Photon and heavy-Quark jet production at the hadron collider

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The 36*th* Physics in Collision

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ICISE - Quy Nhon, September 16*th*, 2016

Outline

1. Overview
   - Aspects of interest
   - Goal of this research
   - Framework: JETPHOX
2. $\sigma(pp(\bar{p}) \to \gamma$+Q–jet + X)
   - Method
   - Results
3. Conclusion & Outlook

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- The p p collisions at the LHC open a new era in research on particle physics, also for QCD studies.

- So far $\Longrightarrow$ ATLAS and CMS have published σ(jets), $\sigma(t\bar{t}$+jets), $\sigma(\gamma$+jets), $\sigma(W(Z)$+jets), etc...

- Particularly, the cross sections involving prompt photon production
  $\Longrightarrow$ our interest.
  point-like electromagnetic coupling to the quark.
  $\Longrightarrow$ Clean process for testing QCD.

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Overview

Aspects of interest $\gamma + Q + X$

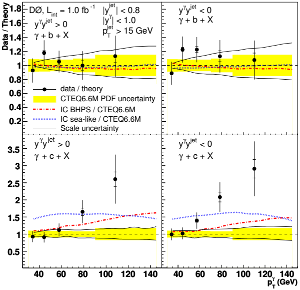
Status of $\sigma(\gamma + Q + X)$

Experimental side

- At the Tevatron, $\sqrt{s} = 1.96$ TeV $\Longrightarrow$precise measurements.
- At the LHC, $\sqrt{s} = 8,\ 13$ TeV...

Theoretical side

- NLO pQCD: invariant mass app. ($M > 4m_Q^2$ for $q\bar{q} \to \gamma Q\bar{Q}$.)
- Agreement with experiment for $\sigma(\gamma + b + X)$
- ✗ But not for $\sigma(\gamma + c + X)$.



The $\gamma + b(c) + X$ production: comparison between theoretical prediction (Owens *et. al.*) and experimental measurement. Taken from D0 Collaboration (2009).

Phys.Rev.Lett.102 (2009) 192002.

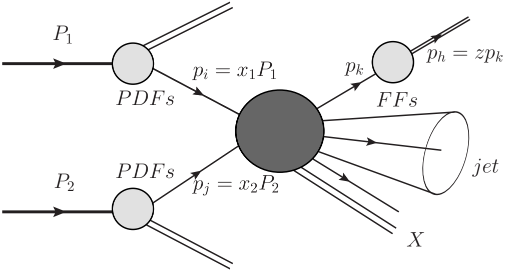
Overview

Goal of this research

Study the discrepancies between theory and data for $\sigma(\gamma + c + X)$.

Overview
Framework

Diagram illustrating the $pp(\bar{p}) \to \gamma$/hadron +jet + X process



To compare between theory and data:

$\Longrightarrow$need a suitable jet algorithm.

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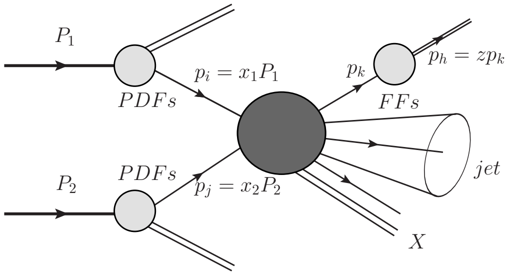
Diagram illustrating the $pp(\bar{p}) \to \gamma$/hadron +jet + X process



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Overview

Framework: JETPHOX

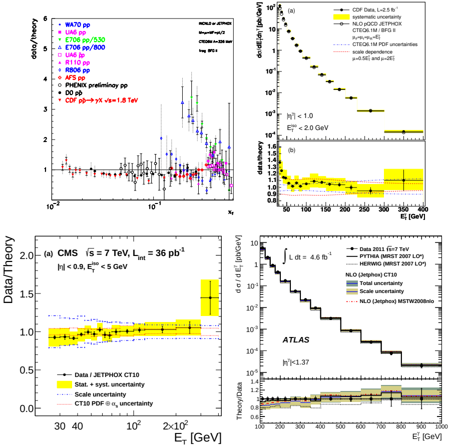
JETPHOX is a parton-level event NLO generator program:

- $hh \to \gamma$(hadron)+jet+X
- γ: direct(D) or fragmentation (F) from parton
  (already deal with the soft and collinear divergences.)
- Easily apply kinematical cuts from experiment: $p_\perp$, y, etc..

Overview

Framework: JETPHOX vs. data

JETPHOX NLO predictions using BFG II (CTEQ6/CT10) for FFs (PDFs)



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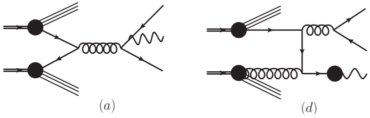
$\sigma(pp(\bar{p}) \to \gamma$+Q–jet + X)

Method

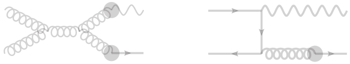
Study the discrepancies between theory and data for $\sigma(\gamma + c + X)$.

