Parton distributions in $\pi^{\pm}$ within `xFitter` framework

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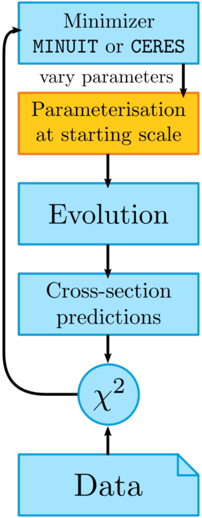
Introduction and motivation

- Pion plays an important role in our understanding of strong interactions: it is, at the same time, a mediator of nucleon-nucleon interactions, a pseudo-Goldstone boson of dynamical chiral symmetry breaking, and the simplest $q\bar{q}$ state in quark-parton model
- In comparison to proton, pion structure is poorly studied experimentally.
- Currently available pion PDF sets in `LHAPDF5/6` library are provided without error bands
- Pion is more straightforward to describe theoretically than baryons: pion PDFs have been calculated in nonperturbative models, such as NJL model, light-front constituent quark model, chiral constituent quark model; first moments of pion PDFs have been calculated on lattice
- Anticipating new DY and direct photon data from `COMPASS++/AMBER` experiment



To describe π^- with a small number of parameters assume at starting scale $Q_0^2 = 1.9\text{GeV}$ SU(3)-symmetric sea and neglect electroweak corrections: $\bar{u} = d$, $\bar{d} = u = s = \bar{s}$

$$v := \frac{(d-\bar{d})-(u-\bar{u})}{2} = d - u \qquad xv = A_v x^{B_v}(1-x)^{C_v}$$

$$s := \frac{u+\bar{d}}{2} = u \qquad xs = A_s x^{B_s}(1-x)^{C_s}$$

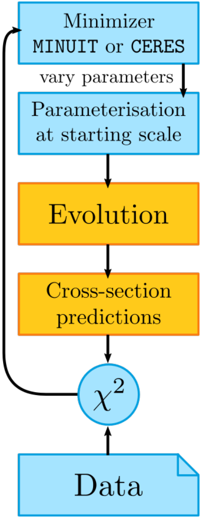
$$g := g \qquad xg = A_g x^{B_g}(1-x)^{C_g}$$

A_v and A_g are fixed by valence and momentum sum rules:

$$\int_0^1 v\mathrm{d}x = 1 \qquad \int_0^1 x(2v+6s+g)\mathrm{d}x = 1$$

Other parameters are varied to minimize χ^2

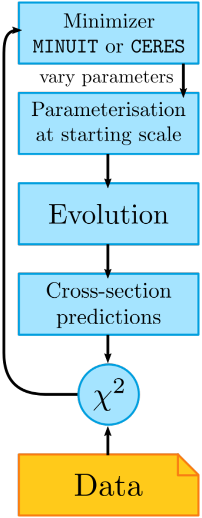
C-parameters determine high-x behavior, B-parameters determine low-x behavior



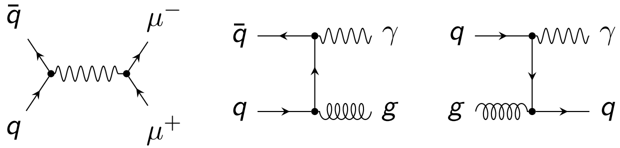
PDFs are evolved from starting scale $Q_0^2 = 1.9$ by solving DGLAP equations numerically. `xFitter` uses `QCDNUM` or `APFEL++` packages.

