ICPPA 2020 MEPHI

PRODUCTION OF DIJETS WITH LARGE RAPIDITY SEPARATION AT COLLIDERS

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MOTIVATION

ENERGY FLOW AND JET VETO

- Many signals of new physics is observed via hadronic jets

- Multiple soft gluon emission can transfer the energy or transverse momentum away from hard jets (ENERGY FLOW)

- It is not possible to forbid very soft real QCD emission as well as virtual QCD corrections experimentally

- Various Veto conditions are introduced experimentally (JET VETO)

- Our aim is to calculate the effect of JET VETO

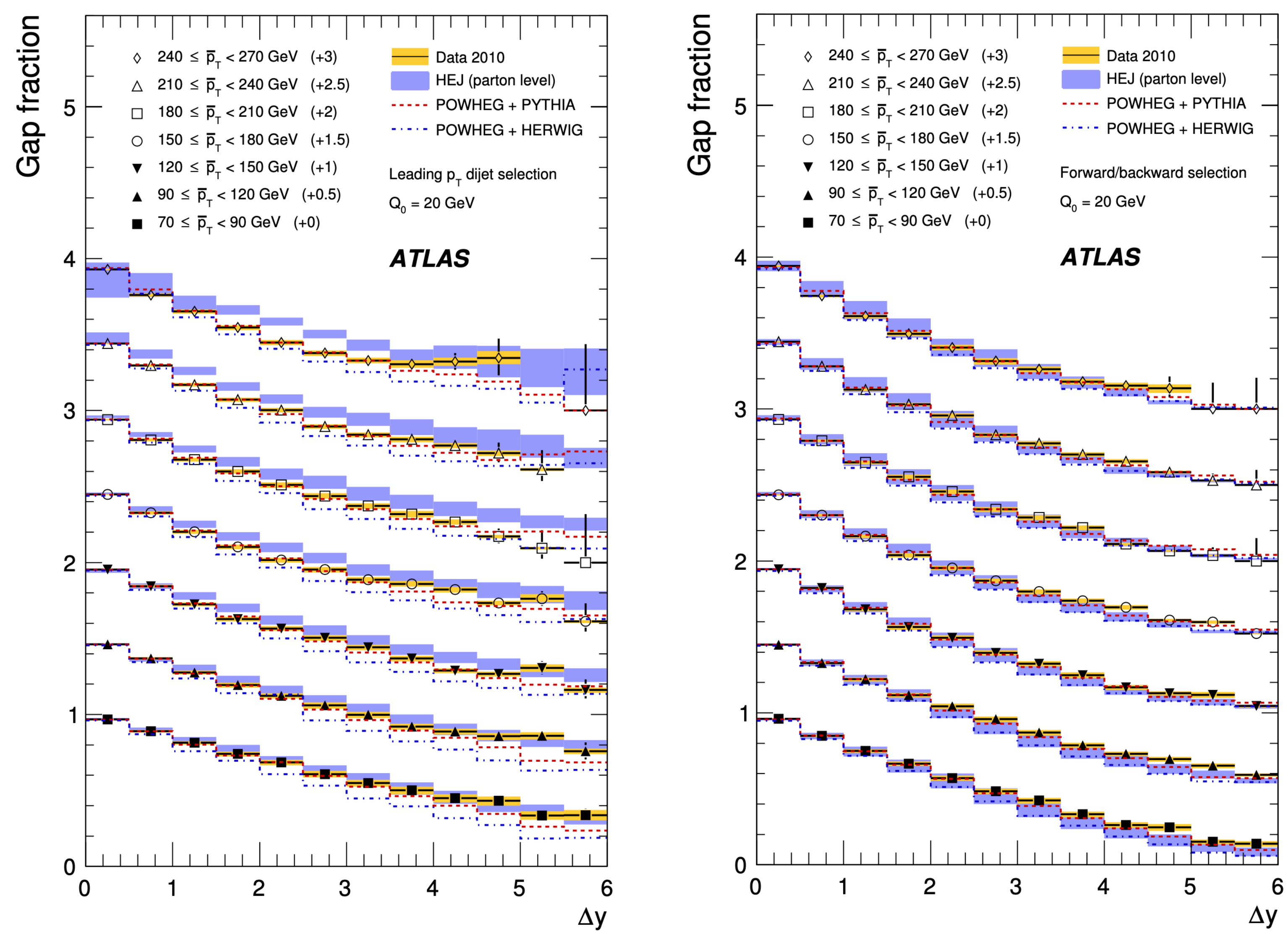
INTERJET VETO

SEARCH FOR THE BALITSKY-FADIN-KURAEV-LIPATOV (BFKL) EFFECTS IN THE ATLAS EXPERIMENT

G.Aad et al. (ATLAS Collaboration) J. High Energy Phys. 09(2011)053

$$\mathscr{R}(\Delta y, \overline{p_T}) = \frac{d\sigma^{dijet\ veto}/d\Delta y d^2\overline{p_T}}{d\sigma^{dijet}/d\Delta y d^2\overline{p_T}}$$

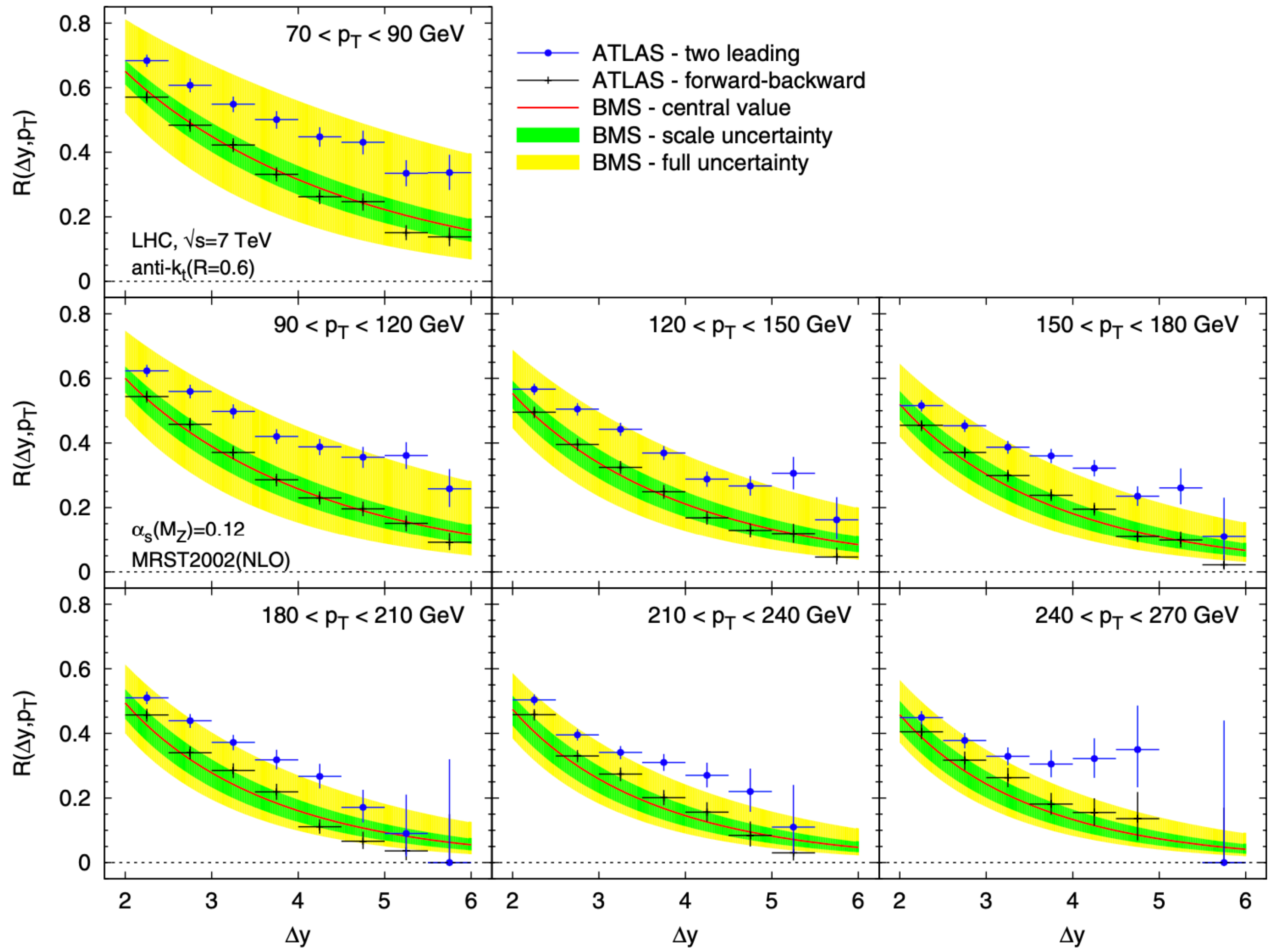
- pp at 7 TeV
- two selection types:
    - Leading p_T dijet
    - Forward/Backward dijet
- $70 < \overline{p_T} < 270$ GeV
- $\Delta y = |y_1 - y_2| < 6$
- Veto $Q = 20$ GeV between jets



