Inclusive b Production Measurements at CMS

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Outline

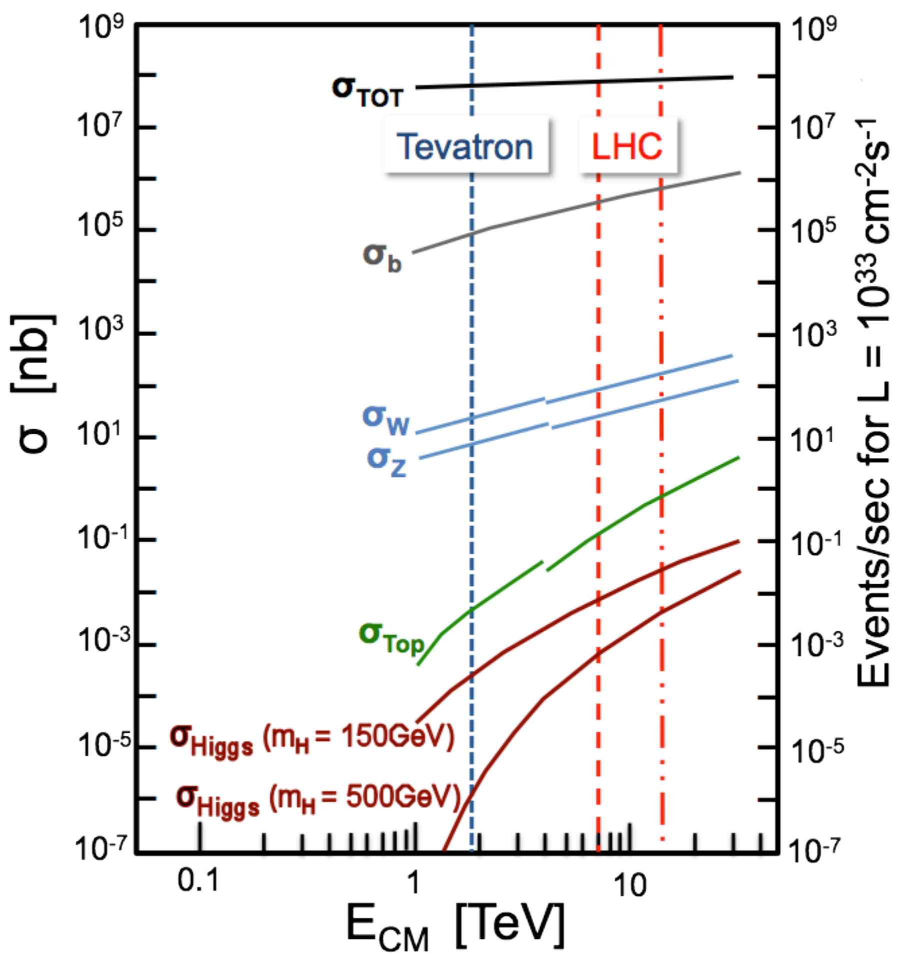
- Introduction
- The CMS Detector and its Performance
- Open Beauty production with Muons
- Inclusive b-jet production
- Conclusions

Introduction

- Heavy Quark production is an important process for the study of QCD

- Many physics processes at the LHC produce b-jets in the final state
  - Pure QCD (access to b PDFs)
  - Decays of various heavy particles (top, W, Z, H, SUSY particles, …)
  - Associated production (with W, Z, H, …)

- Large $b\bar{b}$ production cross section in pp collisions at $\sqrt{s}$ = 7 TeV at LHC
  - Provides access to new regions in phase space and rates
  - b events provide major background to many searches



