Probing gluon densities with prompt photons at RHIC and LHC

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LAPTH, Annecy

Initial Conditions in Heavy-Ion Collisions

Goa – September 2008

Introduction

- Motivations
  - why probing small-x gluons
  - why using prompt photons
- Extracting gluon distributions
  - pQCD prompt photon production in p A collisions
  - limitations
- Phenomenology
  - predictions in p A collisions at RHIC and LHC
  - measuring shadowing without p p data

Reference

FA, T. Gousset, Phys. Lett. B660 (2008) 181 arXiv:0707.2944

Gluon distributions at small x

Accurate knowledge of gluon density in a proton/nucleus is essential

- Fundamental pQCD ingredient
  - tool for reliable predictions of hard processes at LHC
- Probe of non-linear QCD evolution
  - looking for saturation at small x

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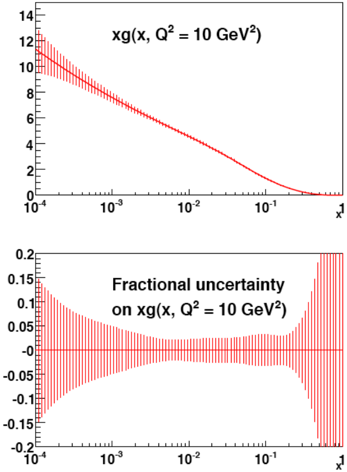
Strong activity over the last decade to probe proton densities

- Impressive results from HERA [H1, ZEUS]
- Important theoretical developments in global fit analyses [CTEQ, GRV, MRST]

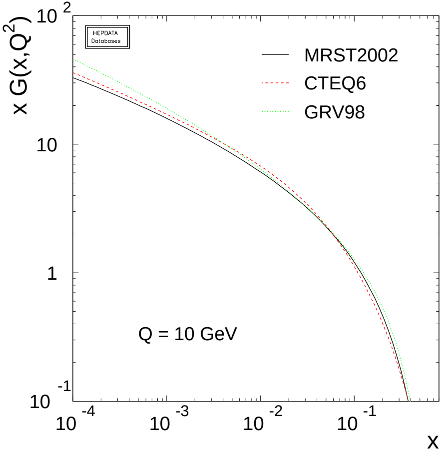
Gluon distributions at small x



[From R. Thorne DIS 2007]

Gluon distributions at small x

Comparison of different gluon densities at NLO



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Current precision

$G^p(x, Q^2)$ fairly well known over a large kinematical range

$$x \sim 10^{-4}\text{–}10^{-1} \text{ and } Q^2 \sim 10\text{–}10^5 \text{ GeV}^2$$

Gluon density in nuclei

Definition

Ratio of gluon distributions in nuclei over that in a proton

$$R_G(x, Q^2) = G^A(x, Q^2)/G^p(x, Q^2)$$

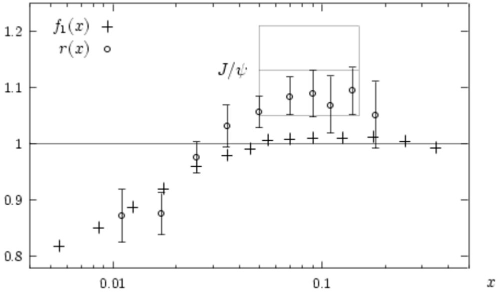
determined indirectly from DIS data

Gluon density in nuclei

Example

Analysis of scaling violations of $F_2^A(x, Q^2)$

[Gousset, Pirner 1996]

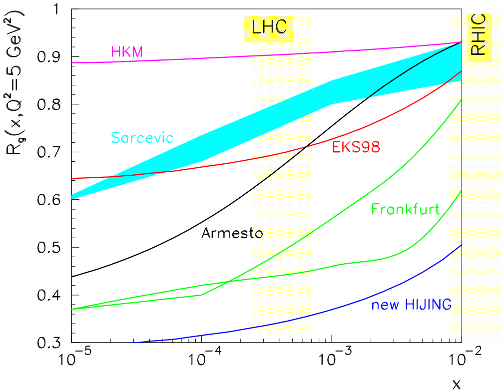


- Tiny constraints from NMC data
- Fairly large $x \sim 10^{-2}$–10^{-1} and low $Q^2 \sim 1$–10 GeV^2

Gluon density in nuclei

Global fit analyses

- DIS and Drell-Yan data [EKS, HKM, nDS, nDSg]
- ... and hadron production at RHIC [EPS]



[Armesto, Salgado 2003]

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Question

How to probe small-x gluon shadowing at LHC ?