APPROACH OF BMS

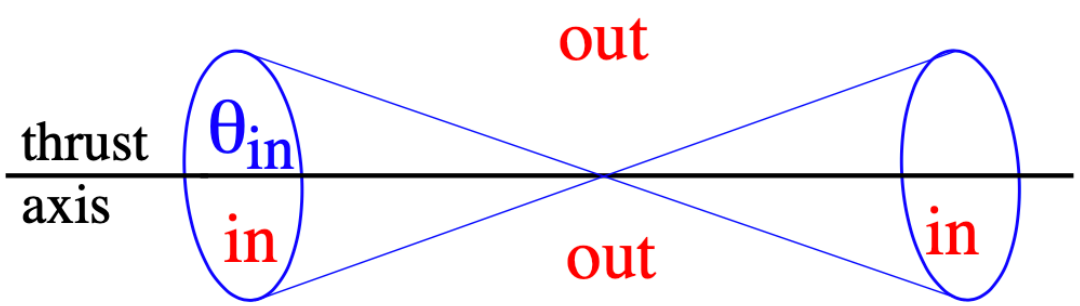
BANFI-MARCHESINI-SMYE (BMS) *JHEP* 08(2002)006

Y.Hatta et al. Phys. Rev. D 87, 054016 (2013)



BMS EQUATION

BANFI-MARCHESINI-SMYE (BMS) *JHEP* 08 (2002) 006



$$\Sigma_{out}(Q, E_{out}) = \sum_n \int \frac{d\sigma_n}{\sigma_T} \Theta\left(E_{out} - \sum_{out} q_{ti}\right)$$

Soft gluon approximation, large N_c, energy ordering;

Large angle emission, Sudakov and non-global logarithms;

$$\partial_\tau \Sigma_{ab}(\tau) = -(\partial_\tau R_{ab})\Sigma_{ab} + \int_{in} \frac{d\Omega_q}{4\pi} w_{ab}(q)[\Sigma_{aq}(\tau)\Sigma_{qb}(\tau) - \Sigma_{ab}(\tau)]$$

$$\tau = \int_{Q_0}^{Q} \frac{dq_t}{q_t} \bar{\alpha}_s(q_t); \qquad Q_0 = E_{out}; \qquad \bar{\alpha}_s = \frac{N_c \alpha_s}{\pi} = \frac{C_A \alpha_s}{\pi}$$

$$R_{ab}(\tau) = \int_{E_{out}}^{Q} \frac{dq_t}{q_t} \bar{\alpha}_s(q_t) \int_{out} \frac{d\Omega_q}{4\pi} w_{ab}(q) \approx \tau f_{ab}; \qquad w_{ab}(q) = \frac{1 - \cos\theta_{ab}}{(1 - \cos\theta_{aq})(1 - \cos\theta_{qb})}$$

RATIOS OF X-SECTIONS

VETO TO INCLUSIVE

$$\mathcal{R}(\Delta y, p_T) = \frac{d\sigma^{veto}/d\Delta y d^2 p_T}{d\sigma^{incl}/d\Delta y d^2 p_T}$$

inclusive x-section:

$$\frac{d\sigma^{incl}}{d\Delta y d^2 p_T} = \sum_{ij}^{q,\bar{q},g} \int_{Y_{min}(p_T,\Delta y)}^{Y_{max}(p_T,\Delta y)} dY x_1 f_i(x_1, p_T) x_2 f_j(x_2, p_T) \frac{1}{\pi} \frac{d\hat{\sigma}_{ij}}{d\hat{t}}$$

qq′ scattering with one gluon exchange

$$\frac{d\hat{\sigma}_{qq'}}{d\hat{t}} = \frac{1}{16\pi\hat{s}^2} h^A(\hat{s}, \hat{t}, \hat{u}) \qquad h^A(s,t,u) = g^4 \frac{C_F}{N_c} \left(\frac{s^2 + u^2}{t^2} \right)$$

if consider only $\Delta y > 0$

$$\frac{d\hat{\sigma}_{qq'}}{d\hat{t}} = \frac{1}{16\pi\hat{s}^2} (h^A(\hat{s}, \hat{t}, \hat{u}) + h^A(\hat{s}, \hat{u}, \hat{t}))$$

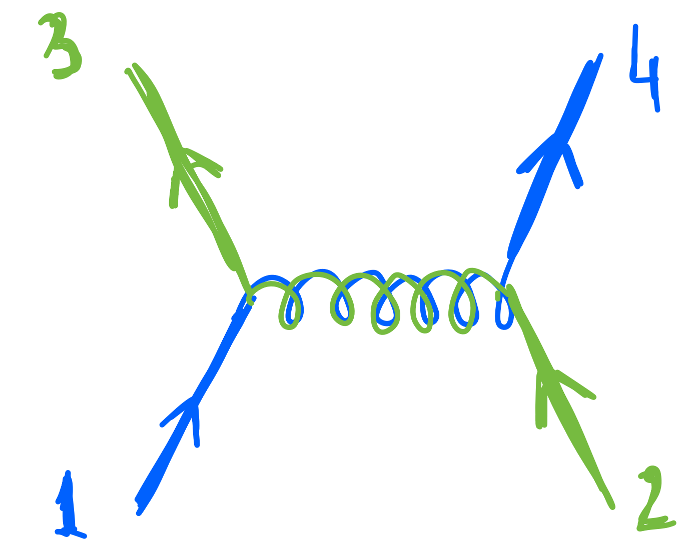
INTERJET VETO

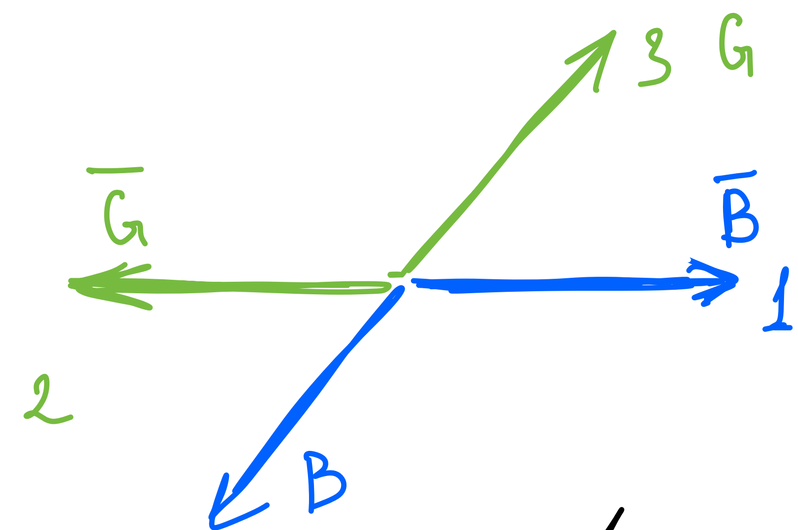
$$\frac{d\sigma^{veto}}{d\Delta y d^2 p_T} = \sum_{ij}^{q,\bar{q},g} \int_{Y_{min}(p_T,\Delta y)}^{Y_{max}(p_T,\Delta y)} dY x_1 f_i(x_1, p_T) x_2 f_j(x_2, p_T) \frac{1}{\pi} \frac{d\hat{\sigma}_{ij}^{veto}}{d\hat{t}}$$