Theory predictions are calculated using `APPLgrid` package as a convolution PDF $\otimes$ precomputed grid. The grids were generated using the `MCFM` generator

Evolution and cross-section calculations are performed at NLO



Experiment	P_{lab}, GeV	Reaction	N_{points}
E615[1]	252	$\pi^- \, {}_{74}\mathrm{W} \to \mu^+\mu^- X$	140
NA10[2]	194	$\pi^- \, {}_{74}\mathrm{W} \to \mu^+\mu^- X$	59
	286	$\pi^- \, {}_{74}\mathrm{W} \to \mu^+\mu^- X$	73
WA70[3]	280	$\pi^{\pm} p \to \gamma X$	99
		Total:	371



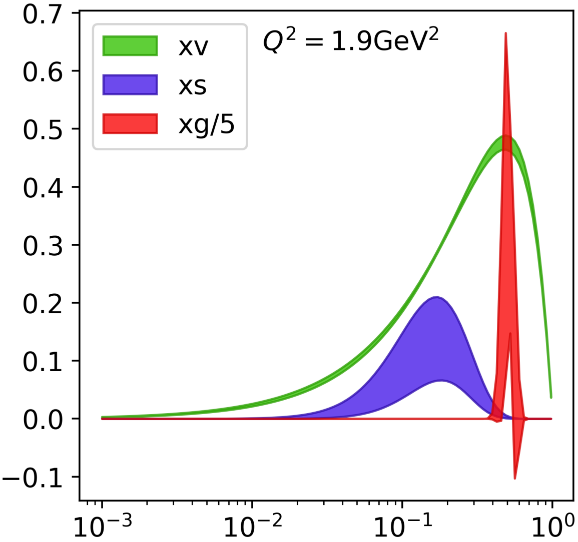
For tungsten target we used nuclear PDF set nCTEQ15[4]

[1] J. S. Conway *et al.*,Phys. Rev. D **39** (1989) 92.
[2] B. Betev *et al.* [NA10 Collaboration], Z. Phys. C **28** (1985) 9. (data revised)
[3] M. Bonesini *et al.* [WA70 Collaboration], Z. Phys. C **37** (1988) 535.
[4] K. Kovarik *et al.*, Phys. Rev. D **93** (2016) no.8, 085037

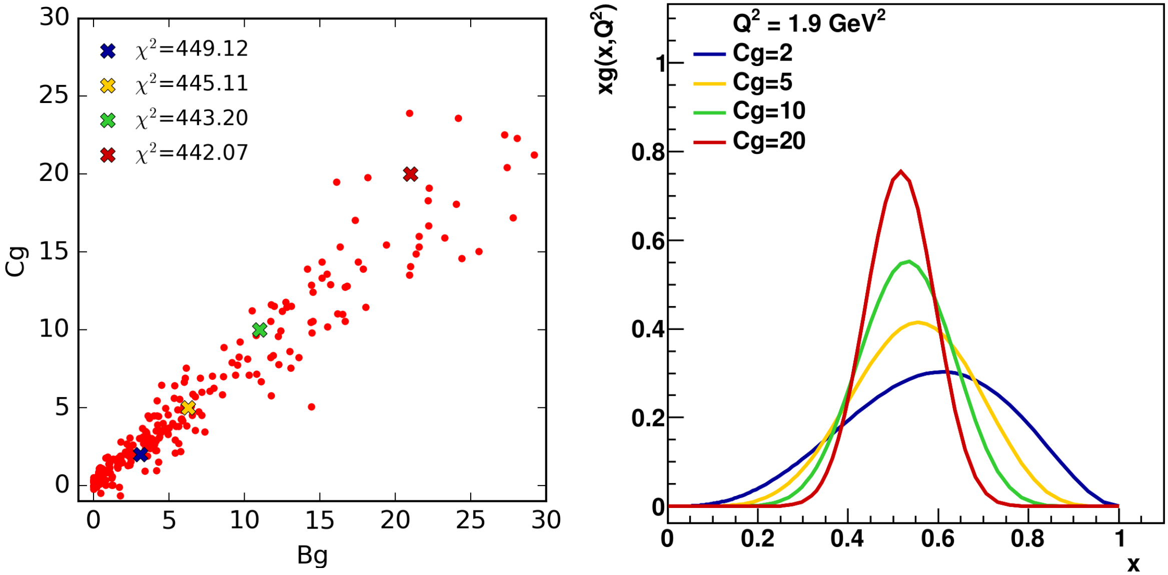
$$\frac{\chi^2}{N_{DoF}} = \frac{438.01}{372} = 1.177$$