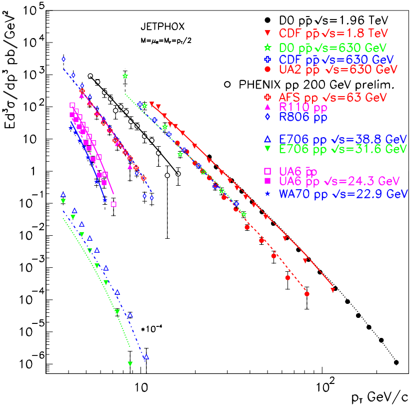
- which observables
- why prompt photons look promising

Comparing observables

Advantages and limitations

- Jets
  - high rates, rich phenomenology, forward rapidities
  - large scales $Q^2 \gtrsim 10^3$ GeV^2
- Large $p_\perp$ dileptons
  - no strong background
  - very low rates
- Heavy-bosons
  - constraints on sea-quark shadowing
  - large scales $Q^2 \gtrsim 10^4$ GeV^2
- Prompt photons
  - low $Q^2 \gtrsim 10$–10^3 GeV^2, rich phenomenology
  - parton-to-photon fragmentation process

Comparing observables



[Aurenche et al. 2006]

- Very good description of isolated/inclusive photon world-data

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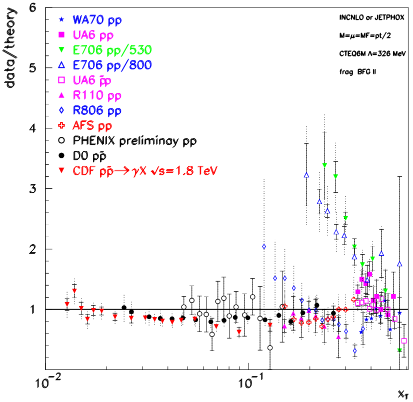

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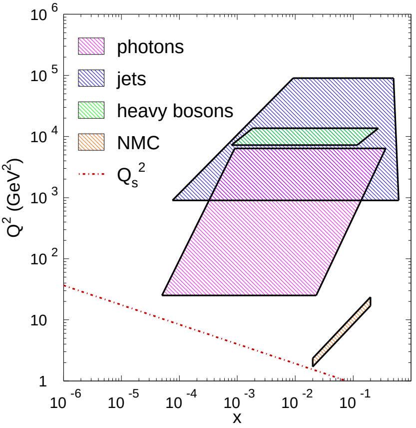
Kinematical range



(x, Q^2) domain covered at the LHC

- Photons and jets are clearly complementary
- Photons cover small Q^2 where shadowing should be large

Prompt photons

Definition

Prompt photons are produced by the hard scattering of two incoming nucleons [hard = w/ large momentum transfer $Q \gg \Lambda_{\mathrm{QCD}}$]

$$\text{Prompt photons carry large } p_{\perp_\gamma} \gg \Lambda_{\mathrm{QCD}} = \mathcal{O}\left(1 \text{ GeV}\right)$$

Consequence

Asymptotic freedom

$$\alpha_s(Q \gg \Lambda_{\mathrm{QCD}}) \ll 1$$

. . . allows for a perturbative treatment of prompt photon production in hadronic collisions

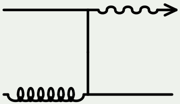
[NB: prompt photons do not include photons coming from hadron decays nor thermal production]