- Invariant mass approach
- Flavor-k_t approach
- Improve `JETPHOX` into `bJETPHOX`
- Charm-meson FFs approach. (using `DIPHOX`)

An example of the NLO processes:



and process with charm fragmentation:



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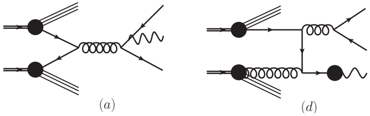

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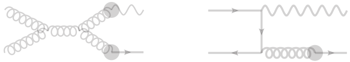

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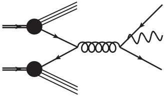
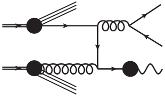
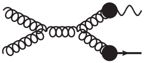


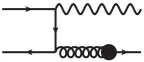
(a)



(d)

and process with charm fragmentation:



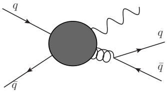


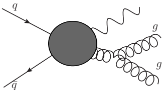
Invariant mass approach

Method

General jet

Consider $q\bar{q} \to \gamma q\bar{q}$, $q\bar{q} \to \gamma gg$





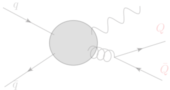
σ including divergence terms $\sim \frac{1}{\epsilon} P_{qg}(z)$, $\frac{1}{\epsilon} P_{gg}$,[a] they are canceled:

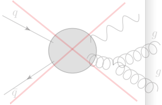
$$\int_0^1 dz\ z\ \left[2\ n_f\ P_{qg}(z) + P_{gg}(z)\right] = 0, \quad (1)$$

[a] $P_{ij}(z)$ are the DGLAP splitting functions.

Qflavor-jet

Select: $q\bar{q} \to \gamma Q\bar{Q}$, ~~$q\bar{q} \to \gamma gg$~~





Divergence term $\sim \frac{1}{\epsilon} P_{Qg}(z)$ remains.

$M^2_{\rm inv} > 4m^2_Q$ *Owens et.al.2009*
$\Leftrightarrow E^2_Q(1-\cos(\theta)) > m^2_Q$

$\Longrightarrow$ remove this divergence.

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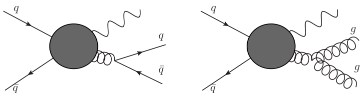

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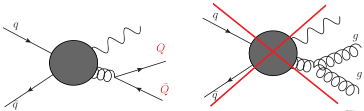

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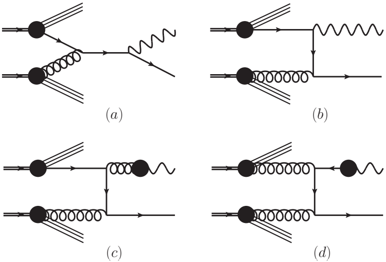
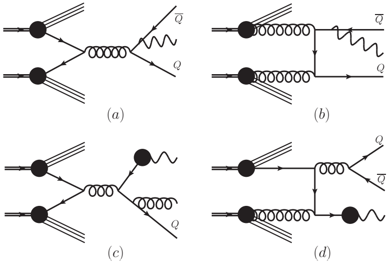
$\sigma(pp(\bar{p}) \to \gamma$+Q–jet + X)

Select partonic processes

An example of processes for $pp(\bar{p}) \to \gamma$+Q–jet + X





LO

NLO

(a,b) are (D) processes
(c,d) are (F) processes.

$\sigma(pp(\bar{p}) \to \gamma$+Q–jet + X)

Select partonic processes

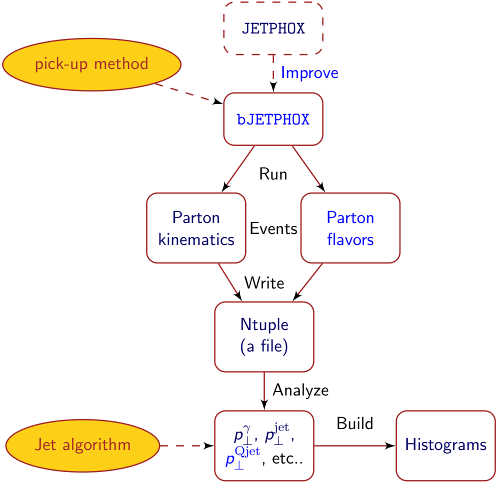
List of possible subprocesses for $pp(\bar{p}) \to \gamma$+Q–jet + X

LO	NLO
	$Qq \to Q\gamma q \quad (Q \leftrightarrow \bar{Q})$
	$Q\bar{q} \to Q\gamma\bar{q} \quad (Q \leftrightarrow \bar{Q})$
	$Q\bar{Q} \to Q\gamma\bar{Q}$
	$QQ \to Q\gamma Q \quad (Q \leftrightarrow \bar{Q})$
	$q\bar{q} \to Q\gamma\bar{Q}$
$Qg \to Q\gamma \quad (Q \leftrightarrow \bar{Q})$	$Qg \to Q\gamma g \quad (Q \leftrightarrow \bar{Q})$
	$gg \to Q\gamma\bar{Q}$

