Beauty production with the CMS experiment

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On behalf of the CMS Collaboration

Workshop on
Heavy Particles at the LHC
5-7 January 2011
ETH, Zurich

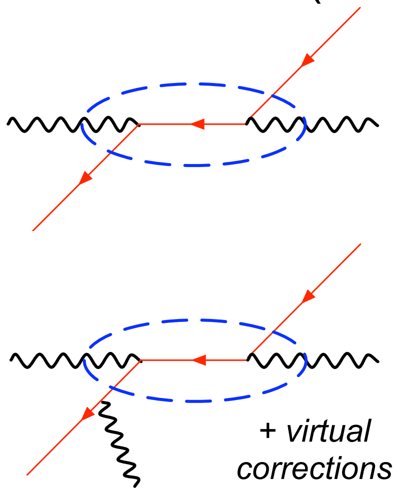
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH

B-quark production at LHC

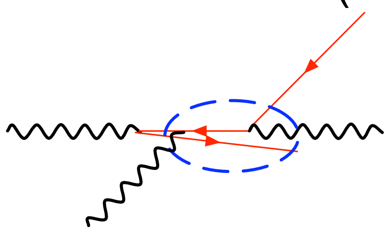
- **Excellent test bench for perturbative QCD and Monte Carlo models**
  - **Tensions between data and theory gradually resolved at hadron colliders with lower c.o.m. energy (Tevatron, HERA)**
  - **Early measurements at LHC can have smaller uncertainties than NLO QCD predictions currently available**
- **B-quark jets are a frequent background to searches for new physics**
  - **Rate and dynamics of b-quark production needs to be well measured and reproduced by MC tools**
  - **Topology of final-state b quarks (e.g. collinear vs. back-to-back production) relevant for designing SM rejection cuts for physics searches**
- **CMS detector is well suited for b-quark cross section measurements, thanks to its excellent tracking, vertexing and muon identification, combined with a flexible trigger system**

Production processes in p-p

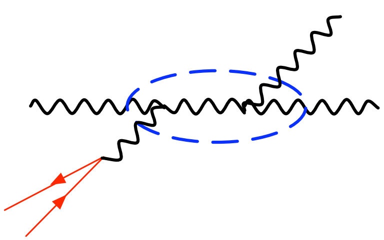
Flavour creation (FCR)



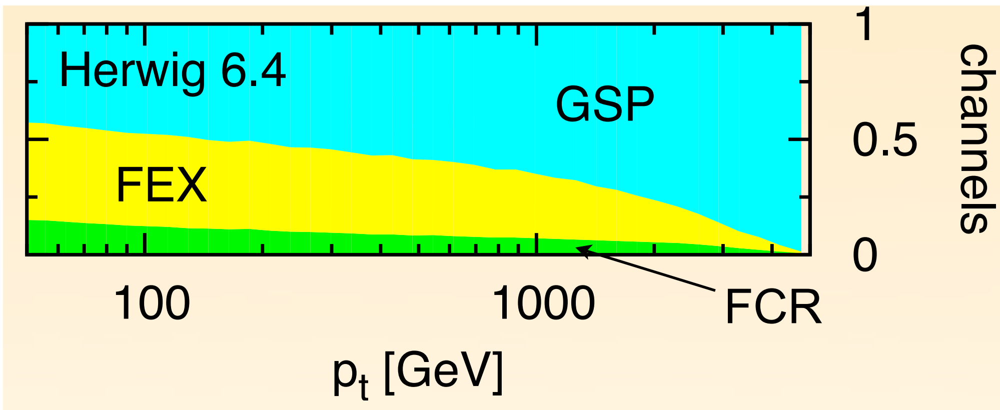
Flavour excitation (FEX)



Gluon splitting (GSP)

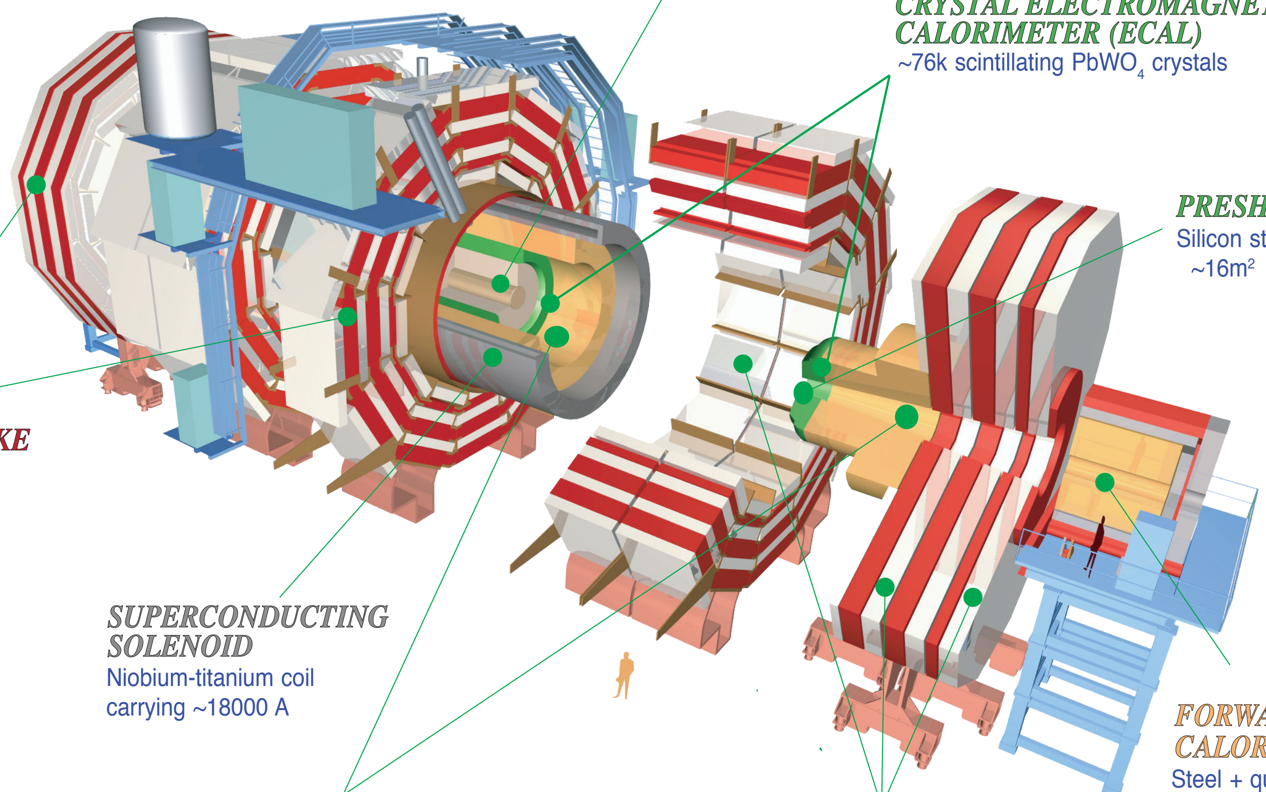


- 2→2 processes:
  - Flavour creation: gluon fusion and qq annihilation
- 2→3 processes:
  - *Flavour Excitation*: bb from the proton sea, only one b participates to the hard scatter, asymmetric transverse momentum for the two b-quarks
  - *Gluon splitting*: g→ bb in initial or final state, b at low pT and close in the azimuthal angle (Δφ)
  - Real and virtual corrections to Flavour creation



2 to 3 processes dominant at the LHC!

CMS Detector



Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

B-quark identification

- **Identification with semi-leptonic decay into muons**
  - Low momentum (3 GeV) single-muon trigger thresholds at CMS startup
  - Can probe inclusive beauty production at low momentum

CMS-PAS-BPH-10-007

- **Secondary vertex identification**
  - Exploit high precision of pixel tracker and long B hadrons lifetimes
  - Efficient secondary vertex reconstruction for E_T^{jet}>20 GeV
  - Excellent for b-jet studies at larger momenta
  - Inclusive secondary vertex finder as a powerful tool for angular correlation studies

CMS-PAS-BPH-10-009

CMS-PAS-BPH-10-010

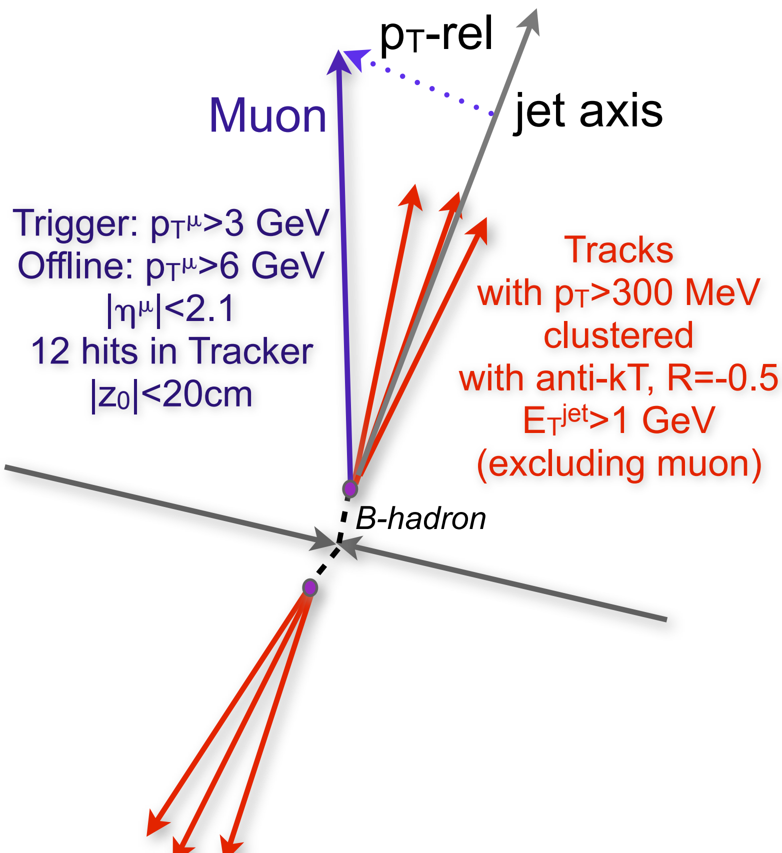
- **B-hadron exclusive decay reconstruction**
  - Competitive performance in $J/\psi+X$ decay channels with $J/\psi\to\mu\mu$
  - First published result: $B^+\to J/\psi K^+$ differential cross section