Perturbative production

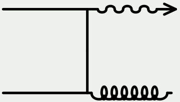
Dynamics

Leading-order $\mathcal{O}(\alpha\ \alpha_s)$ contributions

- Compton scattering $q(\bar{q})g \to q(\bar{q})\ \gamma$



- Annihilation process $q\bar{q} \to g\ \gamma$



Approximation

At high energy, only the Compton scattering process is relevant

Perturbative production

LO production cross section in p A collisions
$\left(x_\perp \equiv 2p_\perp/\sqrt{s},\ F(x) \equiv F_2(x)/x\right)$

$$\frac{1}{A}\frac{\mathrm{d}^3\sigma^{pA}}{\mathrm{d}y\ \mathrm{d}^2p_\perp} = \int \mathrm{d}v\ F^p\left(\frac{x_\perp e^y}{2v}\right) G^A\left(\frac{x_\perp e^{-y}}{2(1-v)}\right)\hat{\sigma}(v) + \int \mathrm{d}v\ G^p\left(\frac{x_\perp e^y}{2v}\right) F^A\left(\frac{x_\perp e^{-y}}{2(1-v)}\right)\hat{\sigma}(1-v)$$

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Problem

The integration over the rapidity of the recoiling jet ($\leftrightarrow v$) does not allow for the arguments of F and G to be fixed

Single photon production not sufficient to probe parton densities

Extracting parton density ratios

Approximation

- R_{F_2} and R_G vary slowly as compared to F_2 and G
- Integrand peaked at $v = 1/2$

$$\frac{1}{A}\frac{\mathrm{d}^3\sigma^{pA}}{\mathrm{d}y\ \mathrm{d}^2p_\perp} \simeq R_G(x_\perp e^{-y}) \int \mathrm{d}v\ F^p\left(\frac{x_\perp e^{y}}{2v}\right) G^p\left(\frac{x_\perp e^{-y}}{2(1-v)}\right) \hat{\sigma}(v)$$
$$+ R_{F_2}(x_\perp e^{-y}) \int \mathrm{d}v\ G^p\left(\frac{x_\perp e^{y}}{2v}\right) F^p\left(\frac{x_\perp e^{-y}}{2(1-v)}\right) \hat{\sigma}(1-v)$$

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$$+ R_{F_2}(x_\perp e^{-y}) \int \mathrm{d}v\ G^p\left(\frac{x_\perp e^y}{2v}\right) F^p\left(\frac{x_\perp e^{-y}}{2(1-v)}\right) \hat{\sigma}(1-v)$$

Simple relationship between prompt photon production

and parton densities!

[NB: especially when one channel is negligible to another]

Nuclear production ratio

Definition

Nuclear production ratio in p A collisions

$$R_{pA}(x_\perp) = \frac{1}{A} \; \frac{\mathrm{d}^3\sigma}{\mathrm{d}y\;\mathrm{d}^2p_\perp}(p + A \to \gamma + \mathrm{X}) \Big/ \frac{\mathrm{d}^3\sigma}{\mathrm{d}y\;\mathrm{d}^2p_\perp}(p + p \to \gamma + \mathrm{X})$$

Most naive estimates

- Around mid-rapidity

$$R_{pA}(p_\perp, y) \simeq 0.5 \; \left[R_{F_2}(x_\perp e^{-y}) \; + \; R_G(x_\perp e^{-y}) \right]$$

- At (very) forward rapidity

$$R_{pA}(p_\perp, y) \simeq R_G(x_\perp e^{-y})$$

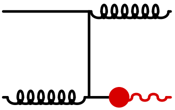
- At (very) backward rapidity

$$R_{pA}(p_\perp, y) \simeq R_{F_2}(x_\perp e^{-y})$$

Limitations (1): Fragmentation photons

Problem

Photons can also be produced by fragmentation



The collinear divergence of this diagram is absorbed into non-perturbative quantities: quark/gluon fragmentation functions into a (collinear) photon

The $q \to q\,\gamma$ splitting process yields large terms $\ln(Q/\Lambda_{\text{QCD}})$ making fragmentation functions into γ to be $\mathcal{O}\left(\alpha/\alpha_s\right)$

The above diagram actually is $\mathcal{O}\left(\alpha_s^2\right)\ D_{\gamma/k} = \mathcal{O}\left(\alpha\,\alpha_s\right) =$ LO !