LO	NLO
$Qq \to Q\mathcal{D}_q^\gamma \quad (Q \leftrightarrow \bar{Q})$	$Qq \to Q\mathcal{D}_q^\gamma g/Q\mathcal{D}_g^\gamma q \quad (Q \leftrightarrow \bar{Q})$
$Q\bar{q} \to Q\mathcal{D}_{\bar{q}}^\gamma \quad (Q \leftrightarrow \bar{Q})$	$Q\bar{q} \to Q\mathcal{D}_{\bar{q}}^\gamma g/Q\mathcal{D}_g^\gamma \bar{q} \quad (Q \leftrightarrow \bar{Q})$
$QQ \to Q\mathcal{D}_Q^\gamma \quad (Q \leftrightarrow \bar{Q})$	$QQ \to Q\mathcal{D}_Q^\gamma g/Q\mathcal{D}_g^\gamma Q \quad (Q \leftrightarrow \bar{Q})$
$Q\bar{Q} \to Q\mathcal{D}_{\bar{Q}}^\gamma/Q\mathcal{D}_{\bar{Q}}^\gamma$	$Q\bar{Q} \to Q\mathcal{D}_{\bar{Q}}^\gamma g/Q\mathcal{D}_g^\gamma \bar{Q}/Q\mathcal{D}_{\bar{Q}}^\gamma g$
$q\bar{q} \to Q\mathcal{D}_{\bar{Q}}^\gamma/Q\mathcal{D}_{\bar{Q}}^\gamma$	$q\bar{q} \to Q\mathcal{D}_{\bar{Q}}^\gamma g/Q\mathcal{D}_g^\gamma \bar{Q}/Q\mathcal{D}_{\bar{Q}}^\gamma g$
$Qg \to Q\mathcal{D}_g^\gamma \quad (Q \leftrightarrow \bar{Q})$	$Qg \to Q\mathcal{D}_{\bar{q}}^\gamma q/Q\mathcal{D}_q^\gamma \bar{q}/Q\mathcal{D}_g^\gamma g \quad (Q \leftrightarrow \bar{Q})$
	$Qg \to Q\mathcal{D}_{\bar{Q}}^\gamma Q/Q\mathcal{D}_Q^\gamma \bar{Q} \quad (Q \leftrightarrow \bar{Q})$
	$qg \to Q\mathcal{D}_{\bar{Q}}^\gamma q/\bar{Q}\mathcal{D}_Q^\gamma q/Q\mathcal{D}_q^\gamma \bar{Q}$
	$\bar{q}g \to Q\mathcal{D}_{\bar{Q}}^\gamma \bar{q}/\bar{Q}\mathcal{D}_Q^\gamma \bar{q}/Q\mathcal{D}_{\bar{q}}^\gamma \bar{Q}$
$gg \to Q\mathcal{D}_{\bar{Q}}^\gamma/\bar{Q}\mathcal{D}_Q^\gamma$	$gg \to Q\mathcal{D}_{\bar{Q}}^\gamma g/\bar{Q}\mathcal{D}_Q^\gamma g/Q\mathcal{D}_g^\gamma \bar{Q}$

$\sigma(pp(\bar{p}) \to \gamma$+Q–jet + X)

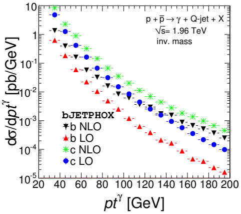
bJETPHOX

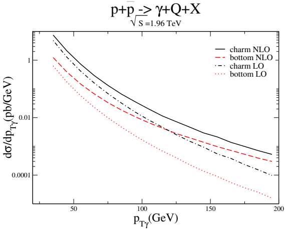


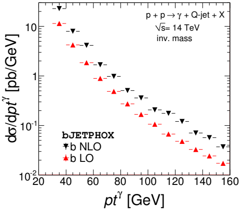
Invariant mass approach

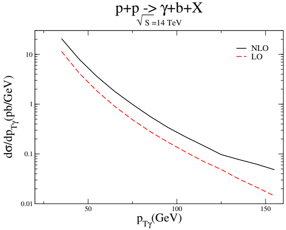
Results: A good agreement

Left: bJETPHOX simulation. Right: Previous results [*Owens et.al.(2009)*].









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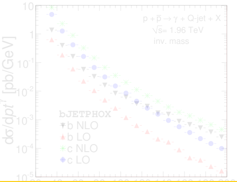
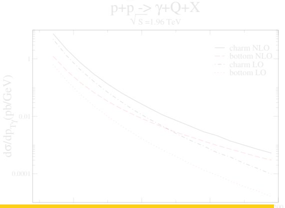
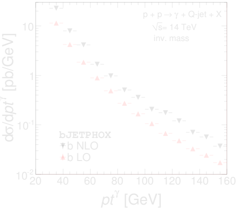
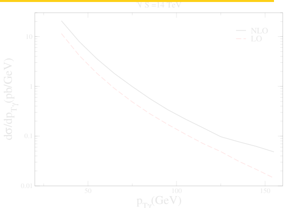




$\Longrightarrow$ This checks our calculation.





Flavor-k_t approach

Method: net flavor

To study b-jets $\Longrightarrow$ assign flavor-value $1(-1)$ to $b(\bar{b})$, 0 to others.

1. $\mathrm{net}^{\mathrm{jet}} = 1(-1) \Longrightarrow$ b-flavor jet.
2. $\mathrm{net}^{\mathrm{jet}} = 0 \Longrightarrow$ b-flavorless jet.

   $\Longrightarrow$ avoid collinearity problem
3. The jet which has the net flavor greater than one unit cannot be identified with a single QCD parton.[1]

[1] This is not the case for the present NLO calculations.

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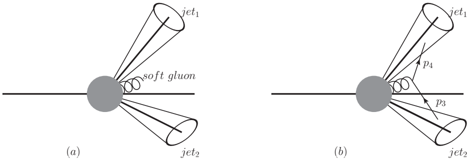
flavor unsafety taken care by flavor-kt algorithm



An example soft-$g \to q(4)\ \bar{q}(3)$ which are added to the jet 1 and 2, respectively.

Flavor-k_t approach

Method: flavor-k_t algorithm

1. Define the distance measure d_{12} between parton 1 and 2:

$$d_{12} = (\Delta y_{12}^2 + \Delta\phi_{12}^2) \times \begin{cases} \max(p_{\perp 1}^2, p_{\perp 2}^2) & \text{if softer is flavored,} \\ \min(p_{\perp 1}^2, p_{\perp 2}^2) & \text{if softer is flavorless.} \end{cases} \quad (2)$$

$$d_{iB(\bar{B})} = \begin{cases} \max(p_{\perp i}^2, p_{\perp B(\bar{B})}^2(y_i)) & \text{if softer is flavored,} \\ \min(p_{\perp i}^2, p_{\perp B(\bar{B})}^2(y_i)) & \text{if softer flavorless} \end{cases} \quad (3)$$

where $p_{\perp B(\bar{B})}(y)$ is given in *Banfi et. al. (2006)*

Eur.Phys.J. C47(2006)113-124.

