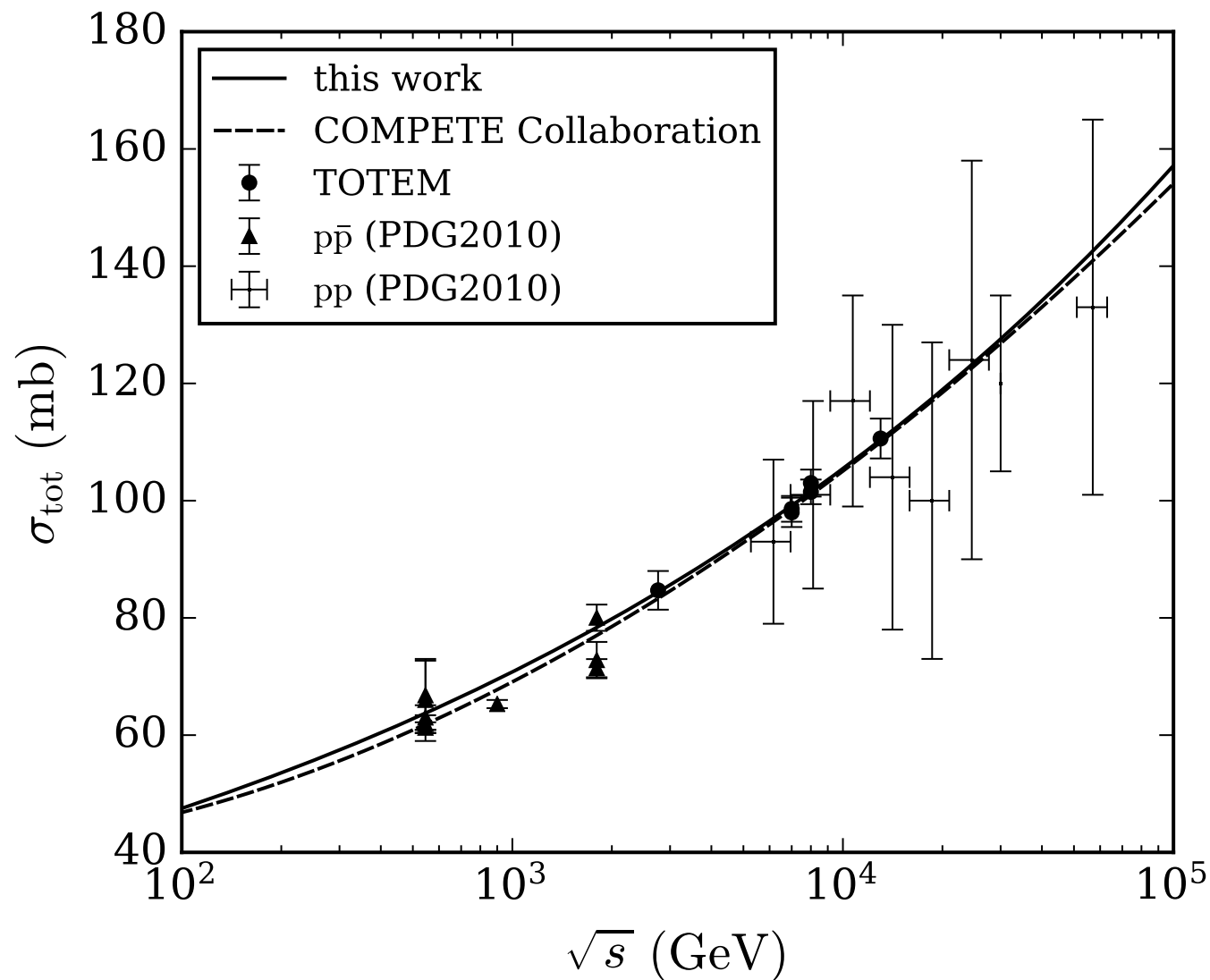
Differential cross section



Differential cross section (TOTEM only)



Total cross section



Summary

- We have investigated the proton-proton differential and total cross sections at high energies in the framework of holographic QCD.
- We have shown that the currently available data, including the new results from TOTEM at 13TeV, can be well reproduced within the present model setup.
- The Pomeron exchange works well in this scale.
- Further improvement of the model is required to investigate the diffractive scattering.