Limitations (1): Fragmentation photons

Problem

Photons can also be produced by fragmentation

$$\frac{d^3\sigma^{\rm frag}(p\,A \to \gamma\,X)}{dy\ d^2p_\perp} \propto \int_0^1 dz \int_0^1 dv\ \ldots (x_\perp/z, Q^2)\ D_{\gamma/k}(z, Q^2)$$

The extra integration spoils the relationship $R_{pA} \Leftrightarrow R_{F_2}$ and R_G

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The extra integration spoils the relationship $R_{pA} \Leftrightarrow R_{F_2}$ and R_G

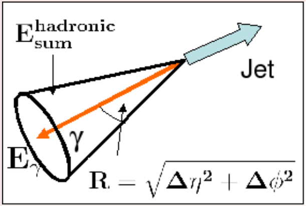
Solution

We get rid of (most of) them by means of isolation criteria

$$E^{\mathrm{had}} \leq E^{\mathrm{max}}$$

for particles in a cone

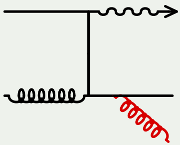
$$(\eta - \eta_\gamma)^2 + (\phi - \phi_\gamma)^2 \leq R^2$$



Limitations (2): NLO corrections

Problem

Next-to-leading order (NLO) corrections



3-body kinematics in the final state ⇒ needs to integrate over the momentum of the extra-particle radiated

Strategy

Let's compute $R_{pA}(x_\perp, y)$ at NLO and check the analytic estimate

Phenomenology

1. Checking the approximation

$R_{pA}(x_\perp, y)$ computed in p A collisions using NLO nDSg parton densities and compared to R_G

- At RHIC
  - $\sqrt{s_{\rm NN}} = 200$ GeV at $y = 3$
- At LHC
  - $\sqrt{s_{\rm NN}} = 8.8$ TeV at $y = 0$ and 2.5

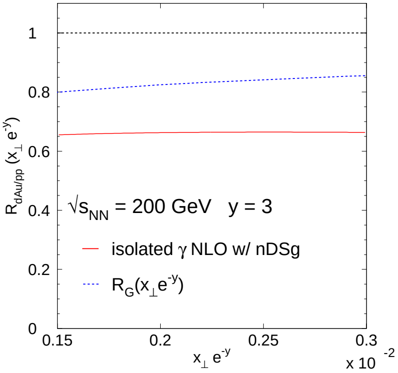
2. Comparing nPDFs

$R_{pA}(x_\perp, y)$ computed in p A collisions at RHIC and LHC

- In pQCD at NLO
  - using EKS, HKM, nDS, nDSg, EPS parton densities
- In the Colour Glass Condensate

Checking the approximation

RHIC at forward rapidity y=3



- Complete mismatch due to isospin effects

Isospin corrections

At large rapidity $x_1 \gg x_2$

Dominant channel $q_v(x_1)g(x_2) \to q_v\gamma$

$$\begin{aligned}
\sigma(dA \to \gamma \mathrm{X}) &\propto \left[\frac{4}{9}u^p(x_1) + \frac{1}{9}d^p(x_1) + \frac{4}{9}u^n(x_1) + \frac{1}{9}d^n(x_1)\right] g^A(x_2) \\
&\propto \left[\frac{4}{9}u^p(x_1) + \frac{1}{9}d^p(x_1) + \frac{4}{9}d^p(x_1) + \frac{1}{9}u^p(x_1)\right] g^A(x_2) \\
&\propto \left[\frac{5}{9}u^p(x_1) + \frac{5}{9}d^p(x_1)\right] g^A(x_2)
\end{aligned}$$

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\end{aligned}
$$

$$
\sigma(pp \to \gamma X) \propto \left[\frac{4}{9}u^p(x_1) + \frac{1}{9}d^p(x_1)\right] g^A(x_2)
$$