2. Find $\min(d_{12},\ d_{iB(\bar{B})})$.
   If d_{12} is the smallest: merge $p_1,\ p_2 \Longrightarrow$ a jet.
3. Otherwise: $p_1,\ p_2 \Longrightarrow$ 2 different jets.

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Notice:

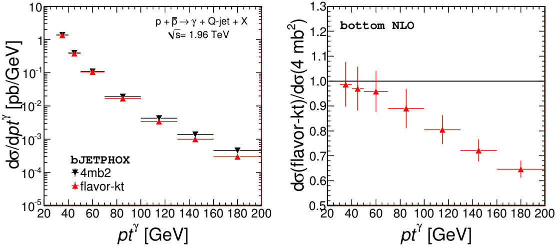
it is required to know

if the cluster heavy-flavor or heavy-flavorless!

Flavor-k_t approach

Results: vs. int. mass approach

$d\sigma/dp_\perp^\gamma$ in p–$\bar{p}$ collisions at the Tevatron, $\sqrt{s} = 1.96$ TeV

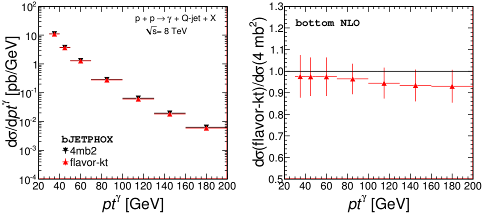


Due to high probability to find $q\bar{q}$ in p–$\bar{p}$ (valence–valence)

Flavor-k_t approach

Results: vs. int. mass approach

$d\sigma/dp_\perp^\gamma$ in p–p collisions at the LHC, $\sqrt{s} = 8$ TeV

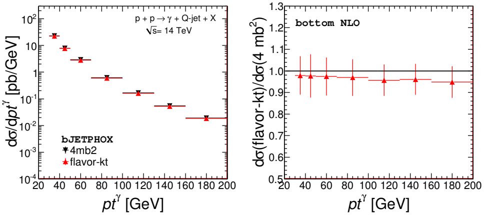


Due to lower probability to find $q\bar{q}$ in p–p (valence–sea)

Flavor-k_t approach

Results: vs. int. mass approach

$d\sigma/dp_\perp^\gamma$ in p–p collisions at the LHC, $\sqrt{s} = 14$ TeV



And due to $\sqrt{s}$ increases $\Leftrightarrow$ x decreases: g-PDF significant increases.

Charm-meson FF approach

Method

General jet

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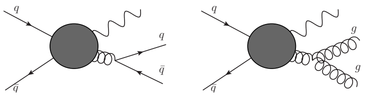

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$$\int_0^1 dz\ z\ \left[2\ n_f\ P_{qg}(z) + P_{gg}(z)\right] = 0, \quad (3)$$

[a] $P_{ij}(z)$ are the DGLAP splitting functions.

Qflavor-jet

Select: $q\bar{q} \to \gamma Q\bar{Q}$, $q\bar{q} \to \gamma gg$

then, divergence term $\sim \frac{1}{\epsilon} P_{Qg}(z)$ remains.

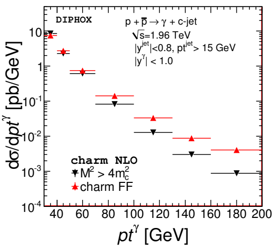
Assumption:
absorb the divergence in the charm(-meson) FF,

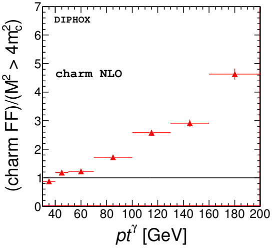
$\Longrightarrow$ remove this divergence.

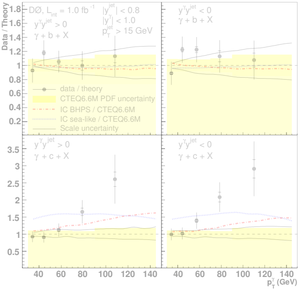
Charm-meson FF approach

Results: vs. int. mass approach.

$d\sigma/dp_\perp^\gamma$ in p–$\bar{p}$ collisions $\sqrt{s} = 1.96$ TeV.







a possible LO subprocesses for charm-meson FF approach:
$qg \to q\gamma$: only $c(\bar{c})g \to \gamma c(\bar{c})$ contributes to inv. mass approach
$q\bar{q} \to \gamma g$: does not contribute to previous approaches.