$B_v = 0.94 \pm 0.03$
$C_v = 1.01 \pm 0.03$
$A_s = 312 \pm 537$
$B_s = 2.9 \pm 0.7$
$C_s = 14 \pm 3$
$B_g = 100 \pm 98$
$C_g = 100 \pm 91$

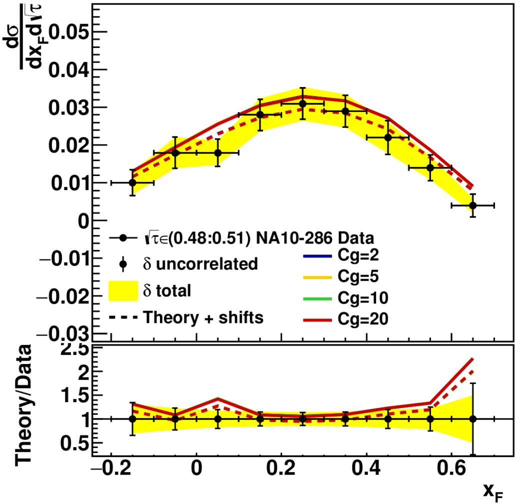
Fitted parameters



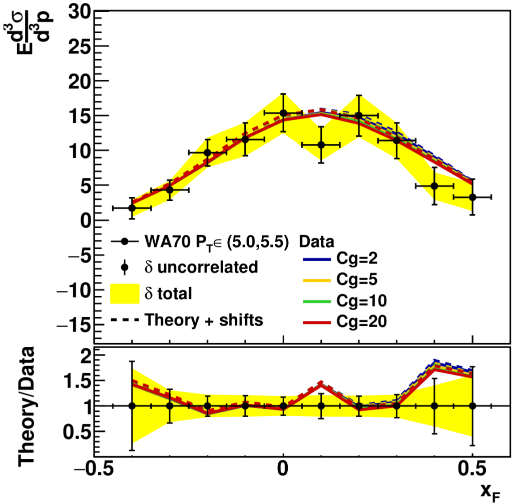
While valence distribution is well-constrained, some sea and gluon parameters cannot be determined from the data



Red dots were obtained using pseudodata generated with central values based on theory and fluctuations based on data uncertainties.

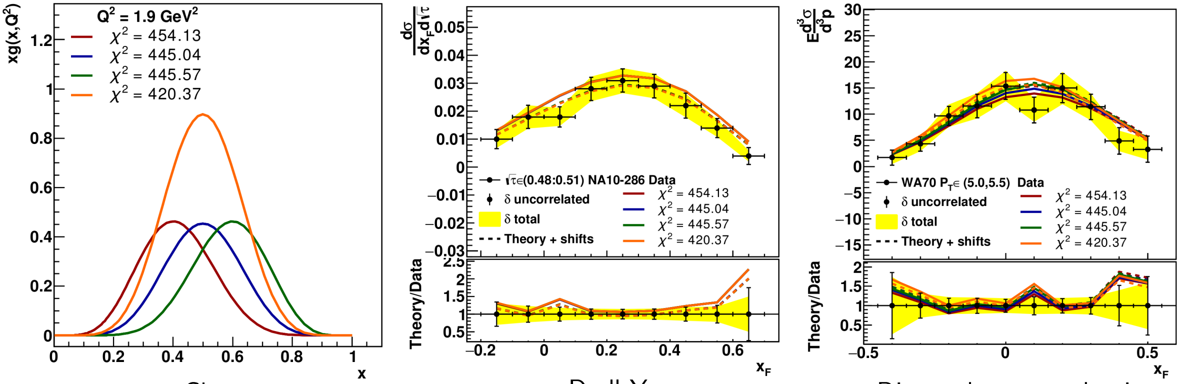


Drell-Yan



Direct photon production

Both Drell-Yan and direct photon data are not sensitive to these gluon variations