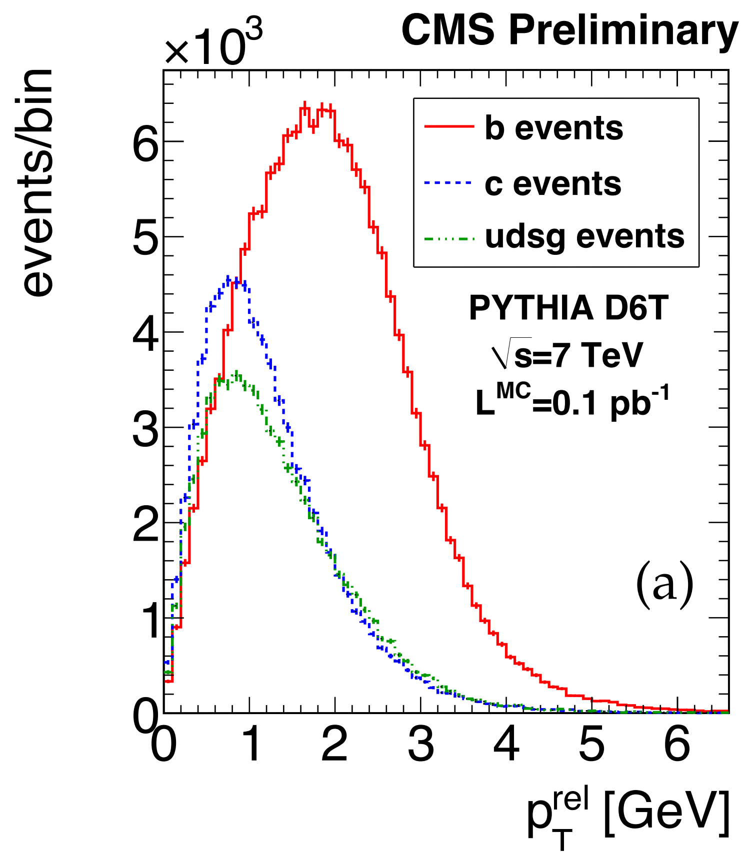
CERN-PH-EP-2010-087

ICHEP2010 results

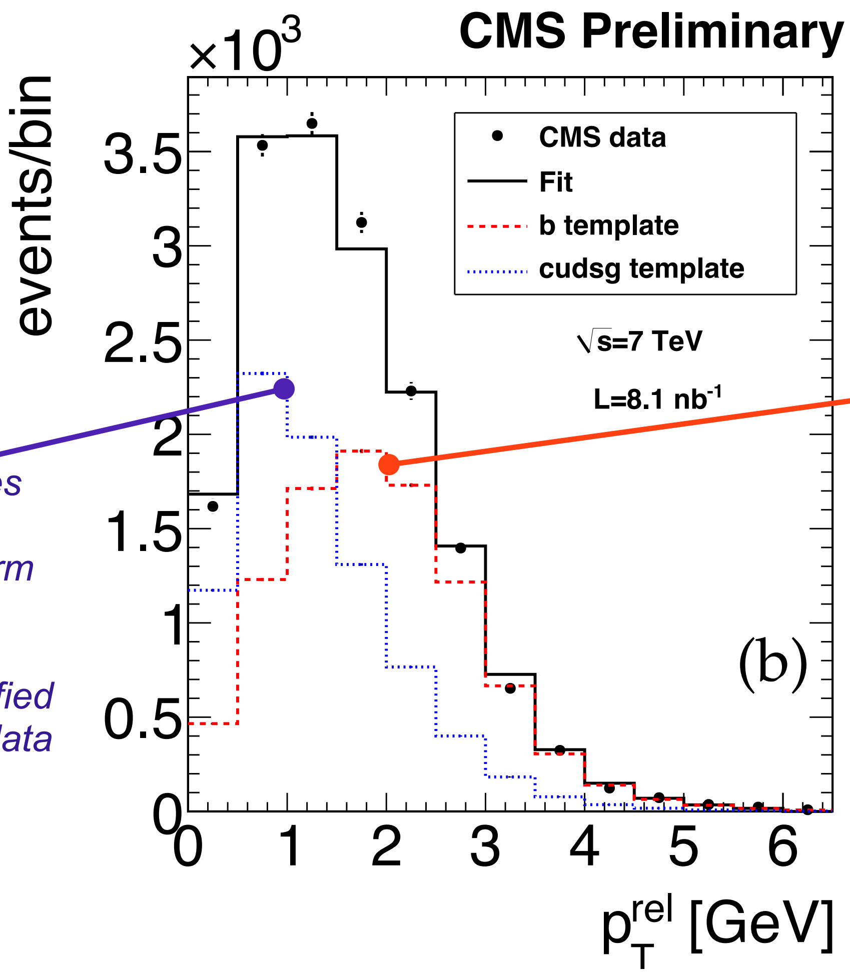
New results!

- Exploit kinematics of semi-leptonic decay due to heavy quark mass
  - Muon transverse momentum w.r.t. jet on average larger for b-quark
  - Fraction of events with b-decays extracted from a fit with simulated p_T^{rel} templates





Cross section calculation



Combination of templates from light quarks/gluons in-flight decays and charm decays.

Template from misidentified hadrons validated with data

b-quark templates from MC, validated with b-enriched data sample

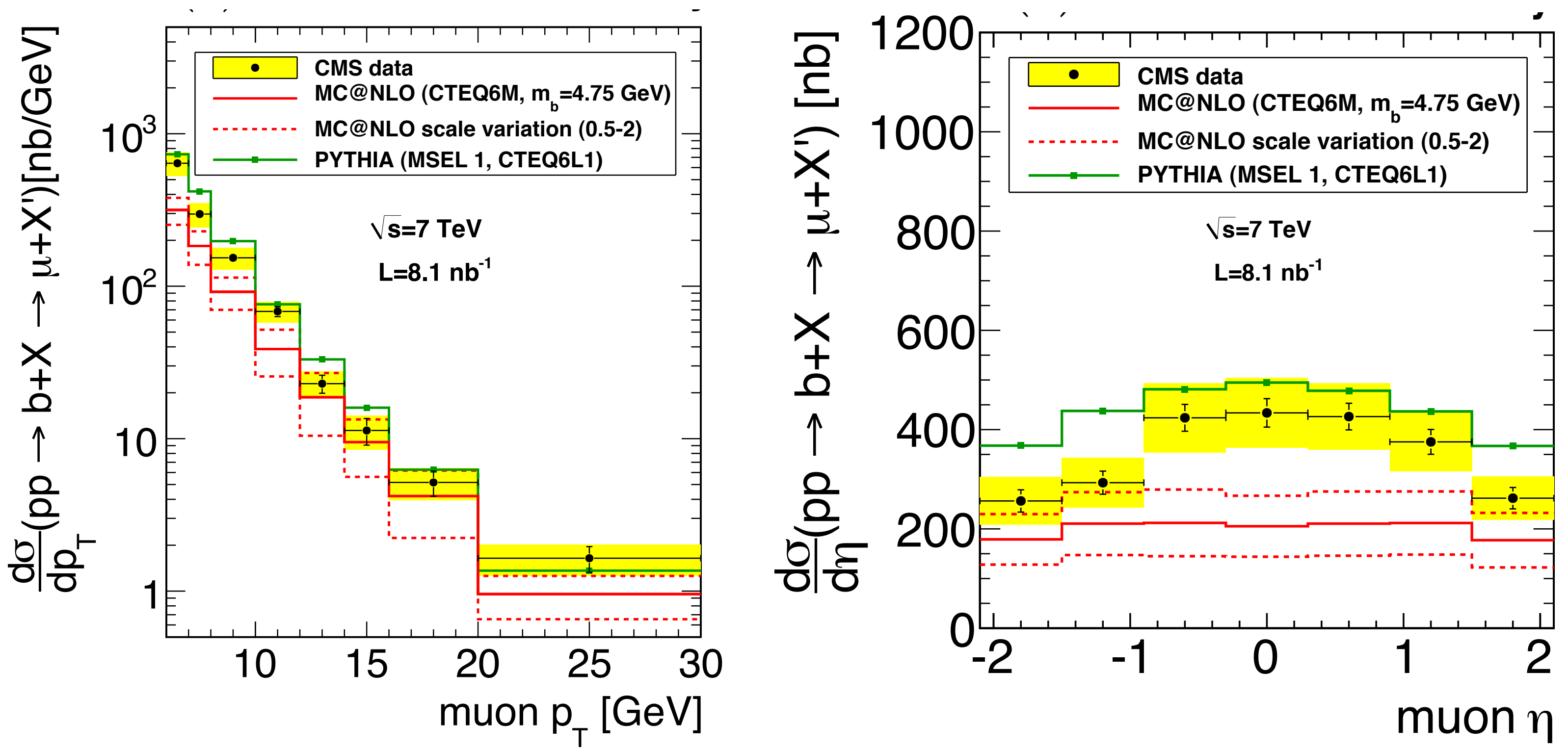
f_b from fit (44±1)%

Efficiencies (ϵ):
Muon trigger ~82% (Data)
Muon reconstruction ~97% (MC)
Muon-jet association ~77% (MC)

Luminosity ($\mathcal{L}$): 8.1 nb^{-1}

Cross section definition $\sigma \equiv \sigma(pp \to b + X \to \mu + X', p_\perp^\mu > 6\,\mathrm{GeV}, |\eta^\mu| < 2.1) = \frac{N_b^{\mathrm{data}}}{\mathcal{L}\,\varepsilon}$

Differential cross sections



$$\sigma = (1.48 \pm 0.04_{\rm stat} \pm 0.22_{\rm syst} \pm 0.16_{\rm lumi})\,\mu{\rm b}$$ **Measured visible cross section**

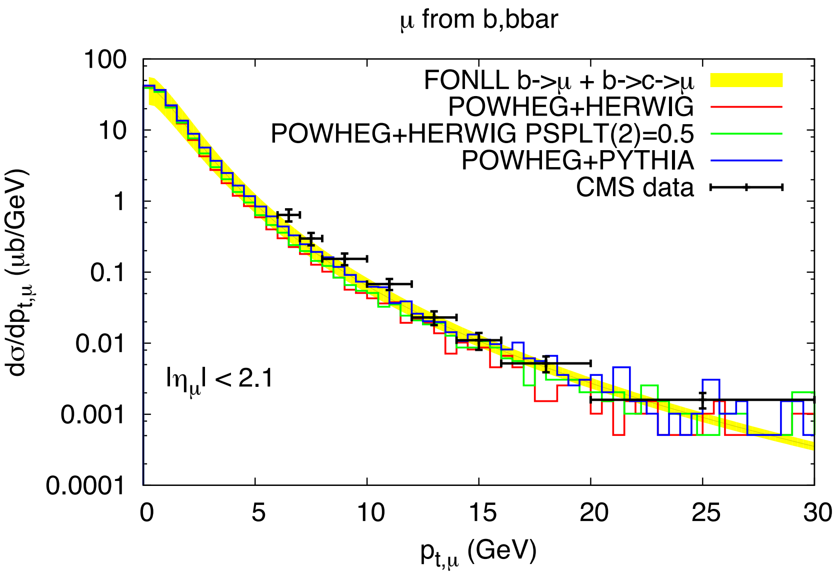
$$\sigma_{\rm PYTHIA} = 1.8\,\mu{\rm b}$$