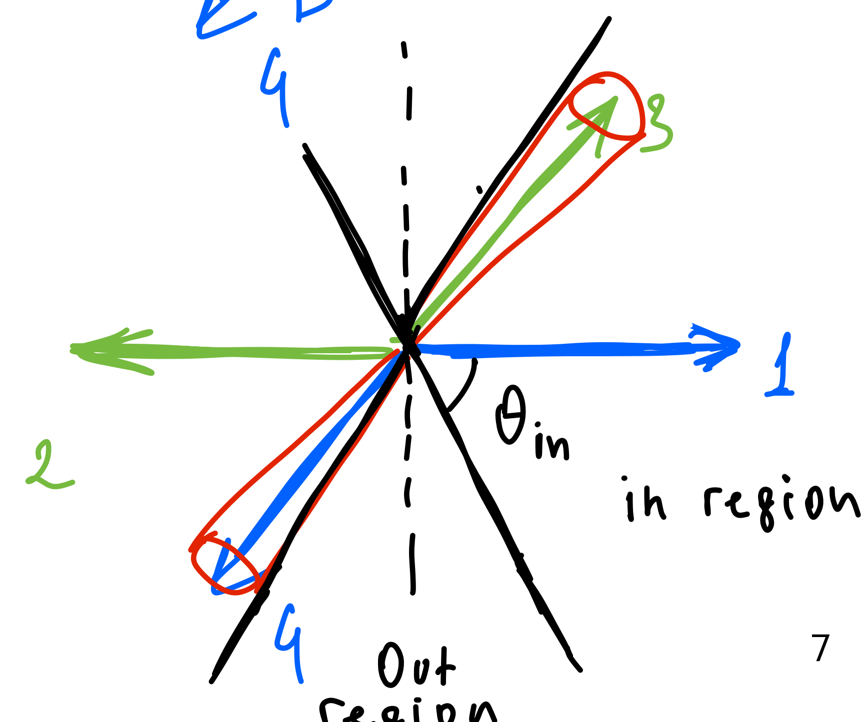
at large N_c limit, and in one-gluon exchange, color flows as $1 \rightarrow 4$ and $2 \rightarrow 3$

$$\frac{d\hat{\sigma}_{qq'}^{veto}}{d\hat{t}} = \frac{1}{16\pi\hat{s}^2}(h^A(\hat{s},\hat{t},\hat{u})\Sigma_{14}\Sigma_{23} + h^A(\hat{s},\hat{u},\hat{t})\Sigma_{13}\Sigma_{24})$$

$$y_{in} = \frac{\Delta y}{2} - R_{jet} \qquad y_{in} = -\log\tan\left(\frac{\theta_{in}}{2}\right)$$



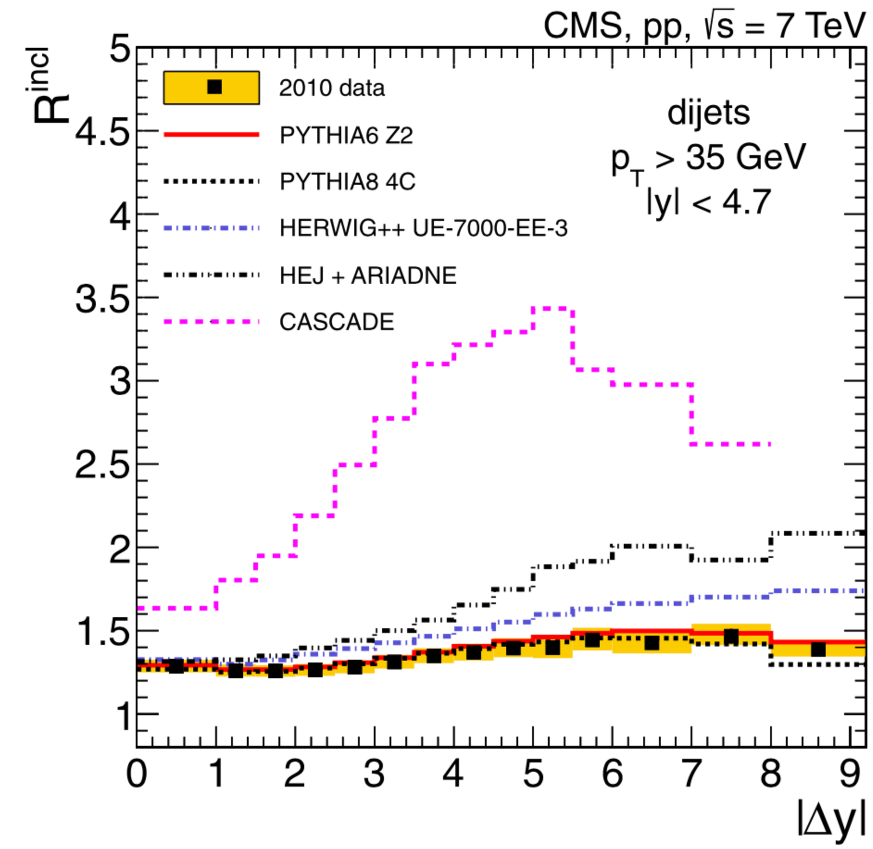


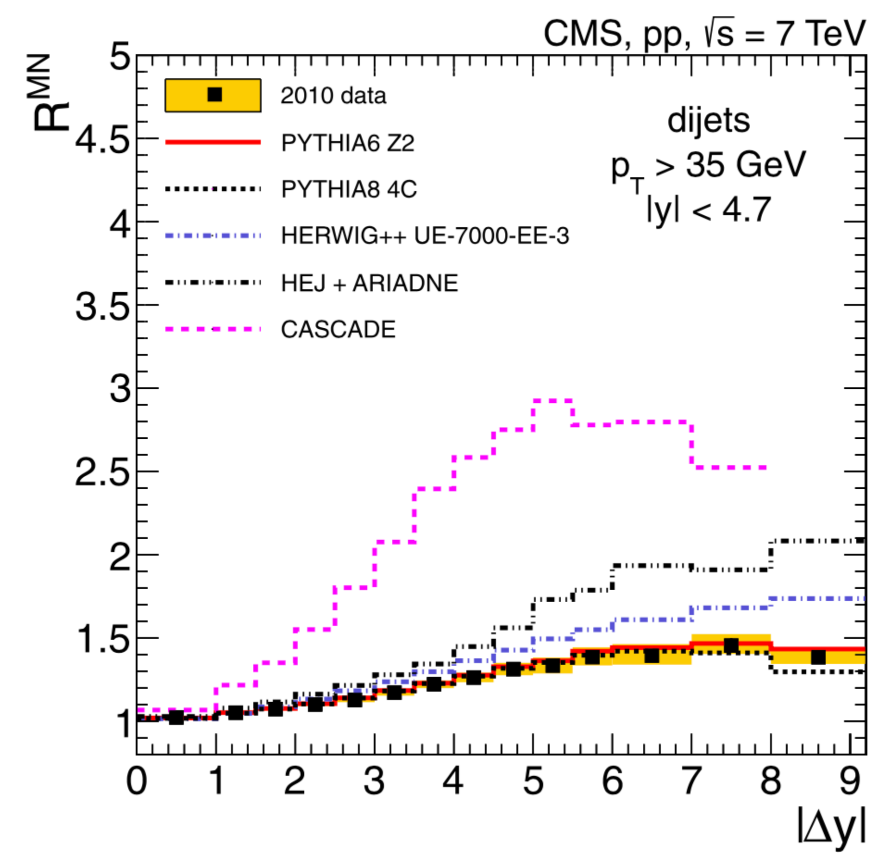


JET VETO

CMS SEARCH OF BFKL EUR. PHYS. J. C (2012) 72:2216

- **pp at 7 TeV**
- **two selection types:**
  - **Inclusive dijets**
  - **Mueller-Navelet dijets**
- $p_T > 35$ **GeV**
- $\Delta y = |y_1 - y_2| < 9.4$
- **Veto** $p_{T\ veto} = 35$ **GeV**



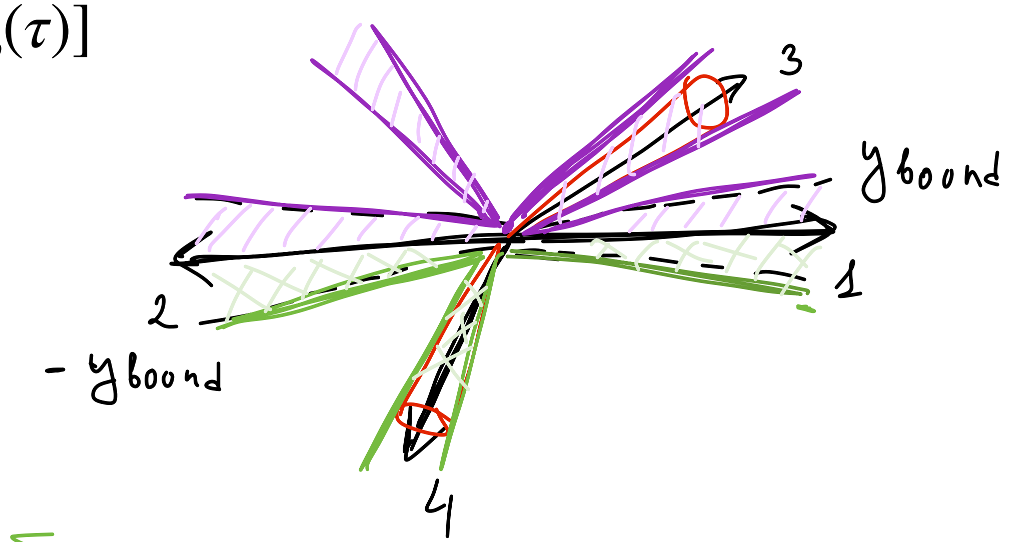


JET VETO

$y_{bound} = 4.7$

$$\partial_\tau \Sigma_{ab}(\tau) = -(\partial_\tau R_{ab})\Sigma_{ab} + \int_{C_{in}} \frac{d\Omega_q}{4\pi} w_{ab}(q)[\Sigma_{aq}(\tau)\Sigma_{qb}(\tau) - \Sigma_{ab}(\tau)]$$

$$R_{ab}(\tau) = \int_{E_{out}}^{Q} \frac{dq_t}{q_t} \bar{\alpha}_s(q_t) \int_{C_{out}} \frac{d\Omega_q}{4\pi} w_{ab}(q) \approx \tau f_{abC_{out}}$$