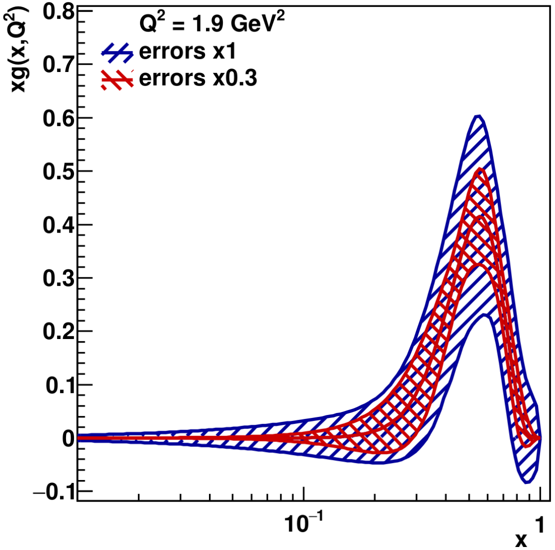
Gluon

Drell-Yan

Direct photon production

In general sensitivity of DY data to gluon is small; direct photon production data is sensitive to gluon, but also has large uncertainties, both uncorrelated and normalization

We compare sensitivity studies using pseudodata with errors based on data and with errors of direct photon production data rescaled by a factor of 0.3. One can see that more precise direct photon production data would allow us to better constrain gluon.



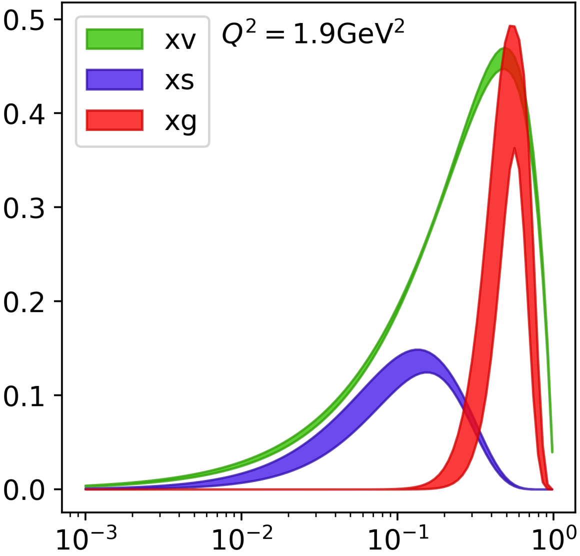
Gluon from sensitivity study

Fix some parameters to be HERA-like:

$$\frac{\chi^2}{N_{DoF}} = \frac{450.23}{374} = 1.204$$

$B_v = 0.89 \pm 0.03$
$C_v = 0.96 \pm 0.03$
$A_s = 6.4 \pm 1.9$
$B_s = 1.35 \pm 0.16$
$C_s = 8$
$B_g = 6.3 \pm 1.3$
$C_g = 5$