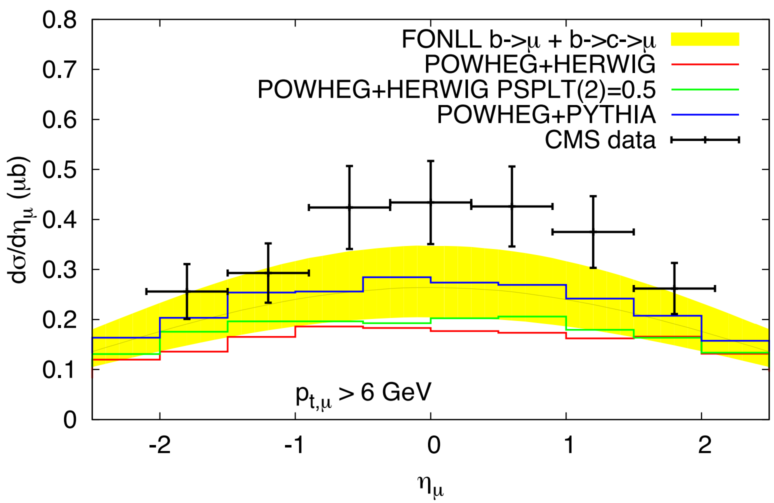
$$\sigma_{\rm MC@NLO} = [0.84^{+0.36}_{-0.19}({\rm scale}) \pm 0.08(m_b) \pm 0.04({\rm pdf})]\,\mu{\rm b} \quad (\mu_F=\mu_R=p_T)$$

Experimental uncertainties (15-20%) dominated by modeling of fake muons and underlying event

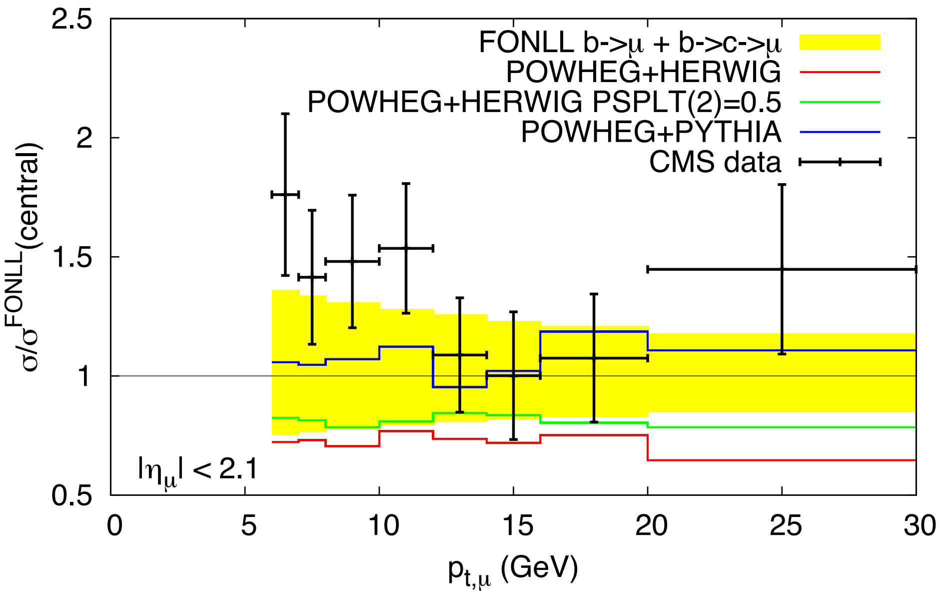
MC@NLO: larger discrepancies at low p_T^{μ} and central region

FONLL and POWHEG



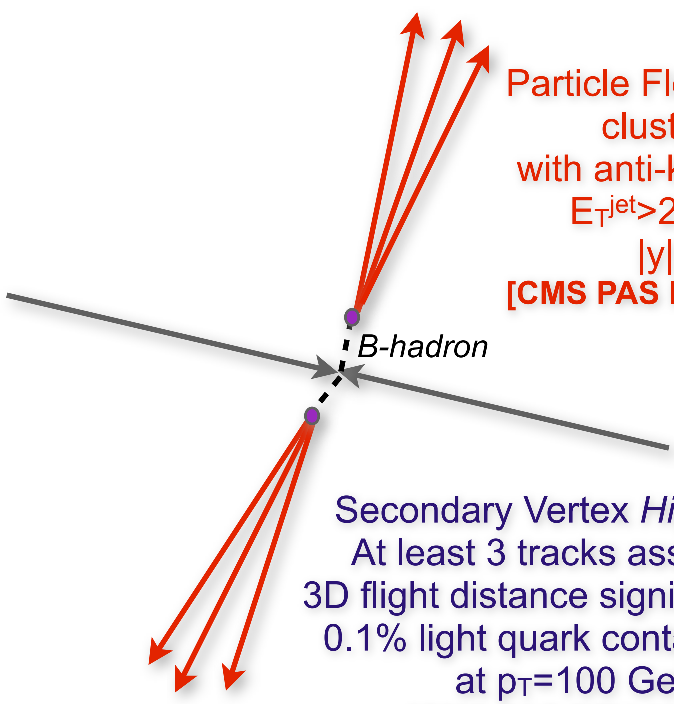


M.Cacciari, P.Nason



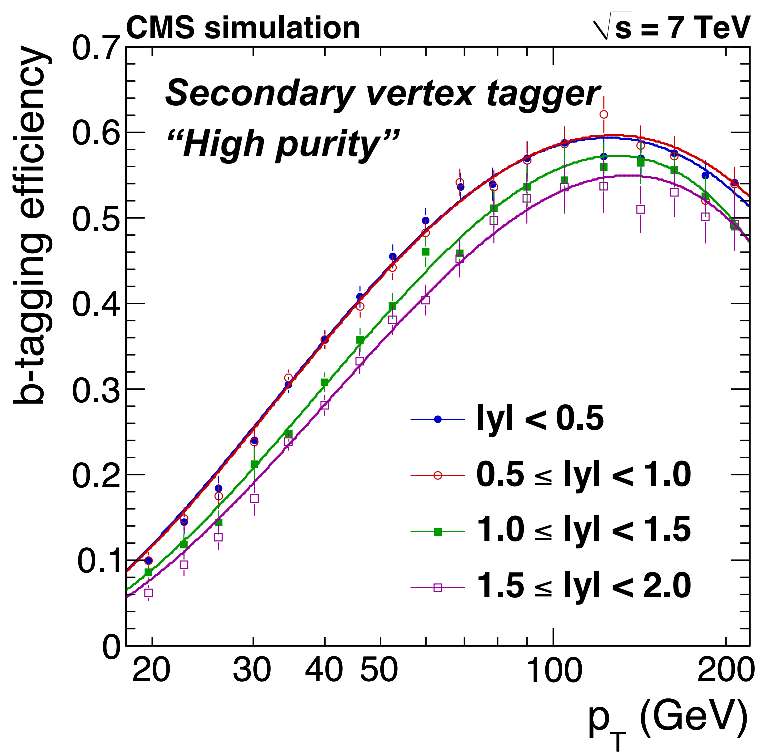
B jets cross section

- By tagging B jets we can extend the cross section measurement to large transverse momenta
  - Exploit secondary vertex reconstruction with silicon pixel detector
  - 50-60% tagging efficiency for p_T=100 GeV with 0.1% background contamination
- Different systematic uncertainties w.r.t. semi-leptonic decays



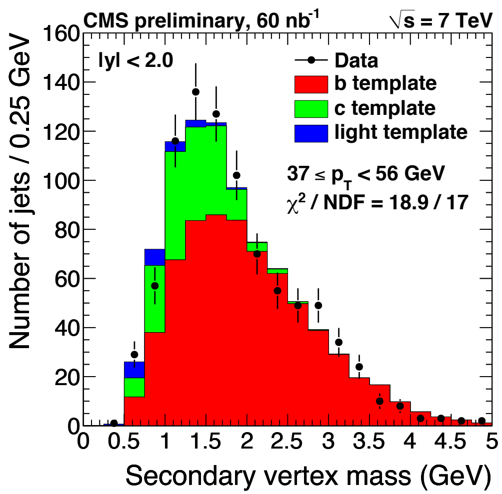
Particle Flow objects clustered
with anti-kT, R=-0.5
E_T^{jet}>20 GeV
|y|<2
[CMS PAS PFT-09-001]

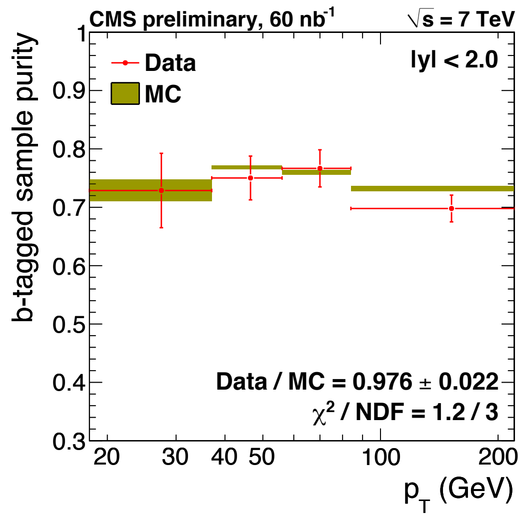
Secondary Vertex *High Purity*
At least 3 tracks associated
3D flight distance significance cut
0.1% light quark contamination at p_T=100 GeV
[CMS PAS BTV-10-001]



Cross section calculation

Cross section definition $$\frac{d^2\sigma_{\mathrm{b-jets}}}{dp_T dy} = \frac{N_{\mathrm{tagged}} f_b C_{\mathrm{smear}}}{\epsilon_{\mathrm{jet}}\epsilon_b \Delta p_T \Delta y \mathcal{L}}$$