Isospin corrections

At large rapidity $x_1 \gg x_2$

Dominant channel $q_v(x_1)g(x_2) \to q_v\gamma$

$$R_{dA/pp} = \frac{5u(x_1) + 5d(x_1)}{8u(x_1) + 2d(x_1)} \times R_G$$

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2 simple cases

- $x_1 = \mathcal{O}\left(10^{-1}\right) \Rightarrow u(x_1) \simeq 2d(x_1)$

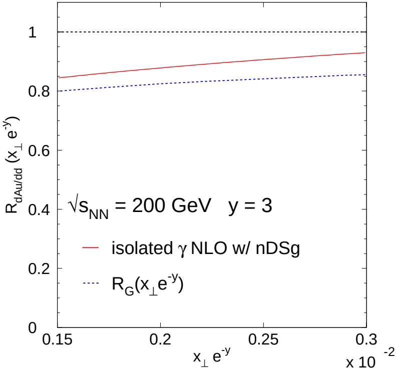
$$R_{dA/pp} = \frac{5}{6}\ R_G$$

- $x_1 = \mathcal{O}\left(1\right) \Rightarrow u(x_1) \gg d(x_1)$

$$R_{dA/pp} = \frac{5}{8}\ R_G$$

Checking the approximation

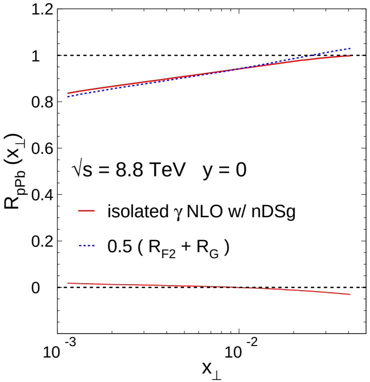
RHIC at forward rapidity y=3



- Fair matching ($\lesssim$ 10%) between R_{pA} and R_G, once corrected for isospin

Checking the approximation

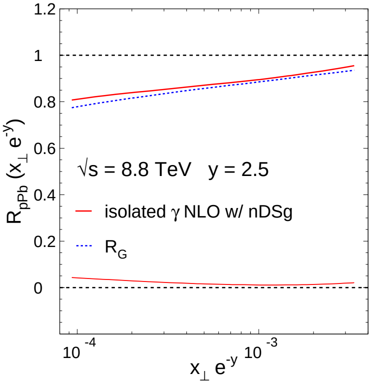
LHC at mid-rapidity



- 20% attenuation at $x_\perp \sim 10^{-3}$ measurable (statistically)
- perfect matching (< 2–3%) between R_{pA} and nuclear density ratios

Checking the approximation

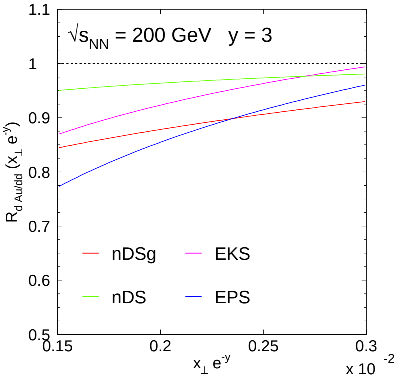
LHC at forward rapidity $y = 2.5$



- Gives “direct” access to R_G (within 5%) at $x = 10^{-4}–10^{-3}$!

Comparing nPDFs

At RHIC (y=3)



- Significant differences between the various nPDF sets

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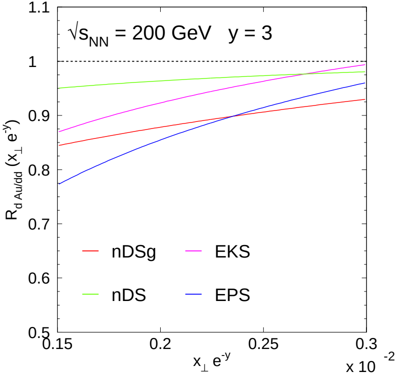
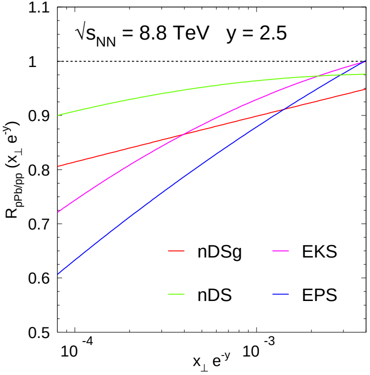


- To be compared with predictions within the CGC

Comparing nPDFs

At LHC (y=2.5)



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Shadowing without p p data

Problem

No p p collision at $\sqrt{s} = 8.8$ TeV

How to measure $R_G(x)$ without any p p reference data ?

Shadowing without p p data

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How to measure $R_G(x)$ without any p p reference data ?