Charm-meson FF approach

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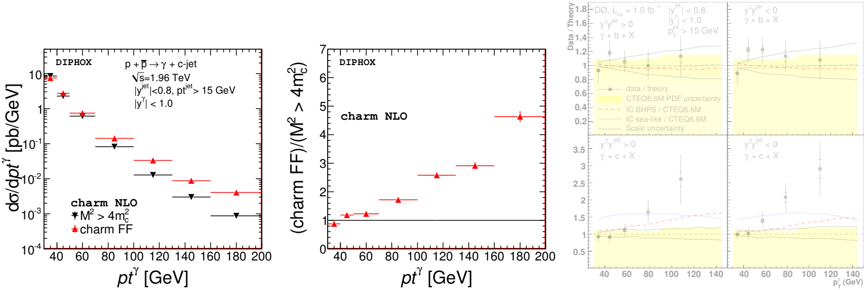

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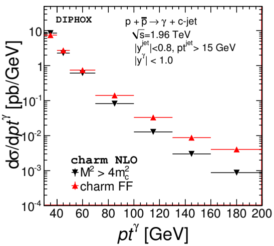
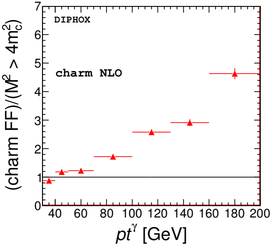
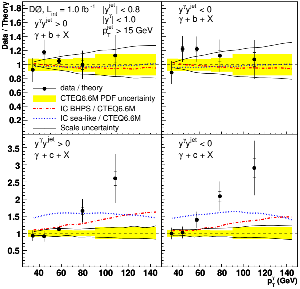




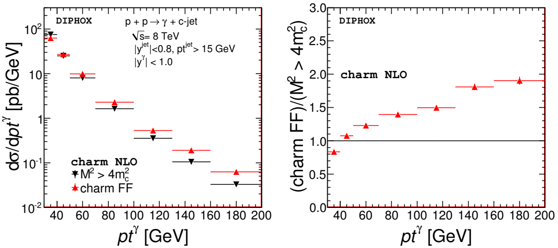


$\Longrightarrow$charm–meson FF approach gives a prediction behaving the same way as data measurement.

Charm-meson FF approach

Results: vs. int. mass approach.

$d\sigma/dp_\perp^\gamma$ in p–p collisions $\sqrt{s} = 8$ TeV.

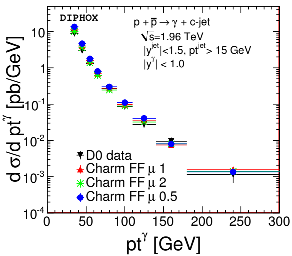


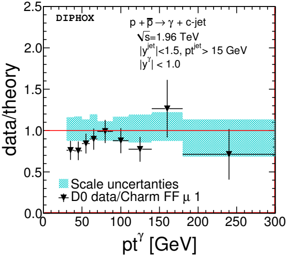
$$\frac{\text{charm} - \text{mesonFF}}{M^2 > 4m_c^2} \sim \frac{\sigma(qg \to q\gamma) + \sigma(q\bar{q} \to \gamma g)}{\sigma(cg \to c\gamma)}$$

Charm-meson FF approach

Results: vs. data at the Tevatron

$d\sigma/dp_\perp^\gamma$ in p–$\bar{p}$ collisions $\sqrt{s} = 1.96$ TeV. DIPHOX: assume $p^D_{\perp\min} \approx p^{\mathrm{c-jet}}_{\perp\min}$.
$p_\perp^{\mathrm{c-jet}} > 15$ GeV



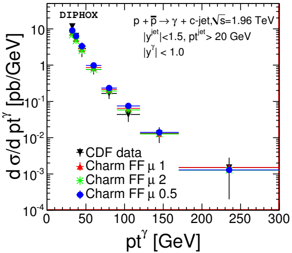


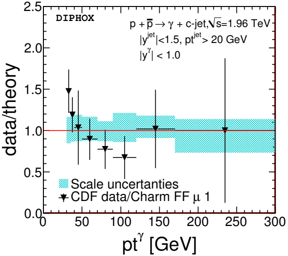
The data is taken from D0 Collaboration (2013) [Phys.Lett.B719(2013)354--361].

Charm-meson FF approach

Results: vs. data at the Tevatron

$d\sigma/dp_\perp^\gamma$ in p–$\bar{p}$ collisions $\sqrt{s} = 1.96$ TeV. DIPHOX: assume $p^D_{\perp\min} \approx p^{\mathrm{c-jet}}_{\perp\min}$. $p_\perp^{\mathrm{c-jet}} > 20$ GeV.



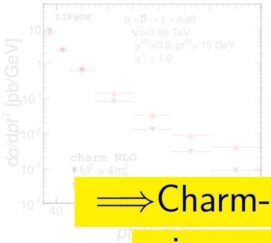


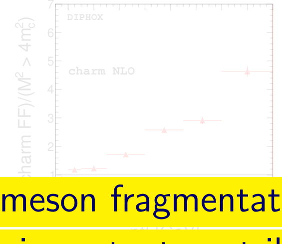
The data is taken from CDF Collaboration (2013) [Phys.Rev.Lett.111(2013)042003].

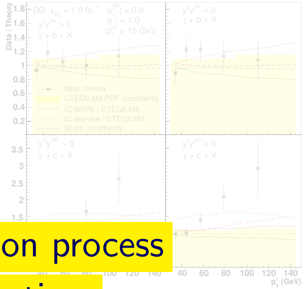
$\sigma(pp(\bar{p}) \to \gamma$+Q–jet + X)

Results – The discrepancy is understood.

$d\sigma/dp_\perp^\gamma$ in p–$\bar{p}$ collisions $\sqrt{s} = 1.96$ TeV.

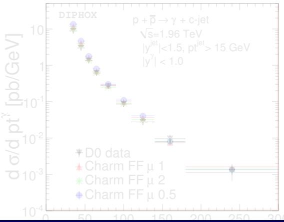


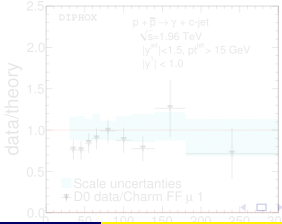


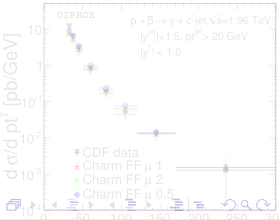


$\Longrightarrow$Charm-meson fragmentation process

gives an important contribution.