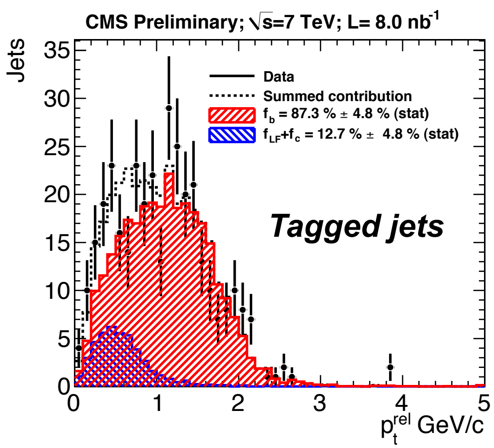


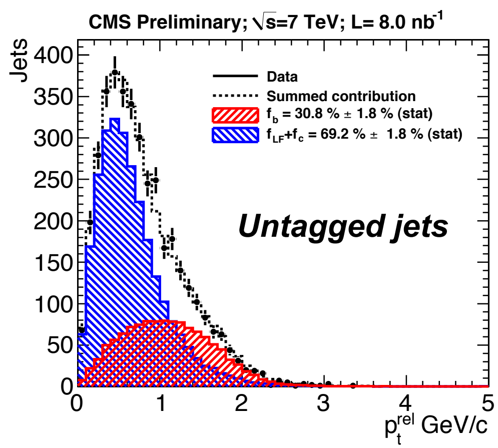
Tagged sample purity f_b from MC and fit to secondary vertex mass ~73%

Tagging efficiency ϵ_b from MC validated with data-driven method

$\epsilon_{data}/\epsilon_{MC}=0.98\pm0.08(stat)\pm0.18(syst)$

$$\epsilon_b^{data} = \frac{f_b^{tag}\cdot N_{data}^{tag}}{f_b^{tag}\cdot N_{data}^{tag} + f_b^{untag}\cdot N_{data}^{untag}}$$

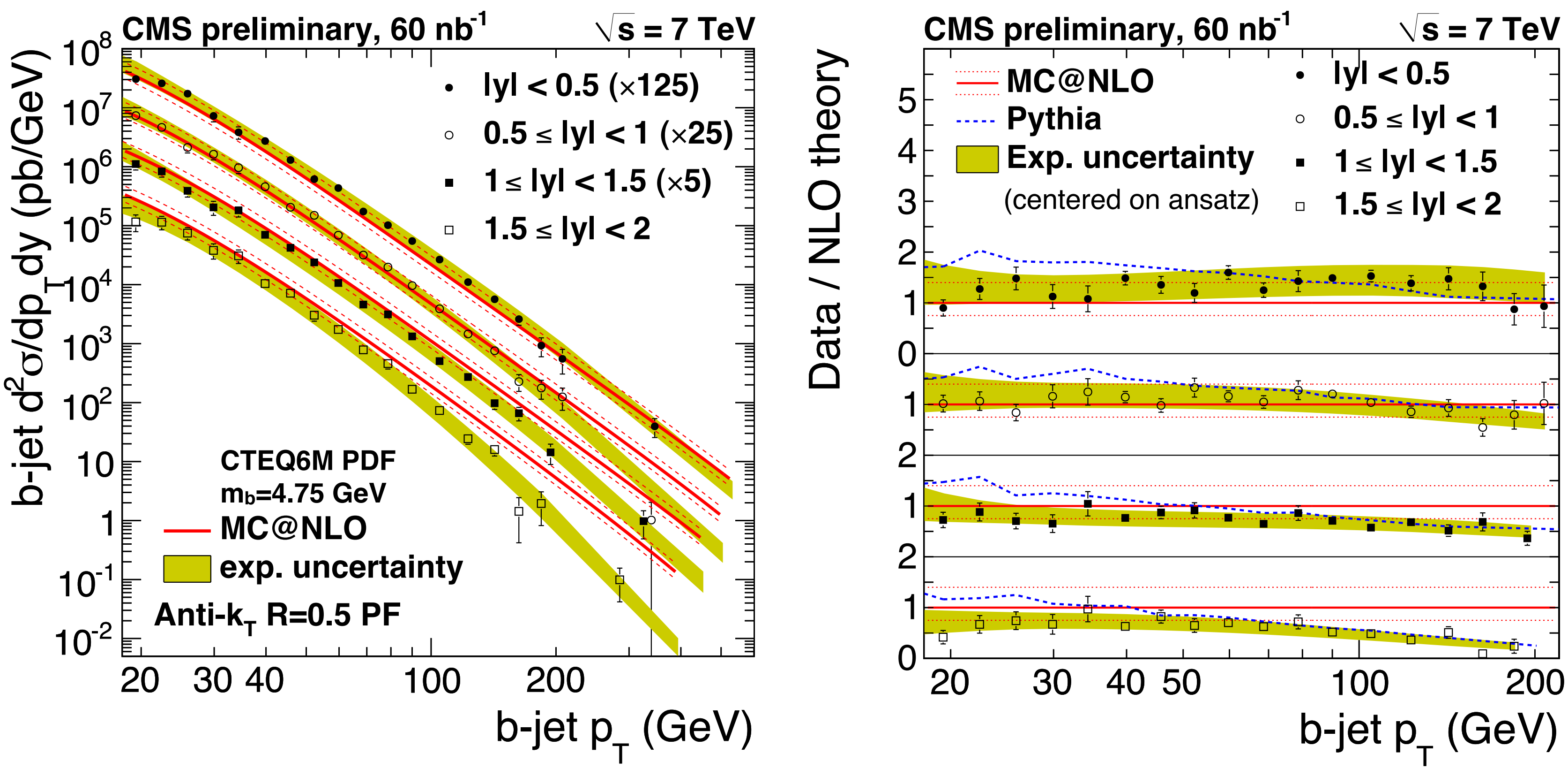




C_{smear} = unfolding correction
[CMS PAS QCD-10-011]

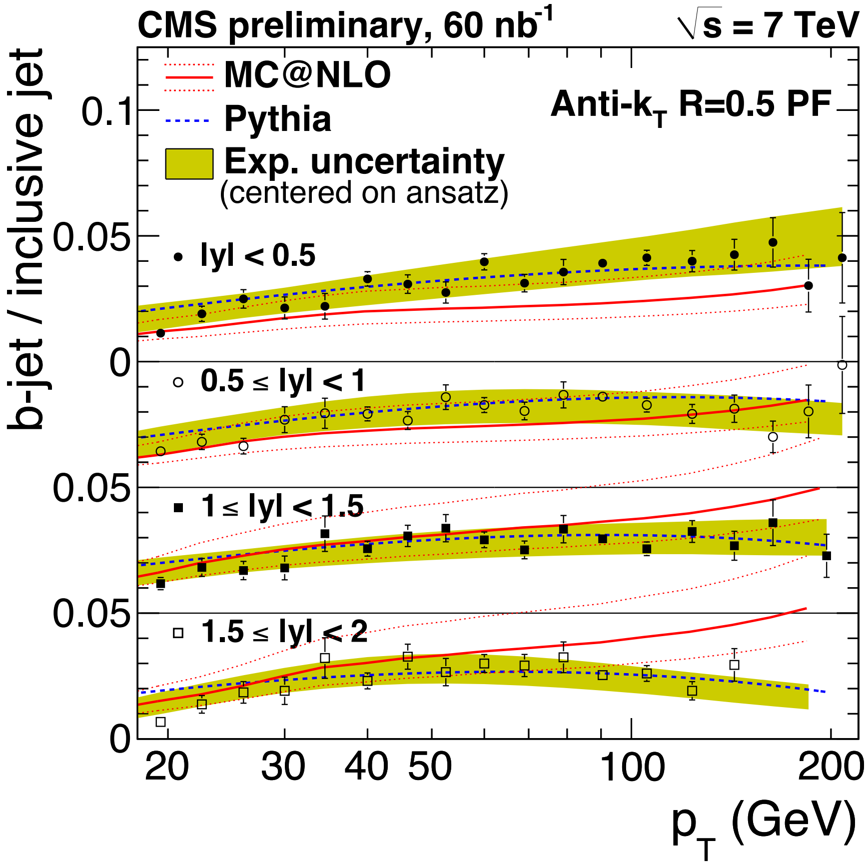
Luminosity ($\mathcal{L}$): 60 nb^{-1}

Results



- Experimental uncertainties (~20%) dominated by b-tagging efficiency and jet energy scale
- MC@NLO uncertainties dominated by scale variations (+40%,-25%) and b-quark mass (+17%,-14%)
- Generally good agreement with Pythia above 40 GeV
- Shape differences with MC@NLO at large p_T and forward region

Ratio to inclusive jets

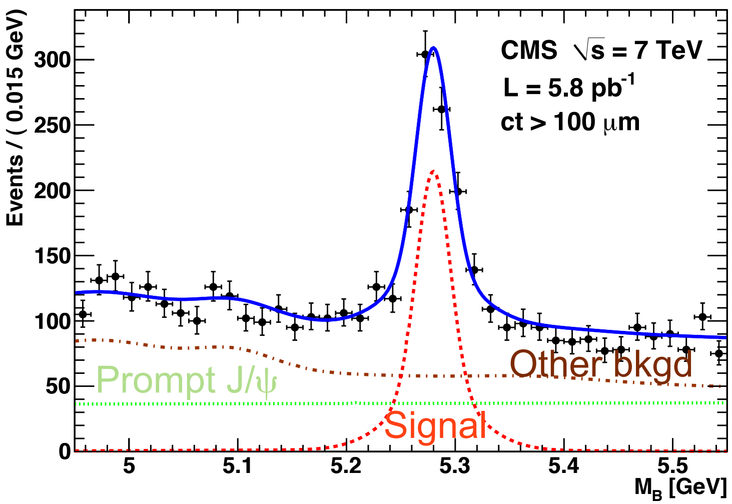


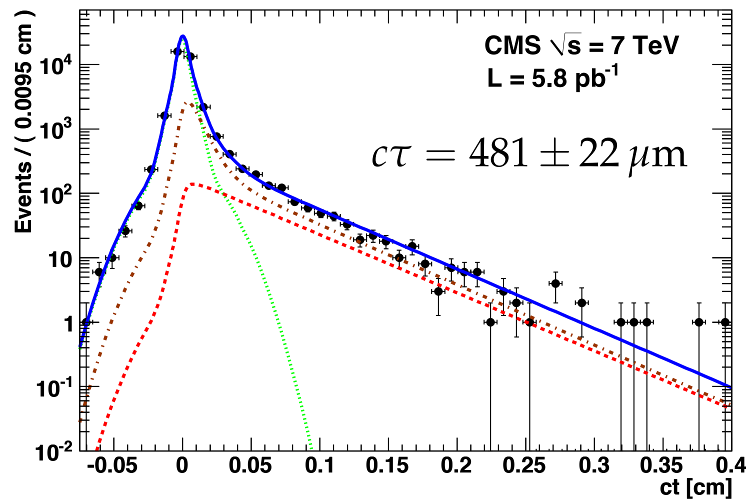
$$R = \frac{\text{B-jets cross section}}{\text{All jets cross section}} \sim 2\text{-}3\%$$