Fitted parameters

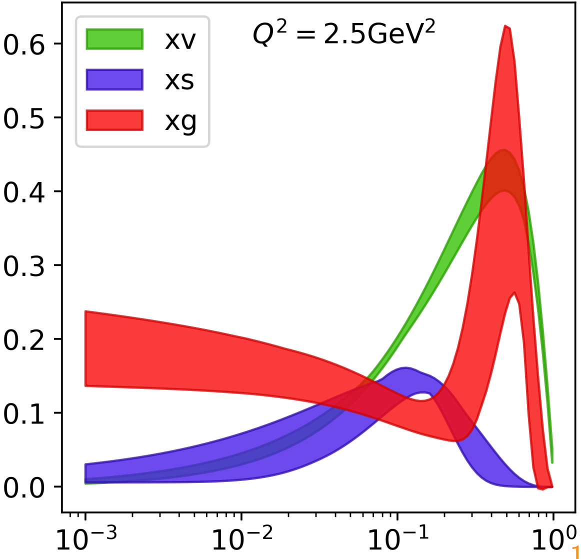


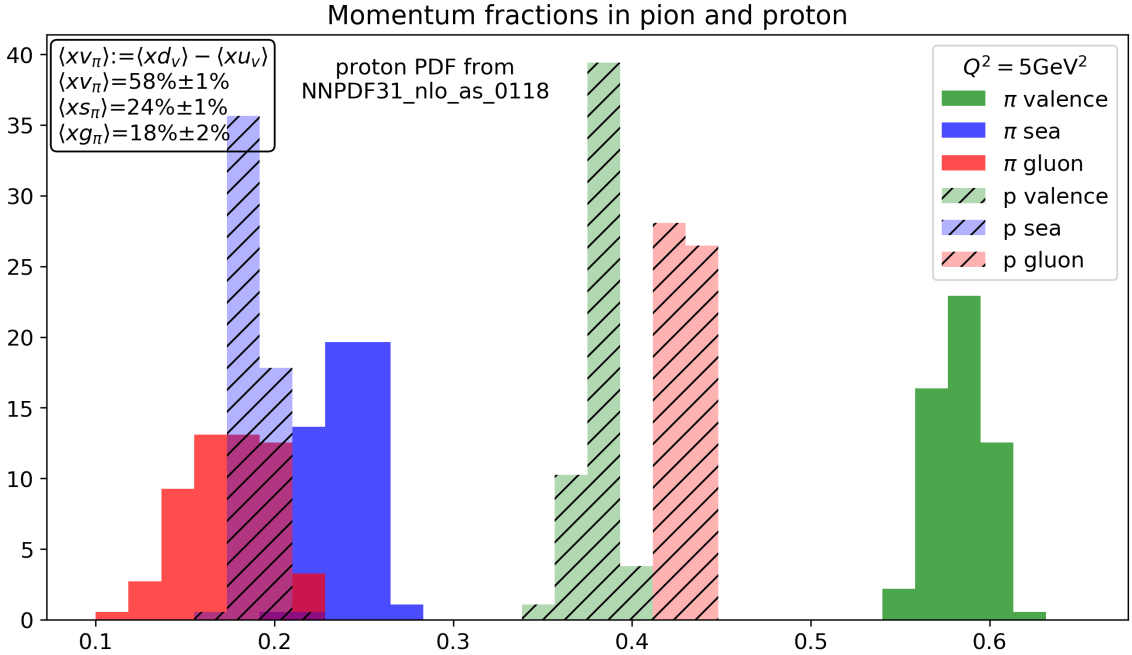
Additional uncertainties

- Uncertainties in PDFs used for tungsten target and $\alpha_S = 0.118 \pm 0.001$ are treated as additional sources of correlated error
- Variation of starting scale $Q_0^2 = 1.9 \pm 0.1$
- Fixed parameters C_g, C_s and renormalization scale μ_R are varied by a factor of 2 up and down. μ_R variation has a strong impact on predictions:

μ_R factor	χ^2
0.5	419.32
1	445.09
2	470.90

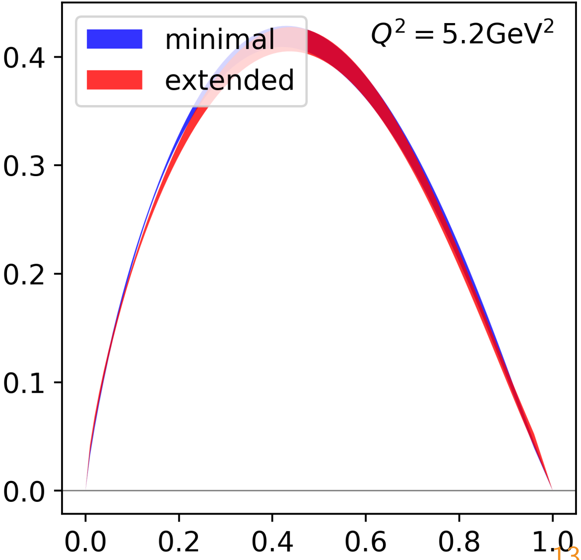
- Valence distribution is well-constrained even with additional uncertainties