Outline

1. Overview
   - Aspects of interest
   - Goal of this research
   - Framework: JETPHOX
2. $\sigma(pp(\bar{p}) \to \gamma$+Q–jet + X)
   - Method
   - Results
3. Conclusion & Outlook

Conclusion & Outlook

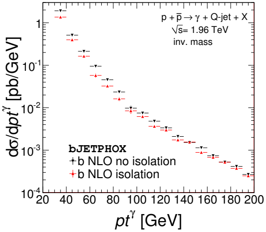
- Conclusion
  - Using the same jet definition, we obtain a good agreement with previous calculation.
  - The predictions using flavor-k_t algorithm are performed.
  - Our prediction, using charm-meson FF approach, agree well with p–$\bar{p}$ data at the Tevatron, $\sqrt{s} = 1.96$ TeV.
    $\Longrightarrow$ The mentioned discrepancy results from the missing of the fragmented heavy-quark process.
- Outlook
  - We hope to have experimental results γB, γD, also $\gamma + Q$jet at LHC
  - To make the reliable comparision betweent experiment and theory, we need to discuss precisely on kinematics, cutoff, how Qjet is defined...

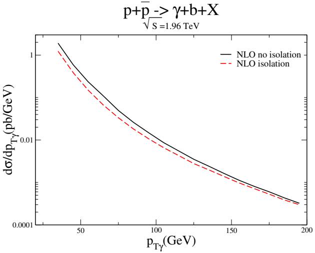
Thank you

Invariant mass approach

Results: Isolation test

Non-isolation (black curve)
Isolation (red curve): $E_t^{\mathrm{h}} < \epsilon E_t^{\gamma}$ within cone $R_{\mathrm{iso}} = 0.4$ around γ, $\epsilon = 0.04$





$\Longrightarrow$ Fragmented γ significantly suppressed at large $p_\perp^\gamma$.

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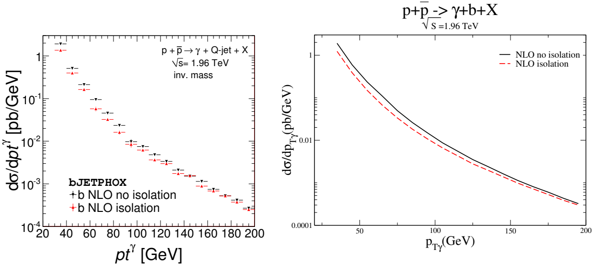

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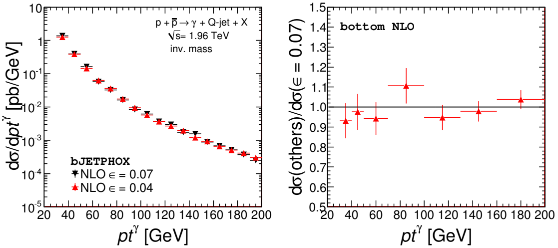

$\Longrightarrow$ Fragmented γ suppressed with $\epsilon = 0.07$.[1]

[1]For D0 (2009): $R_1 < 0.2$, $\epsilon_1 < 0.04$ and $R_1 < 0.4$, $\epsilon_1 < 0.07$.

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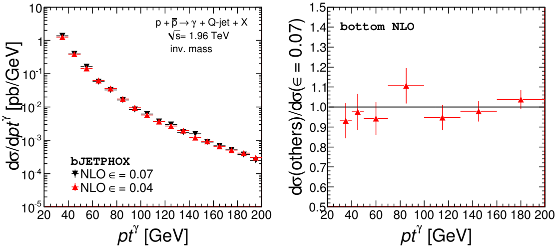

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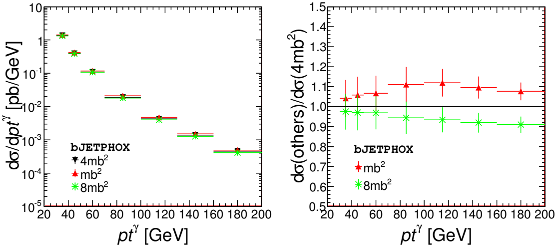
Invariant mass approach

Results: $M^2_{\rm inv} \gtrsim m^2_Q$ test

Isolation parameters: $E_t^{\rm h} < \epsilon E_t^\gamma$ within cone $R_{\rm iso} = 0.4$ around γ, $\epsilon = 0.04$

$d\sigma/dp_\perp^\gamma$ at the Tevatron ($\sqrt{s} = 1.96$ TeV)
for vaious $M^2_{\rm inv}$ cuts: m_b^2, $4m_b^2$, or $8m_b^2$.



$\Longrightarrow$ The effect of $M^2_{\rm inv}$ cut is small.

Invariant mass approach

Results: $M^2_{\rm inv} \gtrsim m_Q^2$ test

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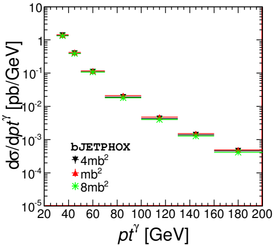

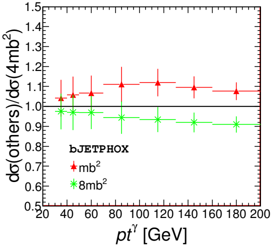

$\Longrightarrow$ The effect of $M^2_{\rm inv}$ cut is small.