- Jet energy corrections and luminosity systematic uncertainties cancel out
- Pythia in agreement over the measured range
- Indicates shape discrepancies with NLOJet++/MC@NLO ratio

Inclusive jet measurement:
CMS PAS QCD-10-011

- **Signal extracted from simultaneous fit to invariant mass and lifetime distributions**

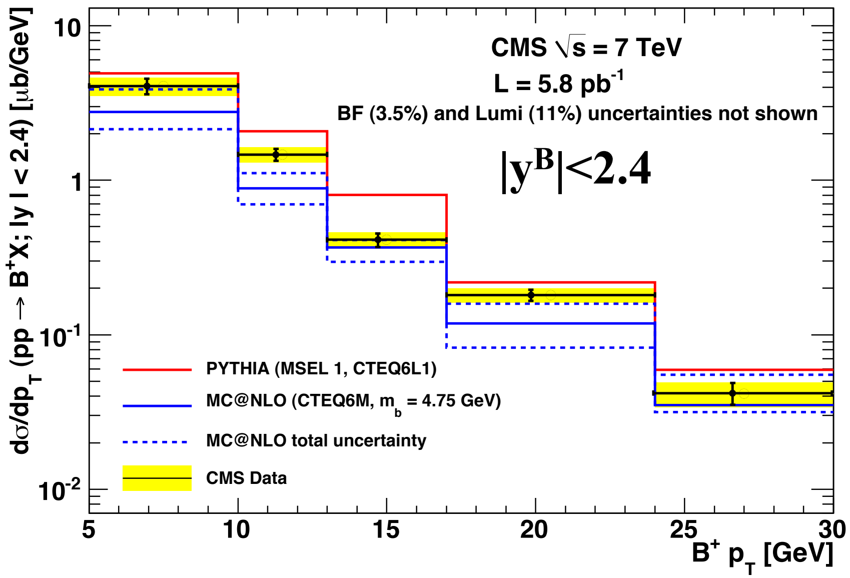


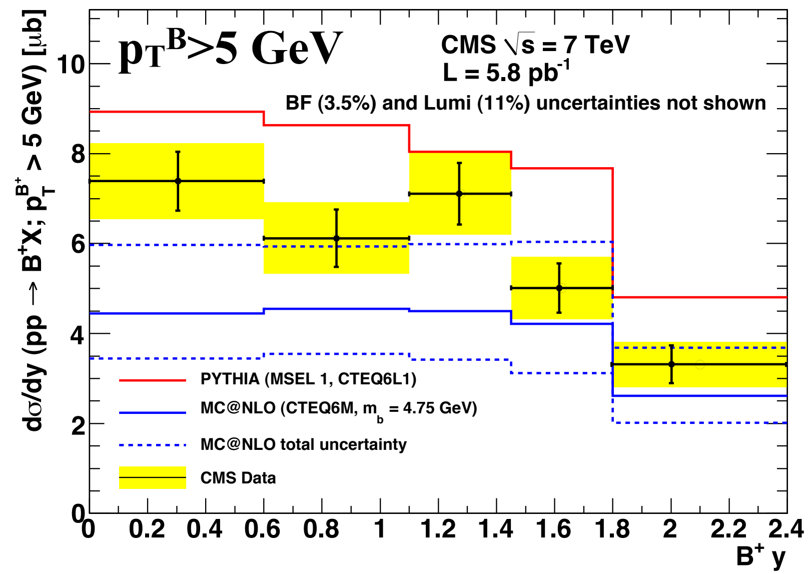


p_T^B>5 GeV
$|y^B|$<2.4

- **Event Selection:**
  - **Muons**: p_T>3.3 GeV for |η| < 1.3; p> 2.9 GeV for 1.3<|η|<2.2, p_T> 0.8 GeV for 2.2<|η|<2.4
  - Invariant J/ψ mass from oppositely charged muons, ±150 MeV from nominal mass
  - **Charged track**: p_T>0.9 GeV, at least 4 silicon tracker hits (of which one in pixels)
  - About **35'400** candidates found with **5.8/pb**
  - **Backgrounds**: dominated by prompt and non-prompt J/ψ production, B → J/ψK*(892)
- **Mass resolution on signal events ~30 MeV, cτ resolution ~30 μm**

$B^+ \to J/\psi\ K^+$





$pp \to B^+X$ $p_T^B > 5$ GeV, $|y^B| < 2.4$

$28.1 \pm 2.4 \pm 2.0 \pm 3.1\ \mu b$ — **Measured visible cross section**

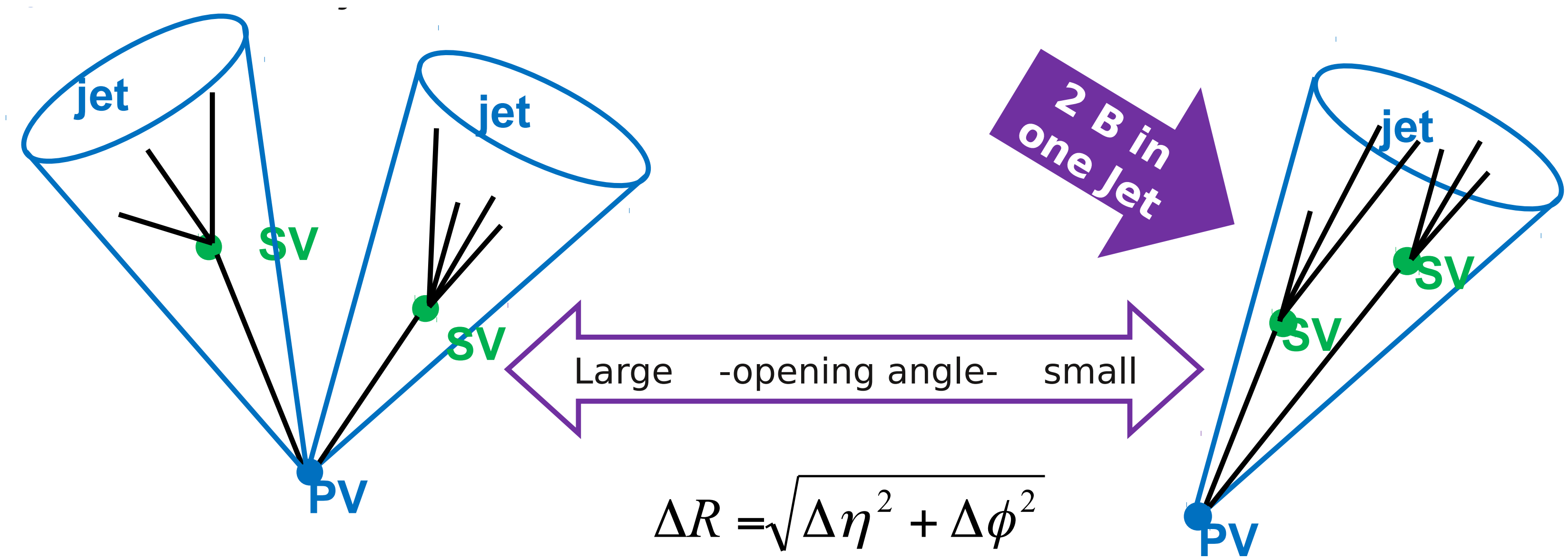
$19.1^{+6.5}_{-4.0}\,(\text{scale})^{+1.7}_{-1.4}\,(\text{mass}) \pm 0.6\,(\text{PDF})\ \mu b$ — **MC@NLO**

$36.2\ \mu b$ — **Pythia**

Experimental uncertainties (~7%) dominated by fit PDF shapes and tracking efficiency
BF (3.5%) and luminosity (11%) uncertainties not shown in figures

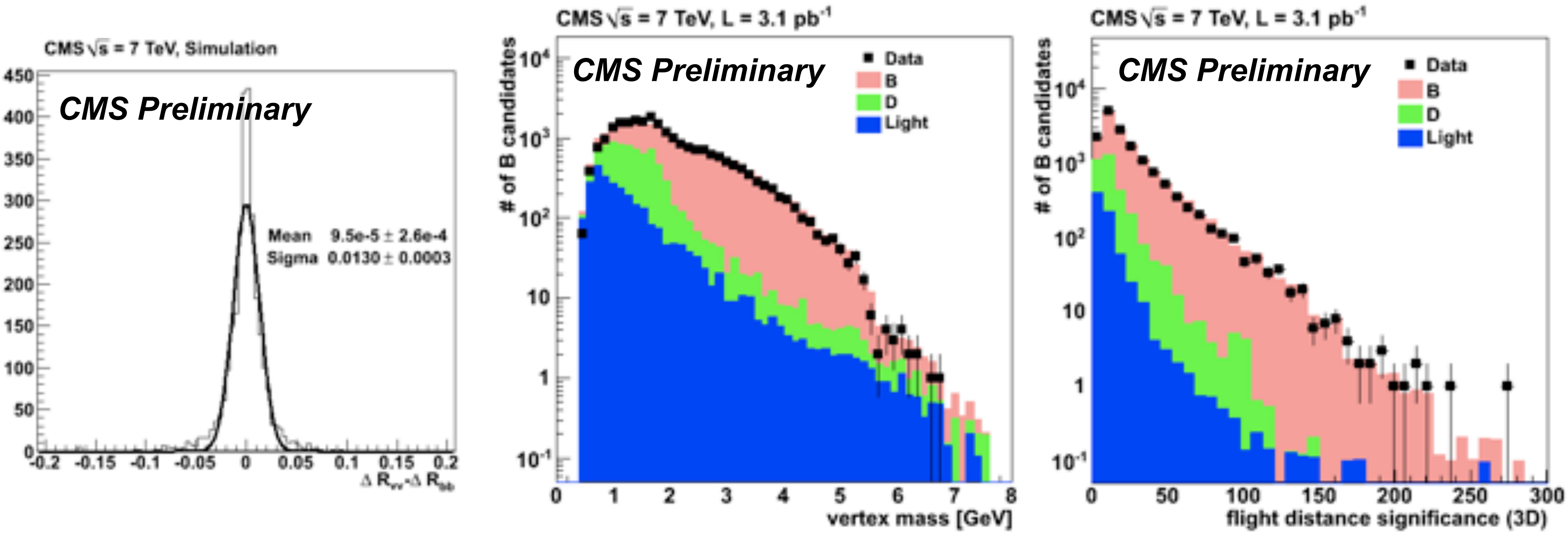
B-hadron angular correlations

- **Motivation**:
  - What fraction of the b-quark cross section is given by collinear b pair production?
  - How does this fraction evolve with the hardness of the scattering process?
- **Experimental problem:**
  - Measurements based on tagged jets have finite resolution due to jet clustering sizes
- **New technique:**
  - Reconstruct B-hadron momentum from primary and secondary vertices
  - Secondary vertex finder seeded with high IP tracks, jet independent
  - Tertiary vertices from chain decays (B→C) merged into a single B candidate