Before C_{out} is controlled by Δy (100 Systems)

Σ_{24} $C_{out} \in [-y_{bound}, y_4 - R]$ $[y_4 + R, y_{bound}]$

Now C_{out} is a function of dipole type as well as:

Σ_{34} $C_{out} \in [-y_{bound}, y_4 - R]$ $[y_4 + R, y_3 - R]$ $[y_3 + R, y_{bound}]$

$y_{bound}, Y, \Delta y$

(100x100x6 = 60k Systems)

LARGE ANGLE SOFT MC

MARCHESINI 2006 ARXIV:HEP-PH/0601068

Generating functional

$$\Sigma_{ab}[Q,u] = \sum_n \frac{1}{n!}\int \frac{d\sigma_{ab}^{(n)}}{\sigma_{abT}} \prod_{i=1}^{n} u(q_i)$$

In soft and planar limit

$$Q\partial_Q \Sigma_{ab}[Q,u] = \int \frac{d\Omega_q}{4\pi}\bar{\alpha}_s w_{ab}(q)\left\{u(q)\Sigma_{aq}[Q,u]\Sigma_{qb}[Q,u] - \Sigma_{ab}[Q,u]\right\}$$

Sudakov form factor

$$\ln S_{ab}(Q,Q_0) = -\int_{Q_0}^{Q} \frac{d\omega_q}{\omega_q}\frac{d\Omega_q}{4\pi}\bar{\alpha}_s(q_{abt})w_{ab}(q)\theta(q_{abt}-Q_0)$$

$$q_{abt}^2 = \frac{2\omega_q^2}{w_{ab}(q)} \qquad w_{ab}(q) = \frac{1-\cos\theta_{ab}}{(1-\cos\theta_{aq})(1-\cos\theta_{qb})}$$

$$\Sigma_{ab}[Q,u] = S_{ab}(Q,Q_0) + \int_{Q_0}^{Q} dP_{ab}(q)u(q)\Sigma_{aq}[\omega_q,u]\Sigma_{qb}[\omega_q,u]$$

MC ALGORITHM

MARCHESINI 2006 ARXIV:HEP-PH/0601068

Splitting probability

$$dP_{ab}(q) = d\left(\frac{S_{ab}(Q, Q_0)}{S_{ab}(\omega_q, Q_0)}\right) dR_{ab}(\Omega_q)$$

Angle distribution

$$\frac{dR_{ab}(\Omega_q)}{d\Omega_q} = \frac{\bar{\alpha}_s(q_{abt}) w_{ab}(q)}{N_{ab}(\omega_q)} \theta(q_{abt} - Q_0)$$

Algorithm: start with ab-dipole.

use r random number to generate energy of branch:

if $r < S(Q, Q_0)$ **- dipole does not branch (with** Q_0 **cutoff).**

if $r > S(Q, Q_0)$ **- dipole split with** ω_q **such that** $S_{ab}(\omega_q, Q_0) \cdot r = S_{ab}(Q, Q_0)$

generate angle with $dR_{ab}(\Omega_q)$

repeat with aq and qb dipoles until Q_0

$$q^2_{abt} = \frac{2\omega_q^2}{w_{ab}(q)}$$

MC ALGORITHM DOES NOT REPRODUCE BMS EQUATION

MC

$$\ln S_{ab}(Q, Q_0) = -\int_{Q_0}^{Q} \frac{d\omega_q}{\omega_q}\frac{d\Omega_q}{4\pi}\bar{\alpha}_s(q_{abt})w_{ab}(q)\theta(q_{abt} - Q_0)$$

BMS

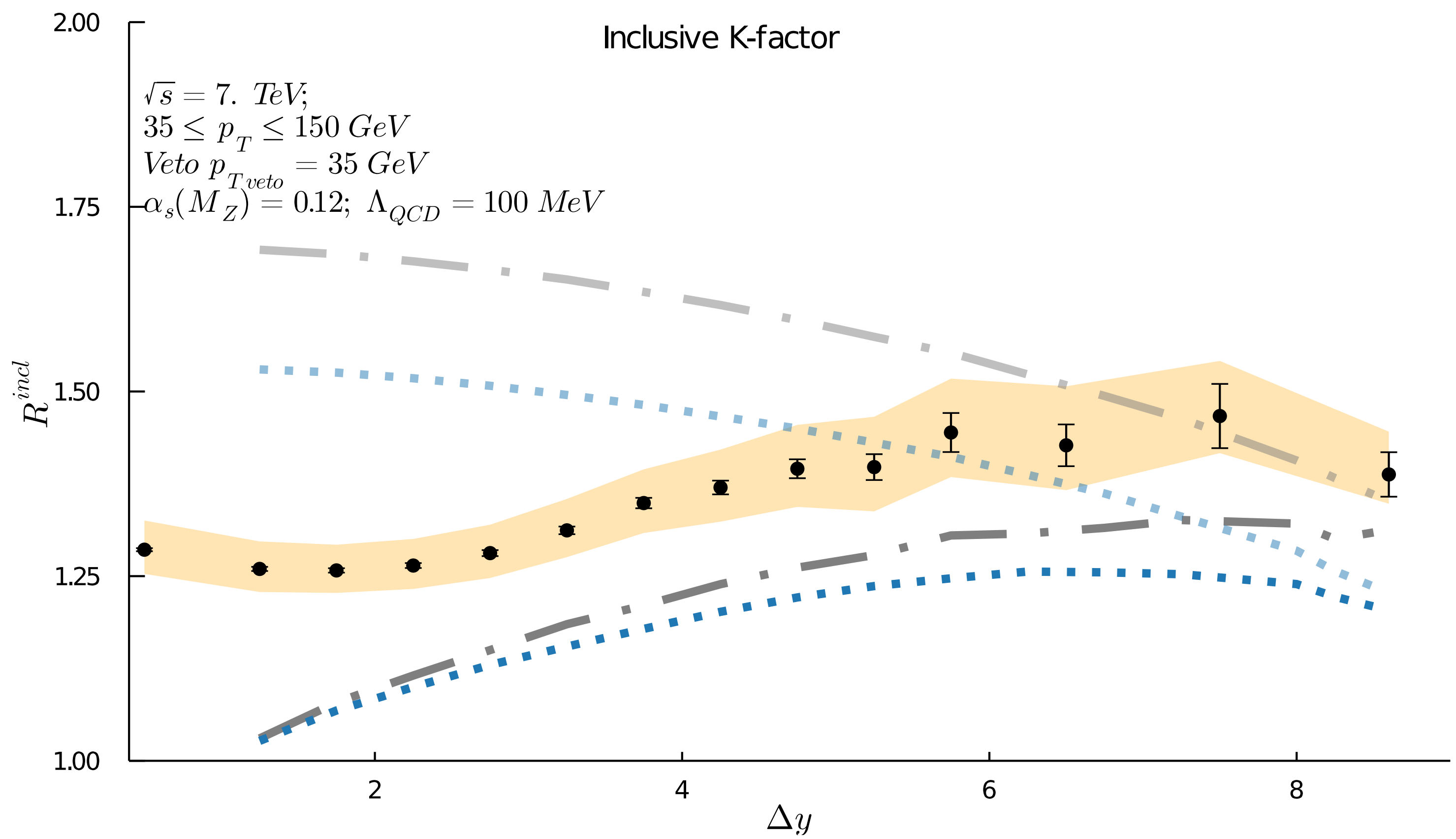
$$\ln S_{ab}(Q, Q_0) = -\int_{Q_0}^{Q} \frac{d\omega_q}{\omega_q}\frac{d\Omega_q}{4\pi}\bar{\alpha}_s(\omega_q)w_{ab}(q)$$