Proposal

Compare forward w/ backward production in p A collisions

$$\frac{\mathrm{d}\sigma(p\ A \rightarrow\ \gamma(+y)\ \mathrm{X}\,)}{\mathrm{d}\sigma(p\ A \rightarrow\ \gamma(-y)\ \mathrm{X}\,)} = R_{pA}(x_\perp, +y)/R_{pA}(x_\perp, -y)$$

$$\simeq R_G(x_\perp e^{-y})/R_{F_2}(x_\perp e^{y})$$

Shadowing without p p data

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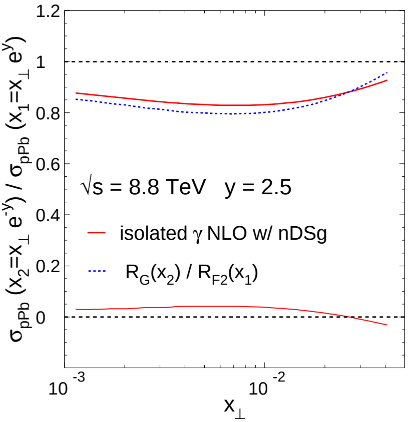
$$\simeq R_G(x_\perp e^{-y})/R_{F_2}(x_\perp e^{y})$$

R_{F_2} at large x gives access to R_G at small x !

Shadowing without p p data



- Encouraging yet a larger *y* would be better
- Need to correct for isospin effects

Counting rates

- LHC $\left(\mathcal{L} = 1.4\ 10^{30}\ \mathrm{cm}^{-2} s^{-1},\ \Delta t = 10^6 \mathrm{s}\right)$

$$\left.\frac{\mathrm{d}\sigma}{\mathrm{d}y\ \mathrm{d}p_\perp}\right|_{p_\perp = 100\ \mathrm{GeV}} \simeq\ 8\ 10^2\ \mathrm{pb/GeV}\ \Rightarrow\ \mathcal{N} \sim 10^3/\mathrm{GeV}$$

- RHIC $\left(\mathcal{L}_{\mathrm{int}} = 0.45\ \mathrm{pb}^{-1}\right)$

$$\left.\frac{\mathrm{d}\sigma}{\mathrm{d}y\ \mathrm{d}p_\perp}\right|_{p_\perp = 7\ \mathrm{GeV}} \simeq\ 8\ 10^3\ \mathrm{pb/GeV}\ \Rightarrow\ \mathcal{N} \sim 4\ 10^3/\mathrm{GeV}$$

[At RHIC-I, $\mathcal{L}_{\mathrm{int}} = 0.02\ \mathrm{pb}^{-1} \Rightarrow p_\perp \lesssim 5$ GeV]

Statistical accuracy in a year much better than the present spread of theoretical predictions for R_G at small x

Summary

- Essential to further constrain $G(x)$ at small x
  - needed for pQCD predictions at LHC
  - looking for saturation
- Prompt photon production in p A collisions
  - an ideal observable to probe parton densities
- Phenomenology at RHIC and LHC
  - reliable estimate of R_G from R_{pA} at forward rapidity
  - comparing the predictions in QCD using various sets (soon CGC)
  - extracting R_G witout p p data at the same energy

Outlook

Gluon densities in a proton usually given by

- Jets
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- (Drell-Yan)

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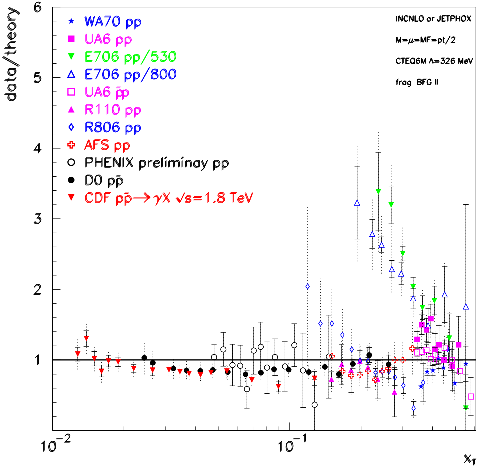

[Aurenche et al. 2006]

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Need to revive this signal and investigate similarly the contraints

given by photons in p p collisions at LHC