Momentum fractions in pion and proton
$\langle xv_\pi \rangle := \langle xd_v \rangle - \langle xu_v \rangle$
$\langle xv_\pi \rangle$=58%±1%
$\langle xs_\pi \rangle$=24%±1%
$\langle xg_\pi \rangle$=18%±2%
proton PDF from
NNPDF31_nlo_as_0118
$Q^2 = 5\mathrm{GeV}^2$
π valence
π sea
π gluon
p valence
p sea
p gluon
0
5
10
15
20
25
30
35
40
0.1
0.2
0.3
0.4
0.5
0.6

High-x behavior of valence distribution

- After trying different parameterisation extensions, we found that $xv = A_v x^{B_v}(1-x)^{C_v}(1+D_v x^{\frac{5}{2}})$ improves χ^2 by 5.4
- For minimal parameterisation $xv = A_v x^{B_v}(1-x)^{C_v}$ determined parameter $C_v = 0.96 \pm 0.03$ is consistent with $C_v = 1$. Behavior near $x = 1$ is linear in $(1-x)$ for both minimal and extended parameterisation.
- Some models, such as pQCD and Dyson-Schwinger equations, predict $Cv \approx 2$. Other models, including Nambu-Jona-Lasinio and Drell-Yan-West relation, favor $C_v \approx 1$.



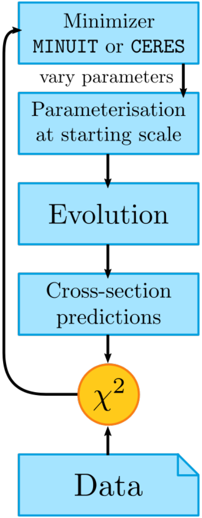
Conclusions

- New look at the pion data using modern tools
- Data are described by NLO QCD reasonably well, sensitivity to μ_R indicates that NNLO corrections are significant
- Fraction of momentum carried by gluon is small in comparison to proton
- Valence distribution $\sim (1-x)^1$ at high x.
- Extracted PDFs with uncertainties will be submitted to `LHAPDF6`
- More precise direct photon data could help constrain gluon and sea

Backup

Data normalization and partial χ^2

Experiment	P_{lab}, GeV	Reported luminosity uncertainty	Fitted normalisation factor	χ^2/N_{points}
E615	252	15%	1.265 ± 0.015	$172.16/140 = 1.230$
NA10	194	6.4%	1.144 ± 0.014	$81.7/67 = 1.219$
	286	6.4%	1.075 ± 0.014	$90.46/73 = 1.239$
WA70	280	6%	0.95 ± 0.03	$87.46/99 = 0.883$



correlated uncertainty

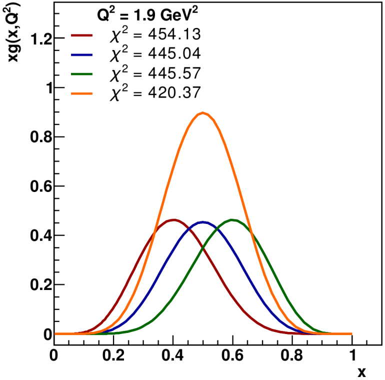
data theory

$$\chi^2 := \sum_i \frac{\left(d_i - t_i - \sum_\alpha \Gamma_{i\alpha} b_\alpha\right)^2}{\Delta_i^2} + \sum_\alpha b_\alpha^2$$

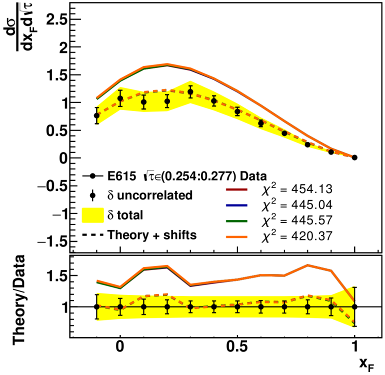
uncorrelated uncertainty

nuisance parameter

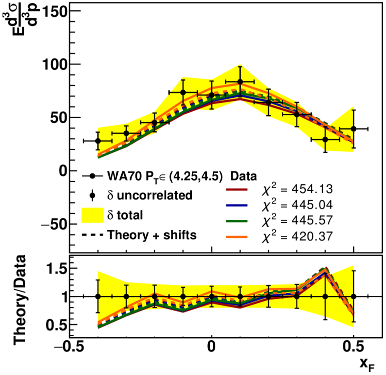
Overall normalization uncertainties of the data is taken into account using nuisance parameters.