↓

$$\ln S_{ab}(Q, Q_0) = -\int_{Q_0}^{Q} \frac{d\omega_q}{\omega_q}\frac{d\Omega_q}{4\pi}\bar{\alpha}_s(\omega_q)w_{ab}(q)\Theta(\cos(\theta)_{\max} - \cos(\theta))$$

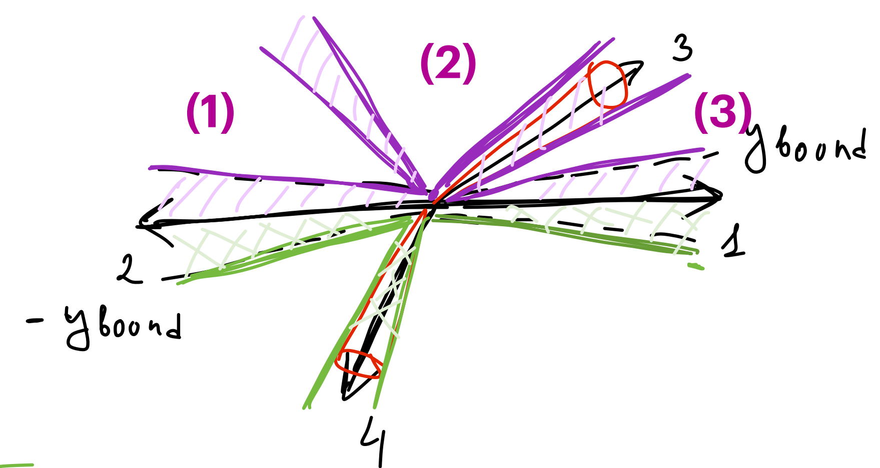
RESULTS

SUDAKOV AND BMS



- BMS

$$\Sigma_{34}(\tau) = \Sigma_{34}(\tau)^{(1)}\Sigma_{34}(\tau)^{(2)}\Sigma_{34}(\tau)^{(3)}$$



Σ_{24} $C_{out} \in [-y_{bound}, y_4 - R]$ $[y_4 + R, y_{bound}]$

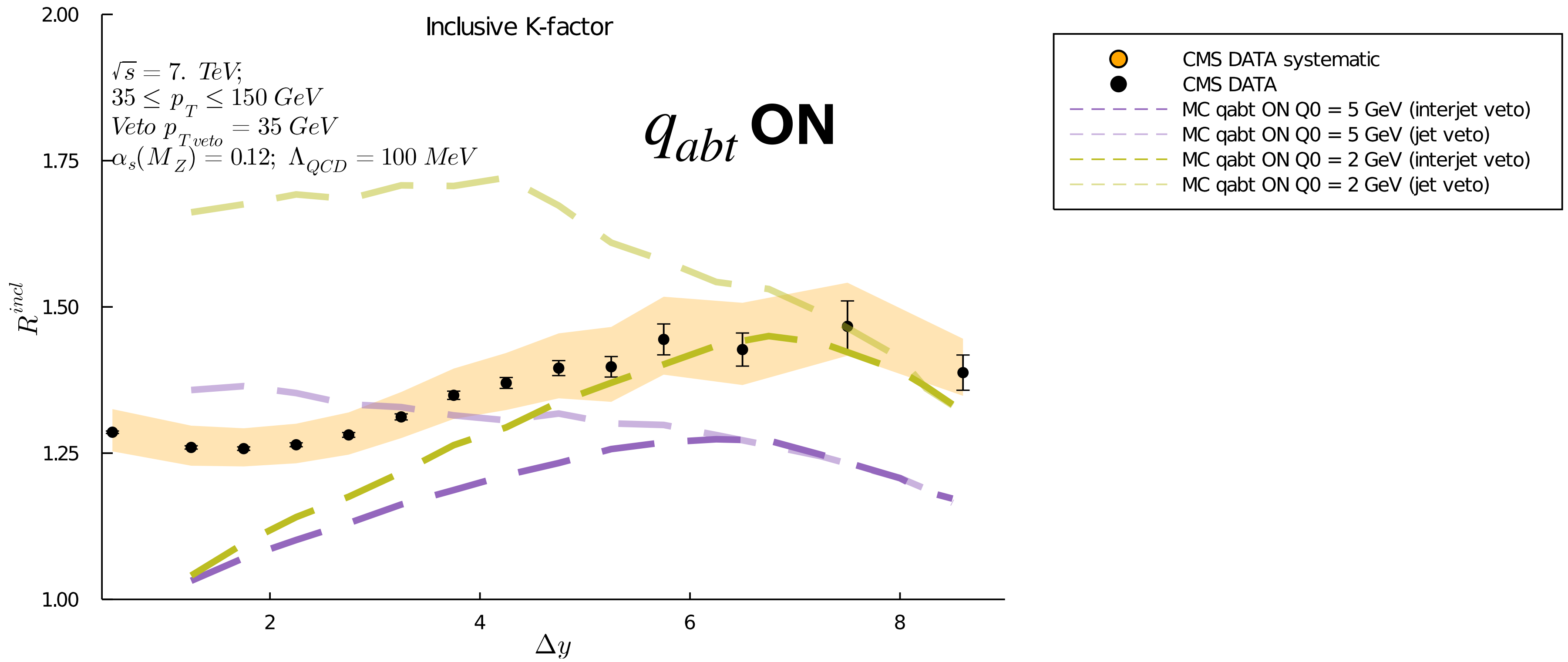
Σ_{34} $C_{out} \in [-y_{bound}, y_4 - R]$ $[y_4 + R, y_3 - R]$ $[y_3 + R, y_{bound}]$

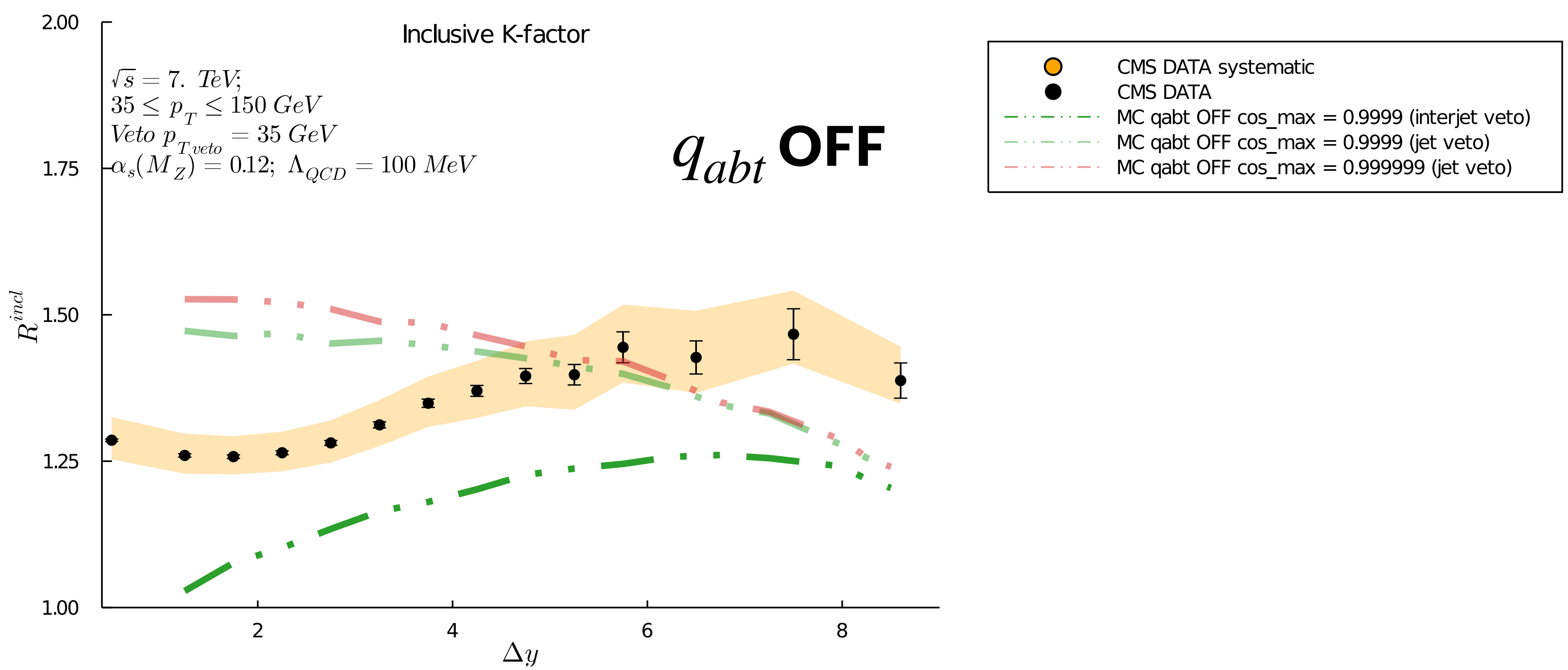
- Sudakov: $\partial_\tau \Sigma_{ab}(\tau) = -(\partial_\tau R_{ab})\Sigma_{ab}$

$$R_{ab}(\tau) = \int_{E_{out}}^{Q} \frac{dq_t}{q_t} \bar{\alpha}_s(q_t) \int_{C_{out}} \frac{d\Omega_q}{4\pi} w_{ab}(q) \approx \tau f_{abC_{out}}$$