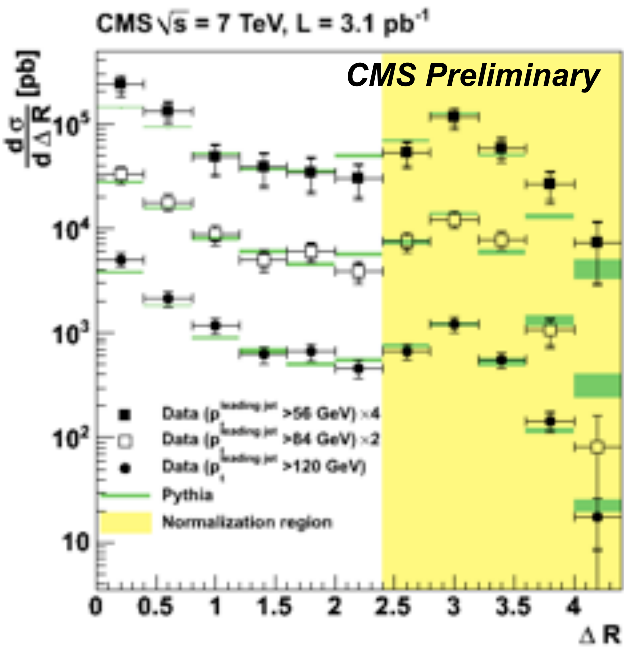
$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$

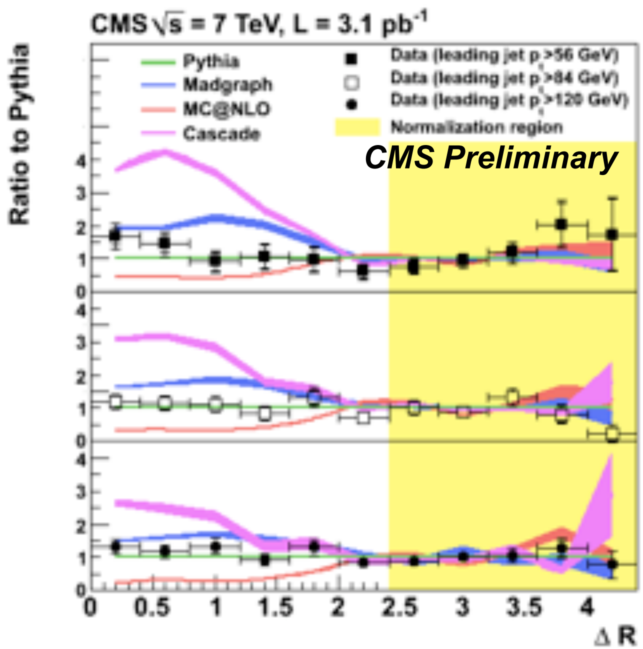
B-hadron angular correlations

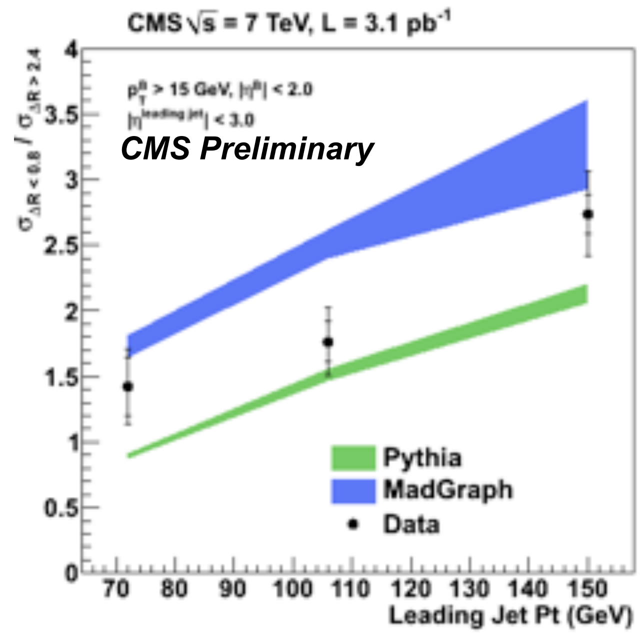


- Angular separation measured ten times more precisely than bin sized allowed by available statistics
- Pythia MC describes very well vertex kinematic variables
  - Used for efficiency and purity correction
  - ΔR and $\Delta\phi$ dependence of secondary vertex finding efficiency cross checked with data-driven technique based on event mixing

Angular correlations: results







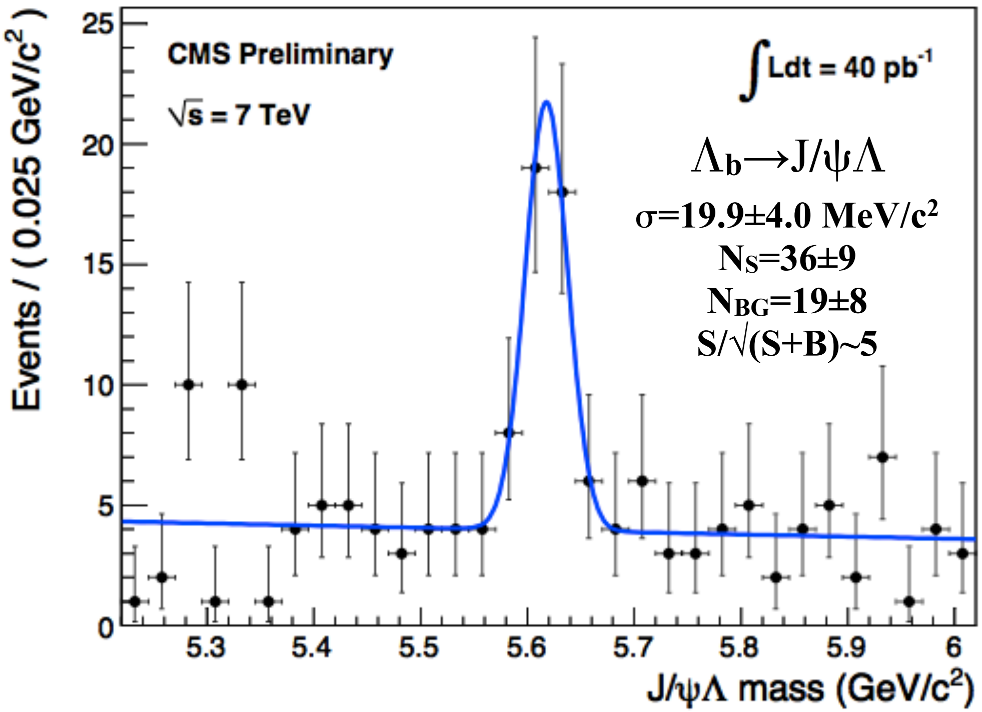
$p_T(B)>15$ GeV, $|\eta(B)|<2$, $|\eta(\text{lead.jet})|<3$

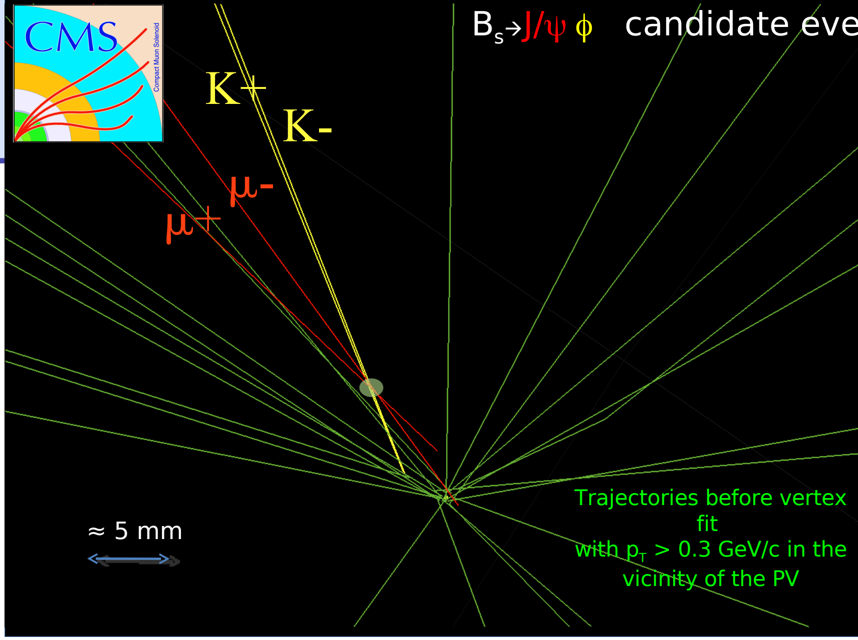
MC normalized to yellow region for shape comparison in the collinear BB region

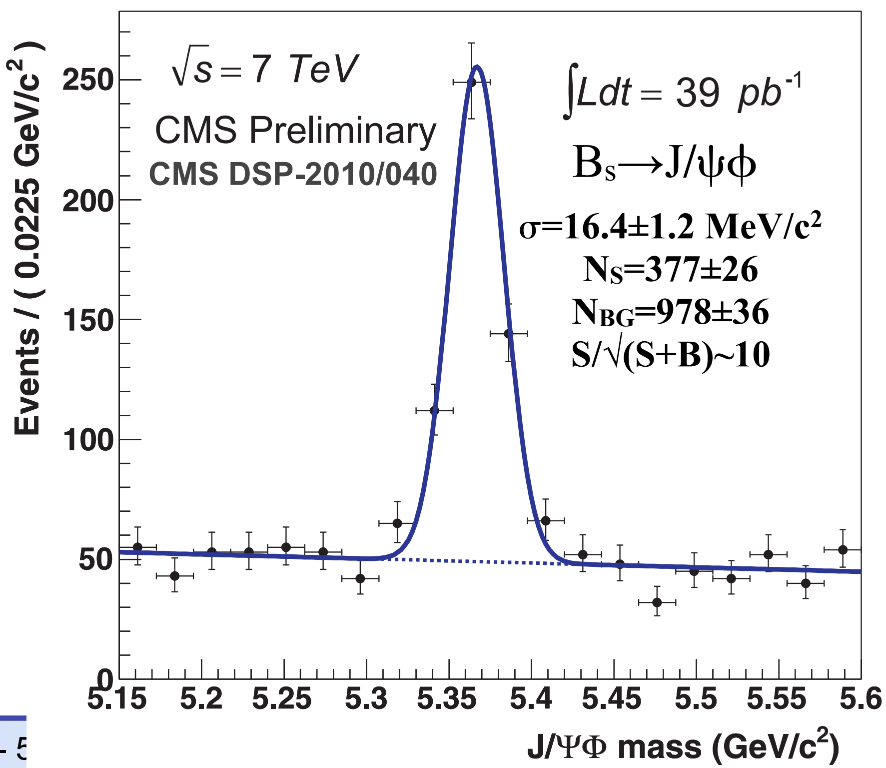
Ratio of collinear over back-to-back region