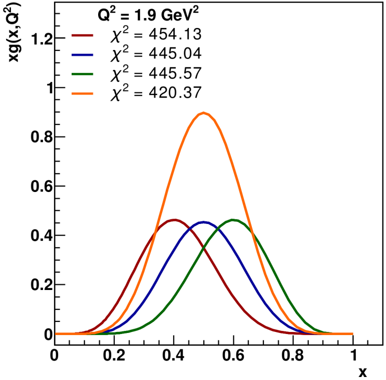
Gluon



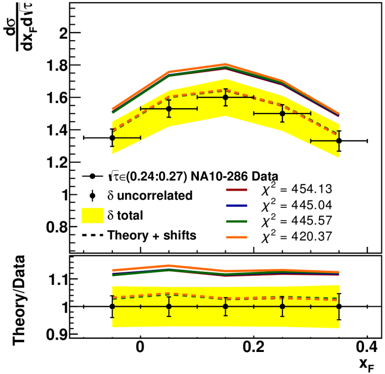
Drell-Yan



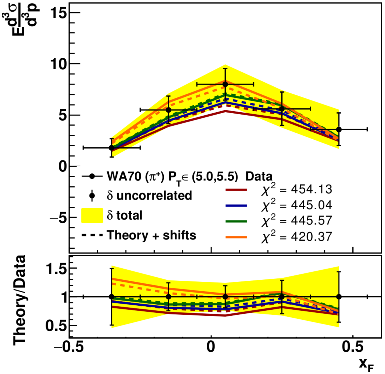
Direct photon production π^-



Gluon

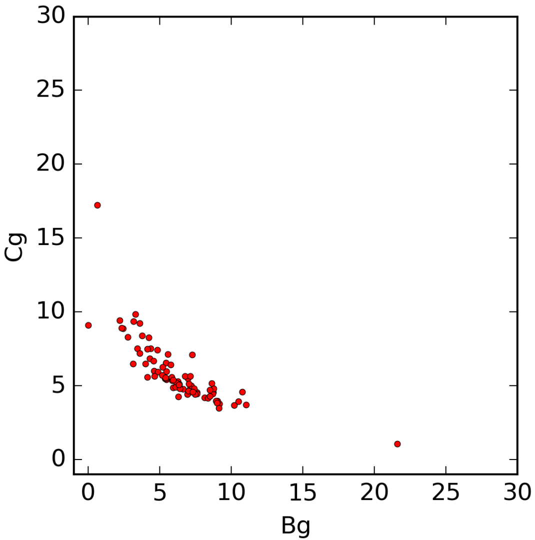


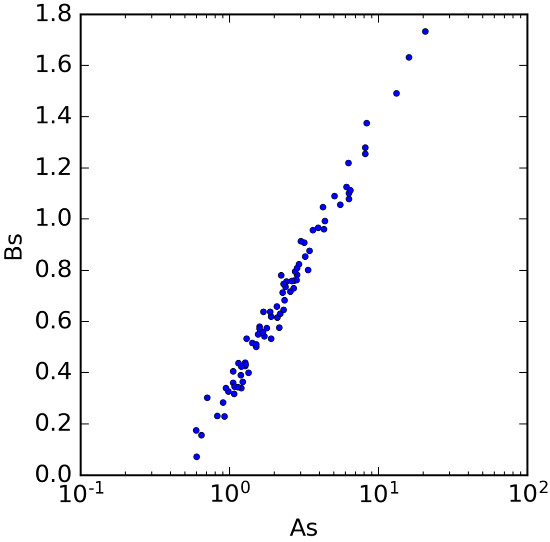
Drell-Yan



Direct photon production

Parameter correlations from MC





Without momentum sum