RESULTS

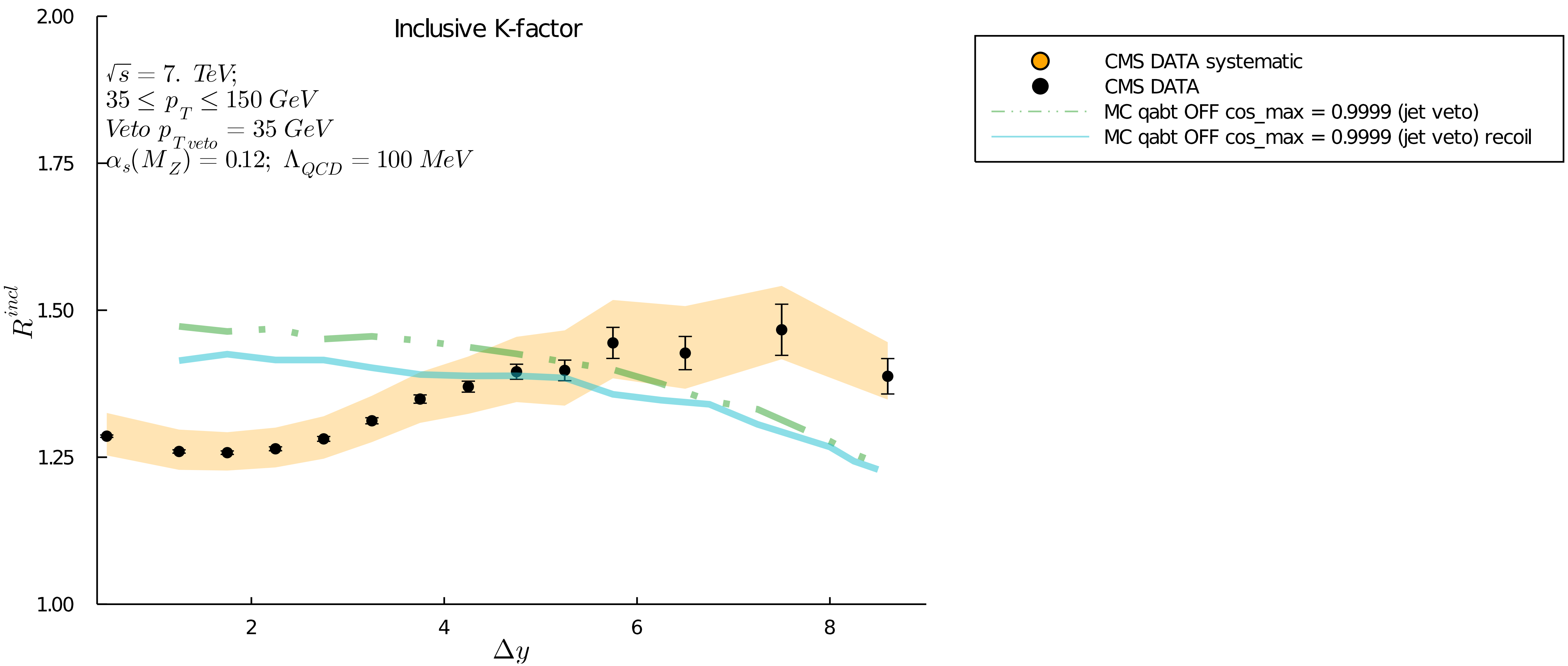
MC


Inclusive K-factor
$\sqrt{s} = 7.\ TeV;$
$35 \leq p_T \leq 150\ GeV$
$Veto\ p_{T\,veto} = 35\ GeV$
$\alpha_s(M_Z) = 0.12;\ \Lambda_{QCD} = 100\ MeV$
q_{abt} ON
CMS DATA systematic
CMS DATA
MC qabt ON Q0 = 5 GeV (interjet veto)
MC qabt ON Q0 = 5 GeV (jet veto)
MC qabt ON Q0 = 2 GeV (interjet veto)
MC qabt ON Q0 = 2 GeV (jet veto)
R^{incl}
Δy


Inclusive K-factor
$\sqrt{s} = 7.\ TeV;$
$35 \leq p_T \leq 150\ GeV$
$Veto\ p_{T\,veto} = 35\ GeV$
$\alpha_s(M_Z) = 0.12;\ \Lambda_{QCD} = 100\ MeV$
q_{abt} OFF
CMS DATA systematic
CMS DATA
MC qabt OFF cos_max = 0.9999 (interjet veto)
MC qabt OFF cos_max = 0.9999 (jet veto)
MC qabt OFF cos_max = 0.999999 (jet veto)
R^{incl}
Δy

IMPROVEMENTS

ATTEMPT TO TAKE RECOIL INTO ACCOUNT (ENERGY-MOMENTUM CONSERVATION)



CONCLUSIONS

- Soft gluon approximation is suitable tool to study the ENERGY FLOW and JET VETO

- MC algorithm gives solution mach faster

- MC algorithm is more suitable for jet veto

- Improvements are needed (such as inclusion the energy-momentum conservation and recoil)

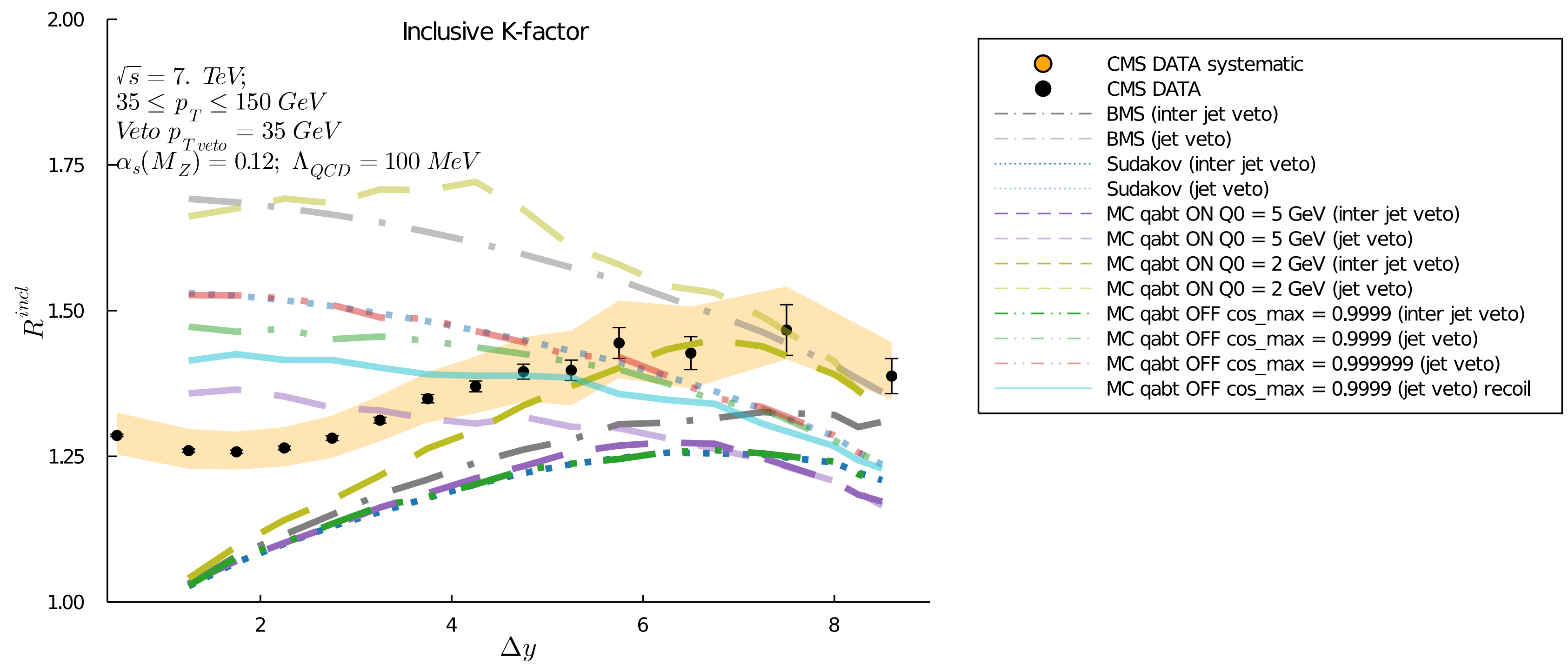
- This tool works better when Veto region is far from jets