Flavor-k_t approach

Method: net flavor

To study b-jets $\Longrightarrow$ assign flavor-value $1(-1)$ to $b(\bar{b})$, 0 to others.

1. $\mathrm{net}^{\mathrm{jet}} = 1(-1) \Longrightarrow$ b-flavor jet.
2. $\mathrm{net}^{\mathrm{jet}} = 0 \Longrightarrow$ b-flavorless jet.

   $\Longrightarrow$ avoid collinearity problem

3. The jet which has the net flavor greater than one unit cannot be identified with a single QCD parton.[2]

[2] This is not the case for the present NLO calculations.

Flavor-k_t approach

Method: net flavor

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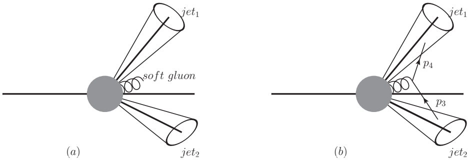
A problem: flavor unsafety



An example soft-$g \to q(4)\ \bar{q}(3)$ which are added to the jet 1 and 2, respectively.

Flavor-k_t approach

Method: net flavor

How to solve

Matrix elements $g \to q\bar{q}$, $q \to gq$:

$$|\mathcal{M}_{g_k \to q_i q_j}|^2 \sim \alpha_S \frac{dE_i}{E_j} \frac{d\theta_{ij}^2}{\theta_{ij}^2}, \quad (\theta_{ij} \ll 1,\ E_i \ll E_j.) \tag{4}$$

No soft quark divergence

(But the collinearity divergence of the two partons.)

A softer is b-quark$\Longrightarrow$ modify d_{12}:

$$\min(p_{\perp 1}^2, p_{\perp 2}^2) \longrightarrow \max(p_{\perp 1}^2, p_{\perp 2}^2) \tag{5}$$

Flavor-k_t approach

Method: flavor-k_t algorithm

1. Define the distance measure d_{12} between parton 1 and 2:

$$d_{12} = (\Delta y_{12}^2 + \Delta\phi_{12}^2) \times \begin{cases} \max(p_{\perp 1}^2, p_{\perp 2}^2) & \text{if softer is flavored,} \\ \min(p_{\perp 1}^2, p_{\perp 2}^2) & \text{if softer is flavorless.} \end{cases} \quad (6)$$

$$d_{iB(\bar{B})} = \begin{cases} \max(p_{\perp i}^2, p_{\perp B(\bar{B})}^2(y_i)) & \text{if softer is flavored,} \\ \min(p_{\perp i}^2, p_{\perp B(\bar{B})}^2(y_i)) & \text{if softer flavorless} \end{cases} \quad (7)$$

where $p_{\perp B(\bar{B})}(y)$ is given in *Banfi et. al. (2006)*

Eur.Phys.J. C47(2006)113-124.

2. Find $\min(d_{12},\ d_{iB(\bar{B})})$.
   If d_{12} is the smallest: merge $p_1,\ p_2 \Longrightarrow$ a jet.

3. Otherwise: $p_1,\ p_2 \Longrightarrow$ 2 different jets.

Flavor-k_t approach

Method: flavor-k_t algorithm

1. Define the distance measure d_{12} between parton 1 and 2:

$$d_{12} = (\Delta y_{12}^2 + \Delta\phi_{12}^2) \times \begin{cases} \max(p_{\perp 1}^2, p_{\perp 2}^2) & \text{if softer is flavored,} \\ \min(p_{\perp 1}^2, p_{\perp 2}^2) & \text{if softer is flavorless.} \end{cases} \tag{6}$$

Notice:

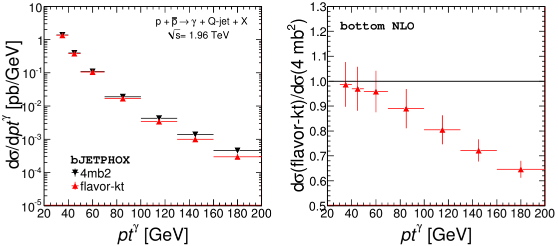
it is required to know

if the cluster heavy-flavor or heavy-flavorless!

Flavor-k_t approach

Results: vs. int. mass approach

$d\sigma/dp_\perp^\gamma$ in p–$\bar{p}$ collisions at the Tevatron, $\sqrt{s} = 1.96$ TeV



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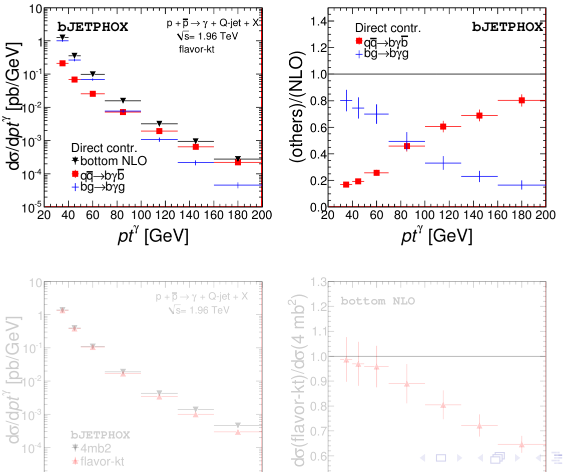