- Sizable fraction of total $B\bar{B}$ cross section from collinear B-hadron pairs
- Fraction of collinear $B\bar{B}$ production increases with leading jet p_T
- Data points between Pythia and Madgraph MC. MC@NLO and CASCADE below and above the data, respectively

Other B hadrons



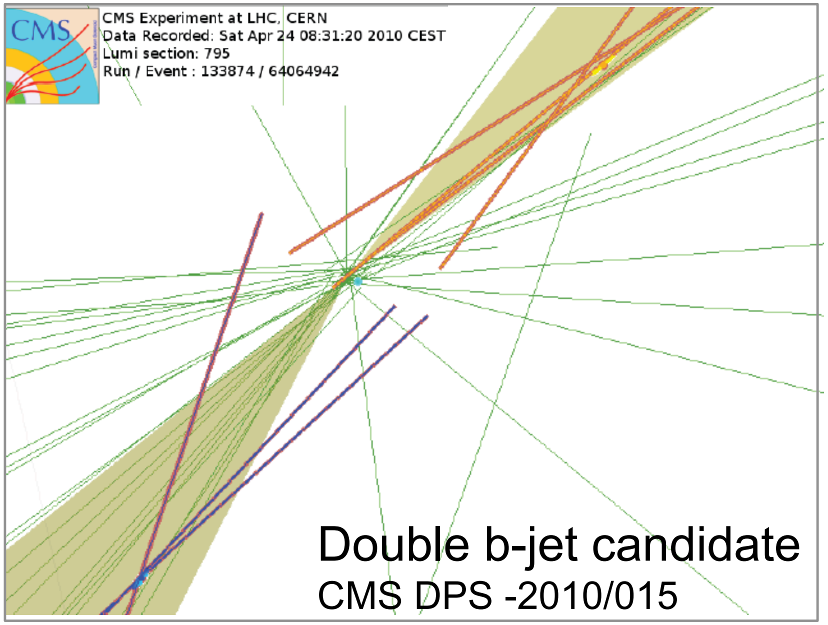


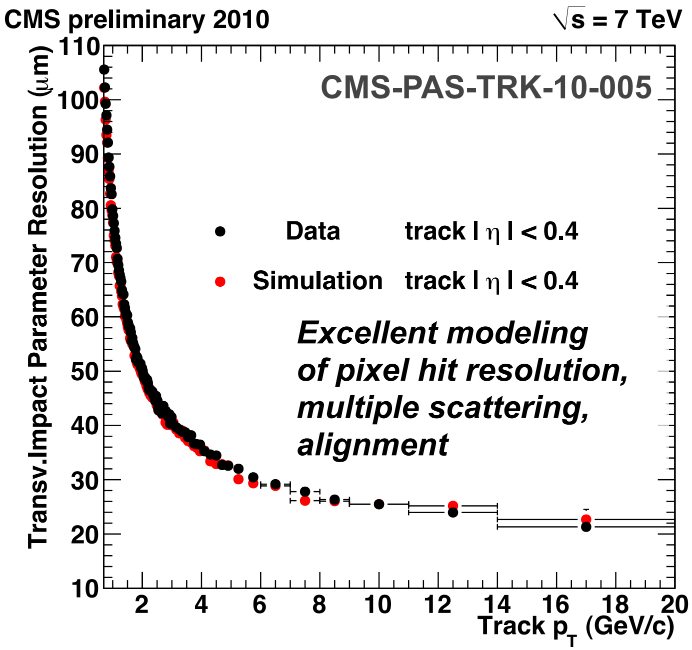


Conclusions

- **First measurements of b-quark production in central region for p-p collisions at $\sqrt{s}$=7 TeV available**
- **Several experimental techniques adopted: semileptonic decays, b-tagged jets, exclusive B hadron decays**
  - **MC@NLO+Herwig generally below the data at very low p_T and central region. Shape differences from jet measurements at large p_T and forward rapidities**
  - **FONLL and POWHEG+Pythia in better agreement with the data**
  - **Pythia above the data for p_T below 50 GeV, does better at high pT**
- **B hadron angular correlations studies. First 3D measurement of collinear BB pairs performed at LHC!**
  - **Collinear BB production is a sizable fraction of the b cross section at the LHC, it increases with the transverse energy of the leading jet**
  - **Fraction of collinear production between Pythia and Madgraph predictions. MC@NLO below the data.**

BACKUP

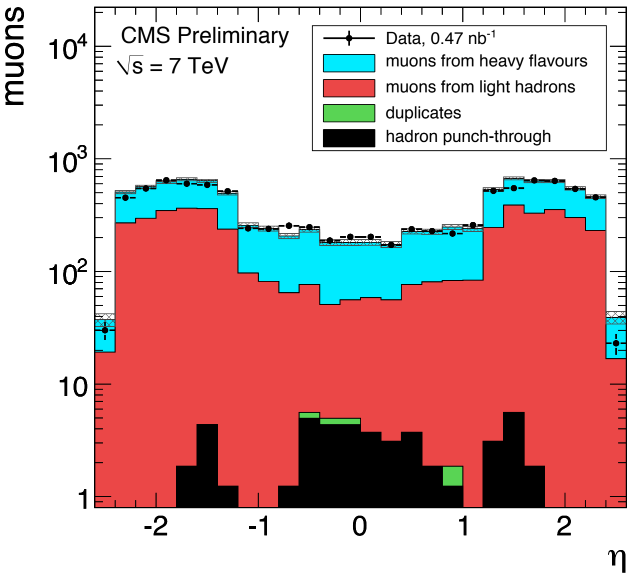

CMS Experiment at LHC, CERN
Data Recorded: Sat Apr 24 08:31:20 2010 CEST
Lumi section: 795
Run / Event : 133874 / 64064942
Double b-jet candidate
CMS DPS -2010/015

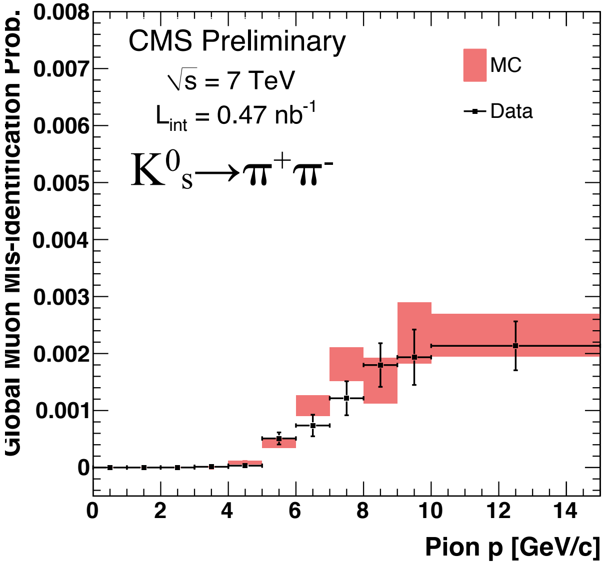

CMS preliminary 2010
√s = 7 TeV
CMS-PAS-TRK-10-005
Data track | η | < 0.4
Simulation track | η | < 0.4
Excellent modeling
of pixel hit resolution,
multiple scattering,
alignment
Transv.Impact Parameter Resolution (μm)
Track p_T (GeV/c)
10
20
30
40
50
60
70
80
90
100
110
2
4
6
8
10
12
14
16
18
20

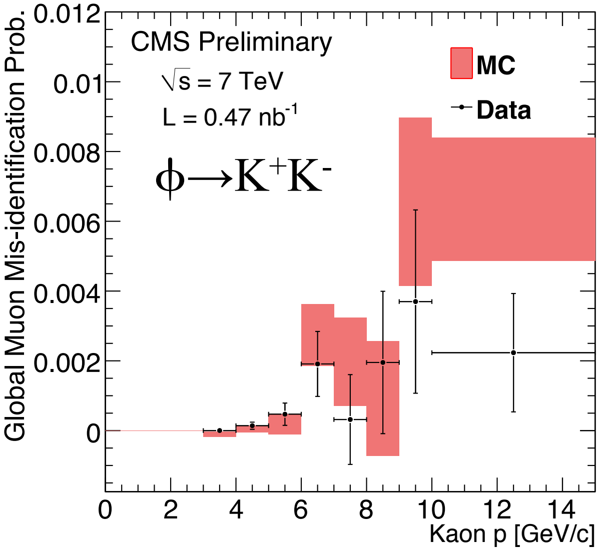
Muon ID performance

Min-bias dataset

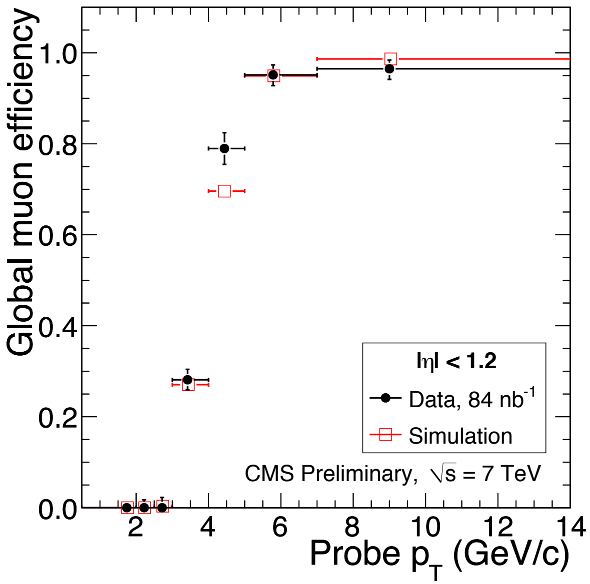
CMS-PAS-MUO-10-002







- Muon identification based on outside-in matching of muon segments with tracks in the inner tracks, "*Global muons*"
- Fraction of muons from Pions, Kaons and Protons verified with resonance decays
- Muon efficiency reconstruction verified with a "tag-and-probe" technique on J/ψ decays