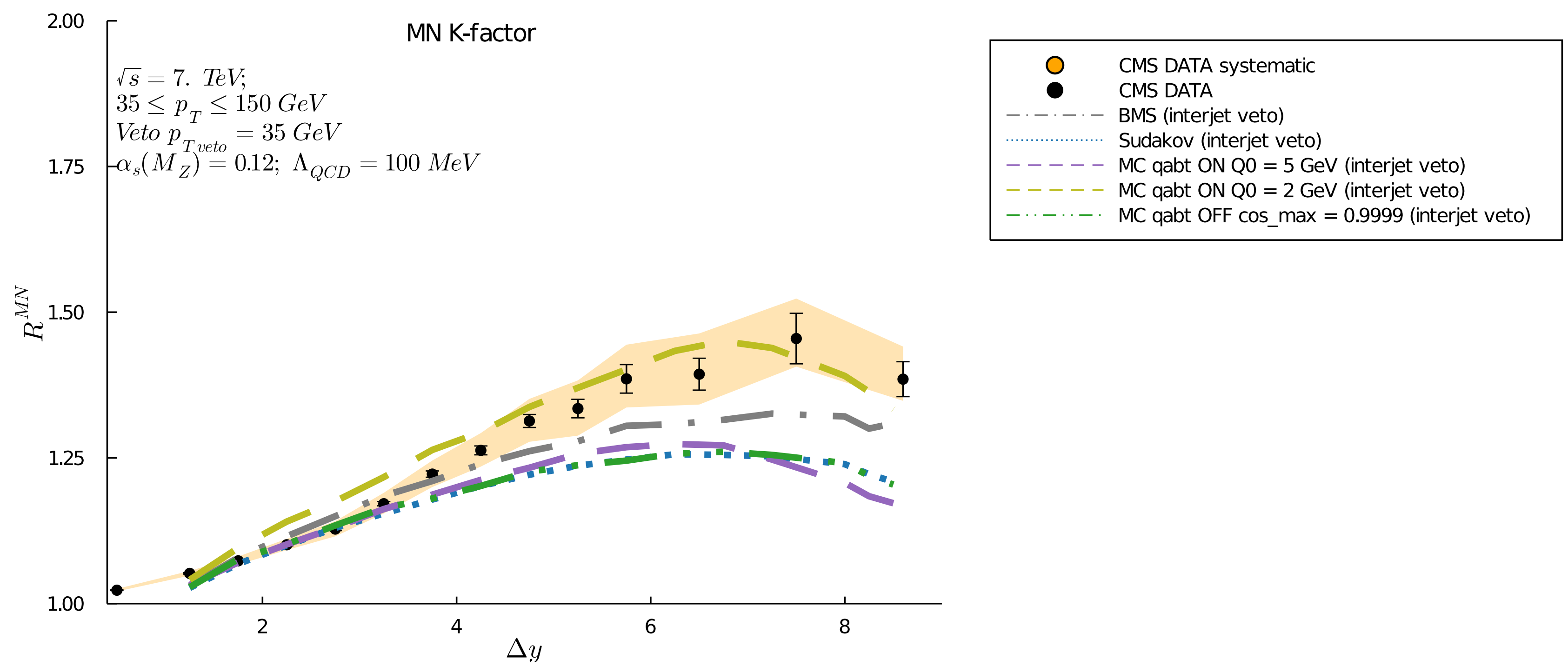
THANK YOU

BACKUP

RESULTS

ALL IN ONE





COLOR FLOW

PDG REVIEW $gg \to gg$ **x-section**

$$\frac{d\sigma_{gg\to gg}}{d\Omega} = \frac{9\alpha_s^2}{8s}\left(3 - \frac{ut}{s^2} - \frac{su}{t^2} - \frac{st}{u^2}\right)$$

BMS *JHEP* 08 (2002) 006

$$\frac{d\sigma_{gg\to gg}}{dt} = \frac{1}{16\pi s}(h^D(s,t,u) + h^D(s,u,t) + h^D(u,t,s))$$

$$h^D(s,t,u) = 2g^4\frac{N_c^2}{N_c^2-1}\left(1 - \frac{tu}{s^2} - \frac{su}{t^2} + \frac{u^2}{st}\right)$$

VETO

$$\frac{d\sigma^{veto}_{gg\to gg}}{dt} = \frac{1}{16\pi s}(h^D(s,t,u)\Sigma_{12}\Sigma_{13}\Sigma_{24}\Sigma_{34} + h^D(s,u,t)\Sigma_{12}\Sigma_{14}\Sigma_{23}\Sigma_{34} + h^D(u,t,s)\Sigma_{14}\Sigma_{24}\Sigma_{13}\Sigma_{23})$$

SOLUTION OF BMS

$$\partial_\tau \Sigma_{ab}(\tau) = -(\partial_\tau R_{ab})\Sigma_{ab} + \int_{in} \frac{d\Omega_q}{4\pi} w_{ab}(q)[\Sigma_{aq}(\tau)\Sigma_{qb}(\tau) - \Sigma_{ab}(\tau)]$$

in region C_{in}

$$\phi_q \in [0,2\pi]; \qquad \theta_q \in [0,\theta_{in}] \cup [\pi - \theta_{in}, \pi]$$

τ **range**

$$\tau = \int_{Q_0}^{Q} \frac{dq_t}{q_t} \bar{\alpha}_s(q_t) \qquad \tau_{max} = \int_{p_{T\ veto}}^{\sqrt{s}/2} \frac{dq_t}{q_t} \bar{\alpha}_s(q_t) = \int_{20}^{7000} \frac{dq_t}{q_t} \bar{\alpha}_s(q_t) = 0.651$$

$$\Sigma_{ab}(\tau) = \Sigma(\theta_a, \phi_a, \theta_b, \phi_b, \tau, \theta_{in}) = \Sigma(\theta_a, \theta_b, \Delta\phi, \tau, \theta_{in})$$

we have to solve the equation for each $\theta_{in}(\Delta y)$

SOLUTION OF BMS

NUMERICAL SOLUTION

Make transform $\Sigma_{ab}(\tau) = e^{-\tau f_{ab}} g_{ab}(\tau)$

$$\partial_\tau g_{ab}(\tau) = \int_{C_{in}} \frac{d\Omega_q}{4\pi} w_{ab}(q) U_{abq} [g_{aq}(\tau) g_{qb}(\tau) - g_{ab}(\tau)] \qquad U_{abq} = e^{-\tau(f_{aq}+f_{qb}-f_{ab})}$$

Calculate θ_{in} **in 100 points from** 0 **to** $\pi/2$

Divide in region $\theta_q \in [0,\theta_{in}] \cup [\pi - \theta_{in}, \pi]$ **in 81 points**

Divide $\Delta\phi \in [0,\pi]$ **in 21 points**

$$\partial_\tau g_{ij}(\tau) = \sum_{k\neq i, k\neq j, k\in C_{in}} \frac{\Delta\Omega_k}{4\pi} w_{ij}(k) U_{ijk} [g_{ik}(\tau) g_{kj}(\tau) - g_{ij}(\tau)]$$