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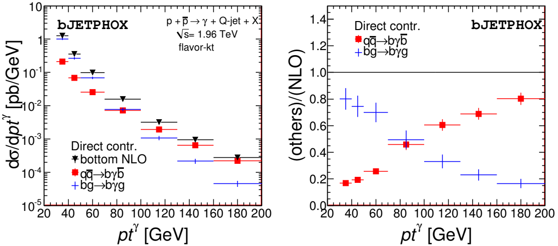
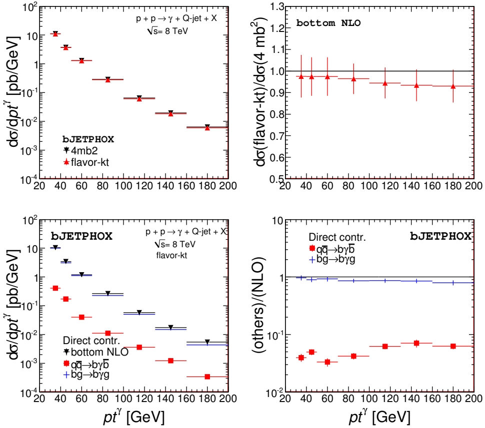


Due to high probability to find $q\bar{q}$ in p–$\bar{p}$ (valence–valence)

Flavor-k_t approach

Results: vs. int. mass approach

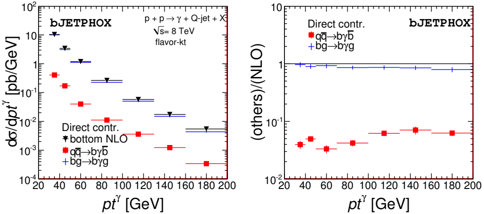
$d\sigma/dp_\perp^\gamma$ in p–p collisions at the LHC, $\sqrt{s} = 8$ TeV



Flavor-k_t approach

Results: vs. int. mass approach

$d\sigma/dp_\perp^\gamma$ in p–p collisions at the LHC, $\sqrt{s} = 8$ TeV

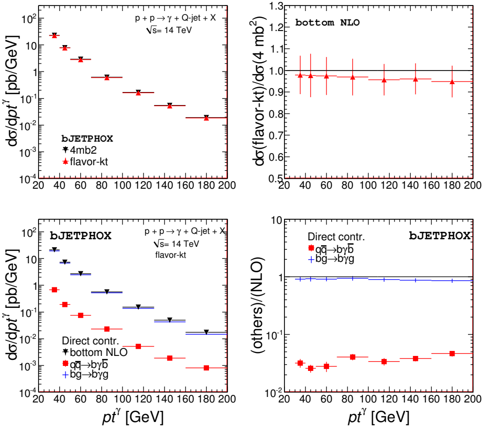


Due to lower probability to find $q\bar{q}$ in p–p (valence–sea) and $\sqrt{s}$ increases $\Leftrightarrow$ x decreases: g-PDF significant increases.

Flavor-k_t approach

Results: vs. int. mass approach

$d\sigma/dp_\perp^\gamma$ in p–p collisions at the LHC, $\sqrt{s} = 14$ TeV

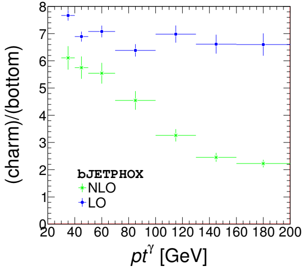


Flavor-k_t approach

Results: charm/bottom

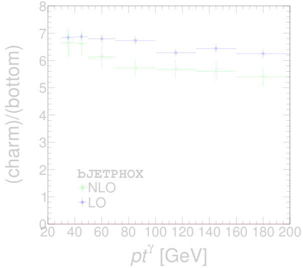
$d\sigma/dp_\perp^\gamma$

p–$\bar{p}$, $\sqrt{s} = 1.96$ TeV



LO: $Qg \to \gamma Q$ only
$e_c^2/e_b^2 \sim 4$
c-PDF/b-PDF is round 2 (at x ~ 0.2).

p–p, $\sqrt{s} = 8$ TeV



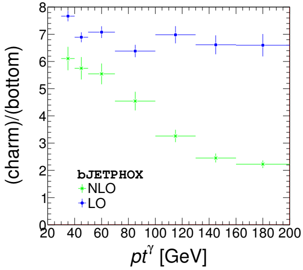
$Qg \to \gamma Qg$ dominates at whole possible range of $p_\perp^\gamma$
(As already discussed.)

Flavor-k_t approach

Results: charm/bottom

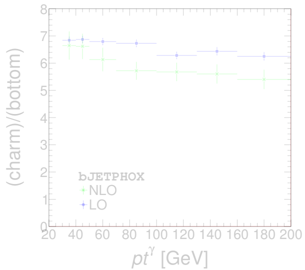
$d\sigma/dp_\perp^\gamma$

p–$\bar{p}$, $\sqrt{s} = 1.96$ TeV



$Qg \to \gamma Qg$ dominates at low $p_\perp^\gamma$
$q\bar{q} \to \gamma Q\bar{Q}$ dominates at large $p_\perp^\gamma$
(As already discussed.)

p–p, $\sqrt{s} = 8$ TeV



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Flavor-k_t approach

Results: charm/bottom

$d\sigma/dp_\perp^\gamma$

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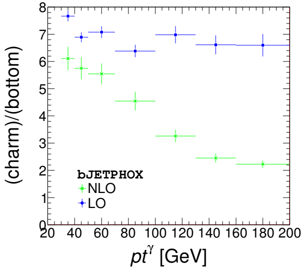

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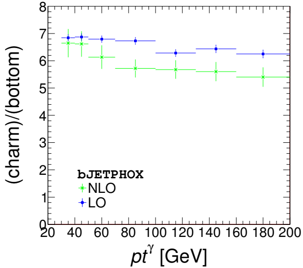

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