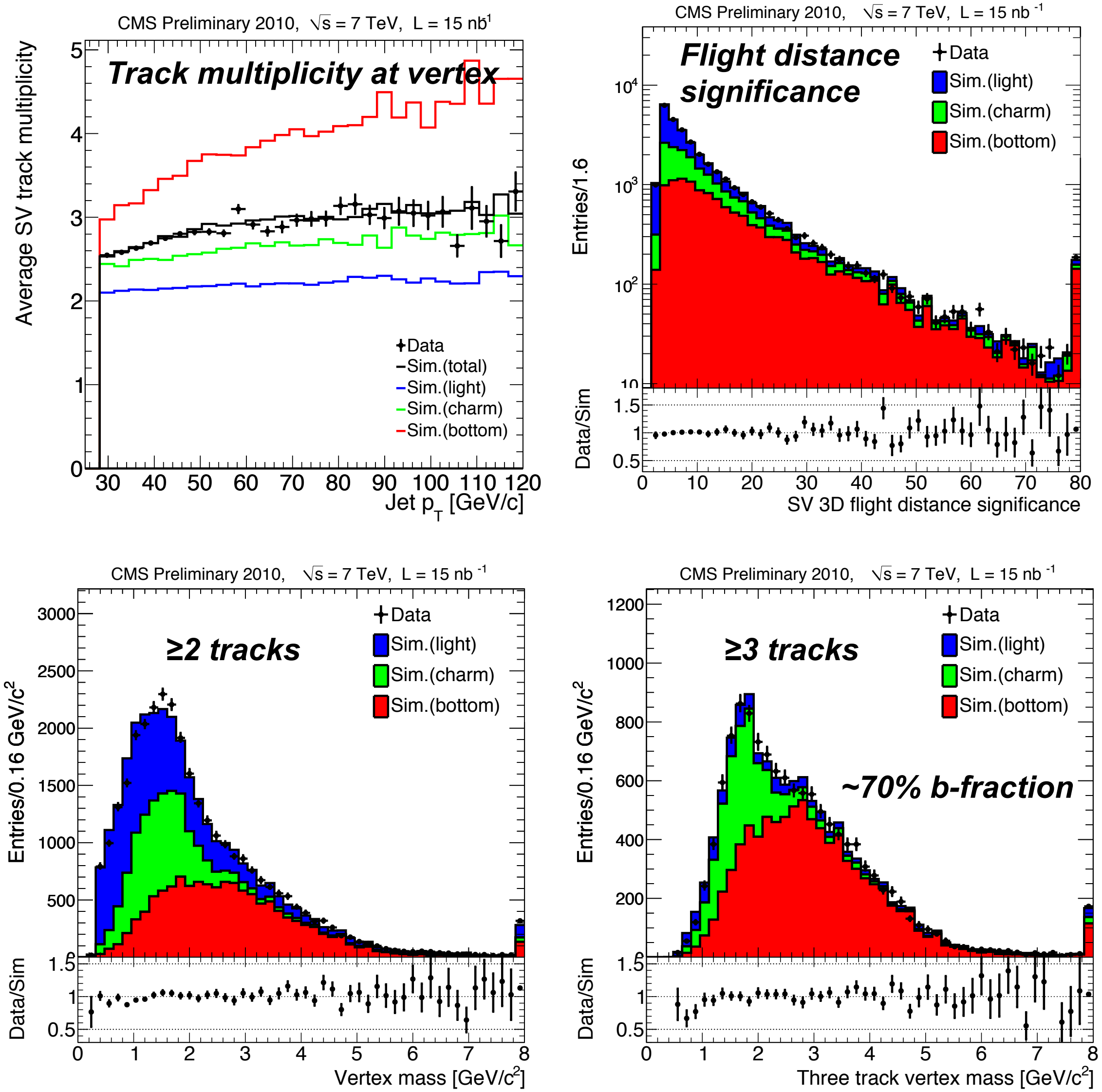


Muon cross section: systematics

source	uncertainty
Trigger	3–5 %
Muon reconstruction	3 %
Tracking efficiency	2 %
Background template shape uncertainty	1–10 %
Background composition	3–6 %
Production mechanism	2–5 %
Fragmentation	1–4 %
Decay	3 %
MC statistics	1–4 %
Underlying Event	10 %
Luminosity	11 %
total	16–20 %

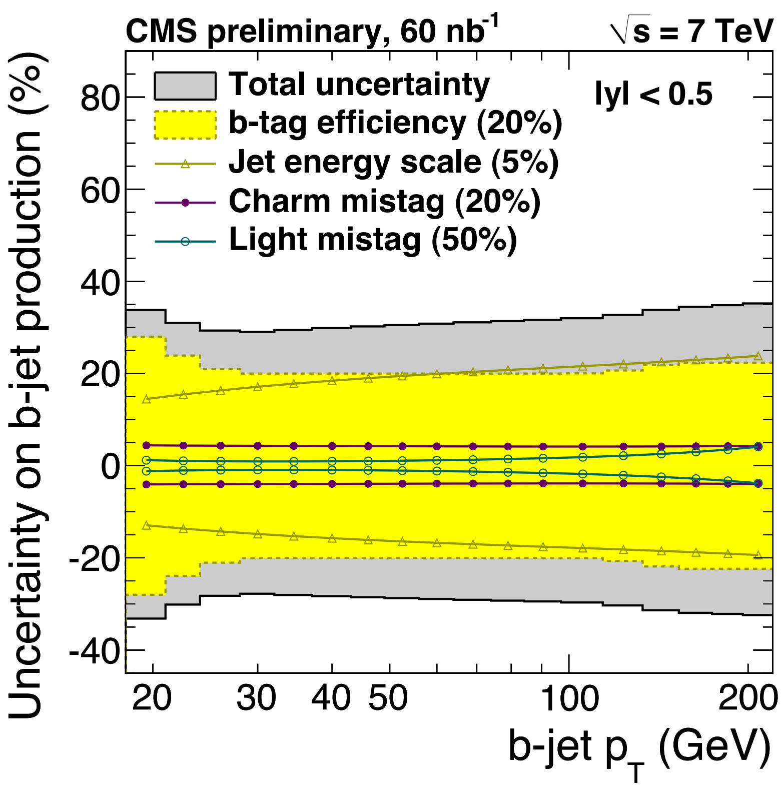
Secondary vertices

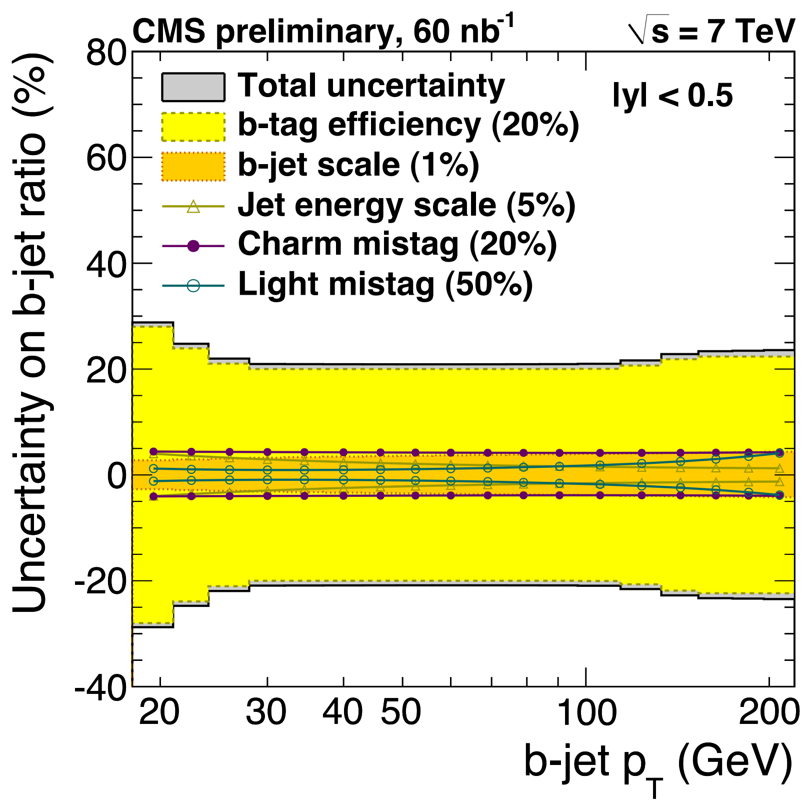
CMS-PAS-BTV-10-001



- Based on primary vertex finder tool applied to tracks in a jet
- Commissioning of secondary vertex reconstruction shows very good understanding of discrimination variables
  - **Track multiplicity**
  - **Flight distance significance**
- Invariant mass of tracks associated to the vertex is a useful tool to verify sample purity after tagging

B jets: systematic uncertainties





B+ cross section

p_T^B (GeV)	n_{sig}	ϵ (%)	$d\sigma/dp_T^B$ (μb/GeV)	MC@NLO	PYTHIA
5–10	223 ± 26	1.56 ± 0.02	$4.07 \pm 0.47 \pm 0.31$	$2.76^{+1.09}_{-0.62}$	4.92
10–13	236 ± 21	7.62 ± 0.11	$1.47 \pm 0.13 \pm 0.09$	$0.88^{+0.23}_{-0.19}$	2.07
13–17	169 ± 17	14.6 ± 0.2	$0.412 \pm 0.041 \pm 0.026$	$0.37^{+0.04}_{-0.07}$	0.81
17–24	207 ± 17	23.3 ± 0.6	$0.181 \pm 0.015 \pm 0.012$	$0.12^{+0.04}_{-0.04}$	0.22
24–30	56 ± 9	31.9 ± 1.5	$0.042 \pm 0.007 \pm 0.004$	$0.035^{+0.020}_{-0.003}$	0.06
> 30	44 ± 8	33.4 ± 2.0	$0.188 \pm 0.034 \pm 0.018$	$0.15^{+0.07}_{-0.01}$	0.20
$\|y^B\|$	n_{sig}	ϵ (%)	$d\sigma/dy^B$ (μb)	MC@NLO	PYTHIA
0.00–0.60	187 ± 17	3.01 ± 0.06	$7.39 \pm 0.65 \pm 0.53$	$4.45^{+1.51}_{-0.99}$	8.9
0.60–1.10	164 ± 17	3.81 ± 0.08	$6.11 \pm 0.64 \pm 0.47$	$4.55^{+1.37}_{-0.99}$	8.6
1.10–1.45	207 ± 20	5.92 ± 0.12	$7.11 \pm 0.69 \pm 0.59$	$4.50^{+1.47}_{-1.07}$	8.0
1.45–1.80	203 ± 22	8.24 ± 0.15	$5.01 \pm 0.55 \pm 0.42$	$4.21^{+1.81}_{-1.09}$	7.7
1.80–2.40	176 ± 22	6.31 ± 0.12	$3.31 \pm 0.42 \pm 0.28$	$2.62^{+1.07}_{-0.59}$	4.8

Charmed mesons