SOLUTION OF BMS

NUMERICAL SOLUTION

System of 81x81x21 ~ 140k ODE for each θ_{in}

$$\partial_\tau g_{ij}(\tau) = \sum_{k\neq i, k\neq j, k\in C_{in}} \frac{\Delta\Omega_k}{4\pi} w_{ij}(k) U_{ijk}[g_{ik}(\tau)g_{kj}(\tau) - g_{ij}(\tau)]$$

$$g_{ij}(0) = 1 \qquad\qquad \tau \in [0,0.8]$$

Runge-Kutta 4 with tau step $\Delta\tau = 0.01$

use cpython

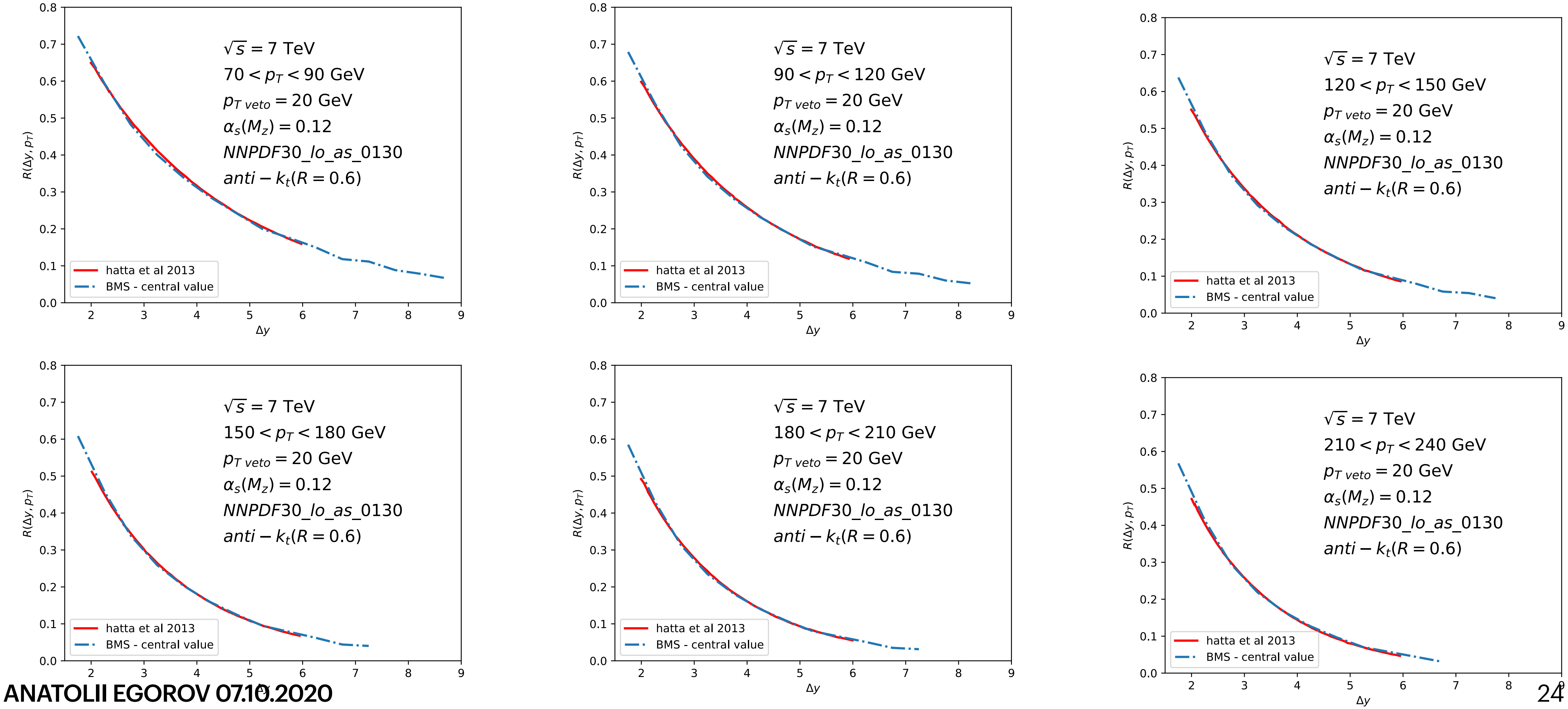
for each θ_{in} **can be solved within 10h in Supercomputing Data Center PIK (SDC PIK)**

Solution is ~8 Gb .npz (numpy) files

REPRODUCE RESULTS

HATTA AT AL. PHYS. REV. D 87, 054016 (2013)

ATLAS MEASUREMENT at 7 TEV $\mathscr{R}(\Delta y, p_T) = \dfrac{d\sigma^{veto}/d\Delta y d^2 p_T}{d\sigma^{incl}/d\Delta y d^2 p_T}$



SHORTCOMINGS

- **Solution known only in knots - difficult to use with MC integration**
- **equal spacing in θ_{in} - rough at large rapidities**

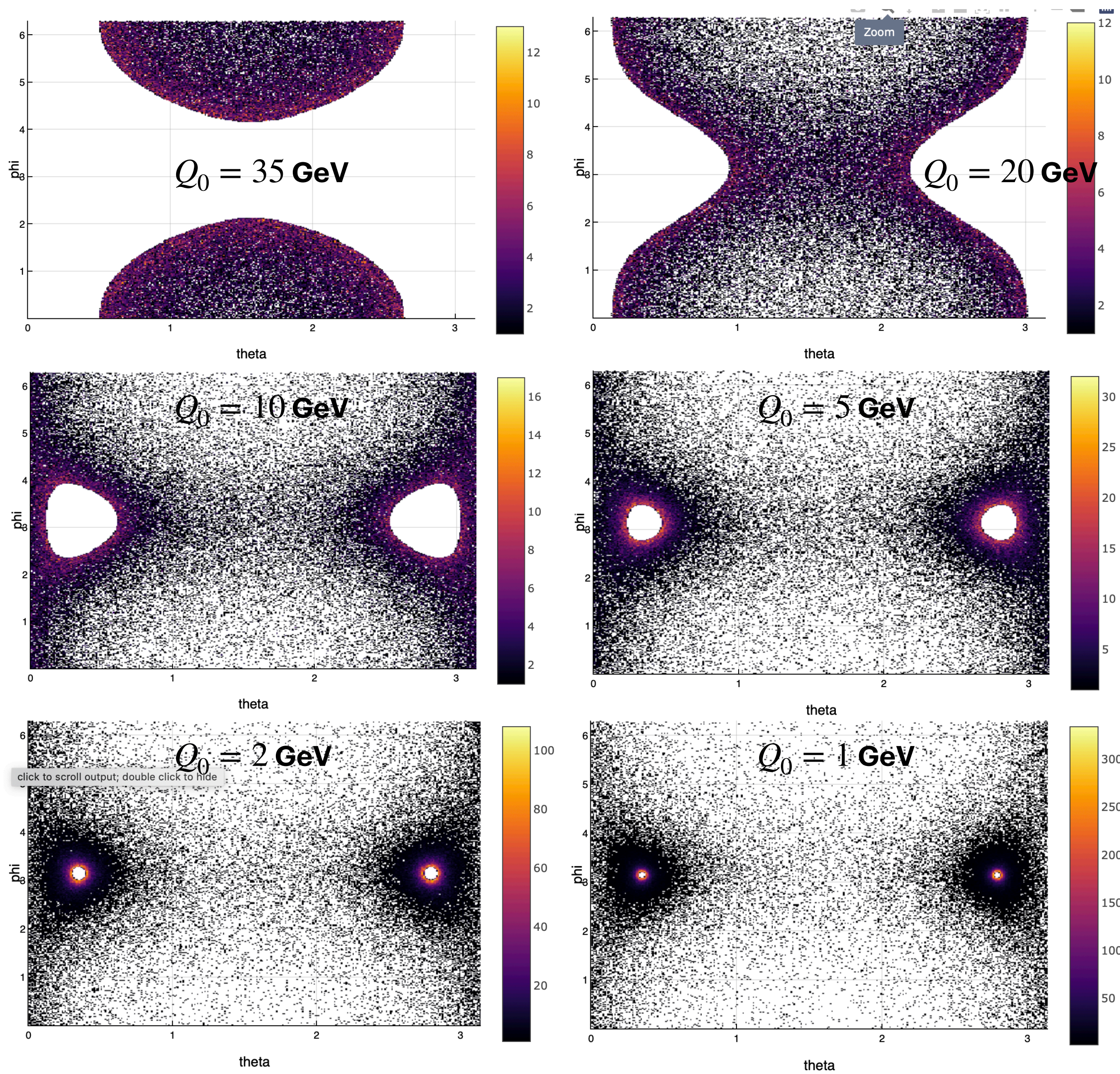
$$\theta_{in} = \{0^\circ,\ 1^\circ,\ 2^\circ,\ 3^\circ,\ 4^\circ,\ 5^\circ\} \Longrightarrow \eta = \{\infty,\ 4.05,\ 3.35,\ 2.94,\ 2.66,\ 2.43\}$$

- **difficult to apply to jet veto (not inter jet veto)**

REALISATION MC

$$S_{ab}(\omega_q, Q_0)\cdot r = S_{ab}(Q, Q_0)$$

$$\ln S_{ab}(Q,Q_0) = -\int_{Q_0}^{Q}\frac{d\omega_q}{\omega_q}\frac{d\Omega_q}{4\pi}\bar{\alpha}_s(q_{abt})w_{ab}(q)\theta(q_{abt}-Q_0)$$



$$\frac{dR_{ab}(\Omega_q)}{\Omega_q} = \frac{\bar{\alpha}_s(q_{abt})w_{ab}(q)}{N_{ab}(\omega_q)}\theta(q_{abt}-Q_0)$$