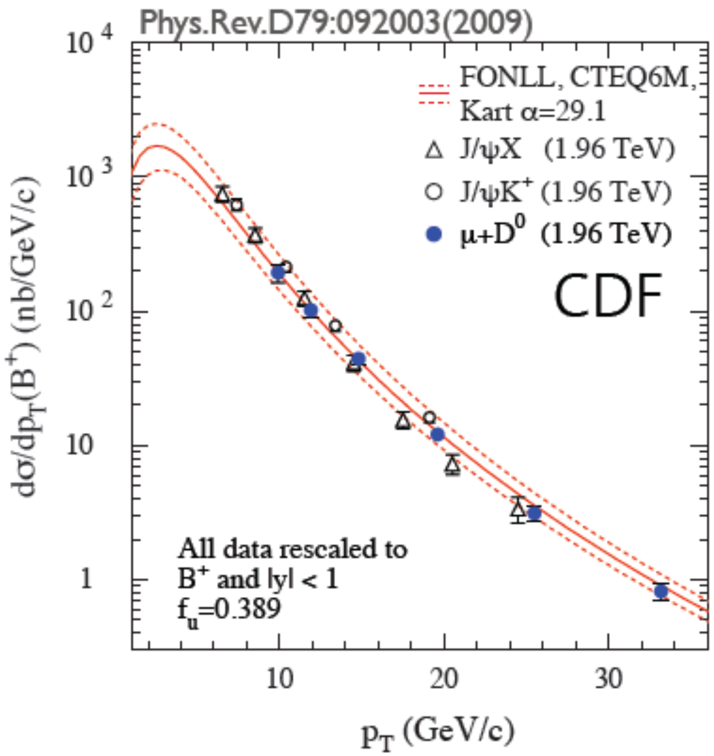
Introduction

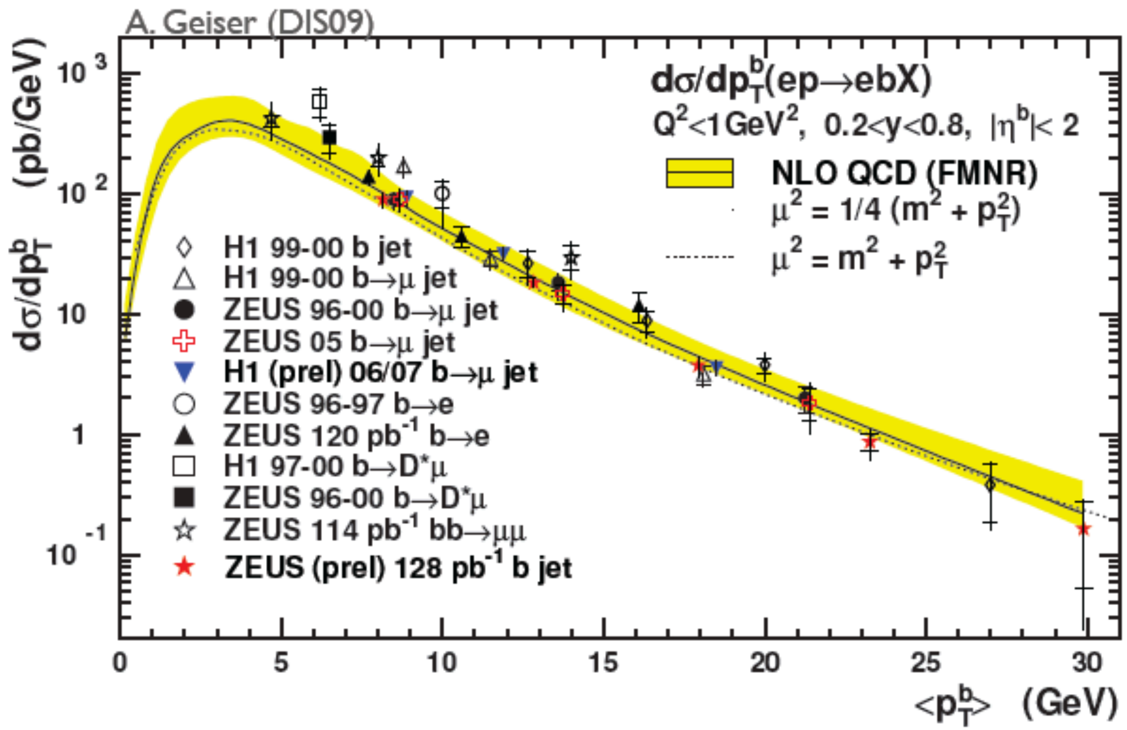
- Previous measurements at other colliders (Tevatron, HERA, LEP, ...)

  - reasonable agreement with NLL/NLO QCD predictions

  - sizeable uncertainties

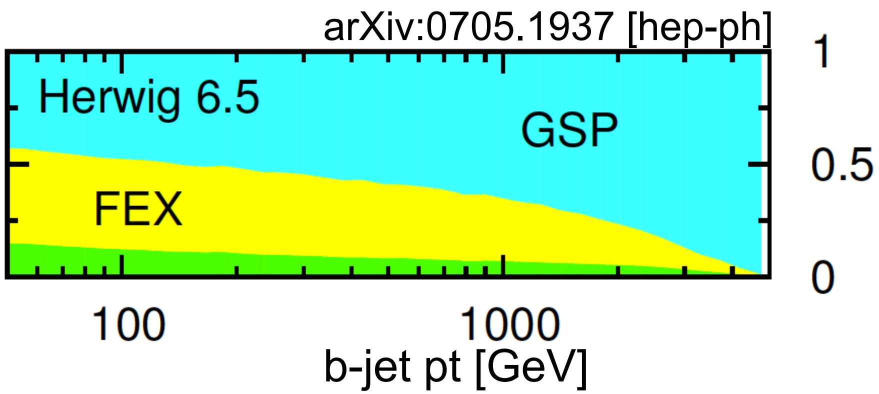
- Great interest to verify the results at higher center-of-mass energy provided by the LHC

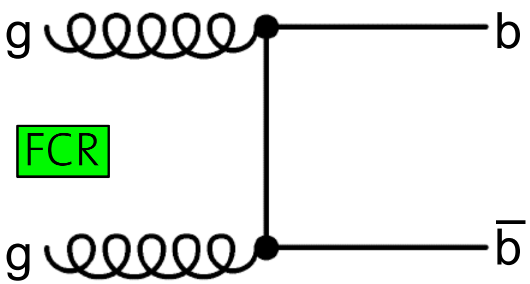


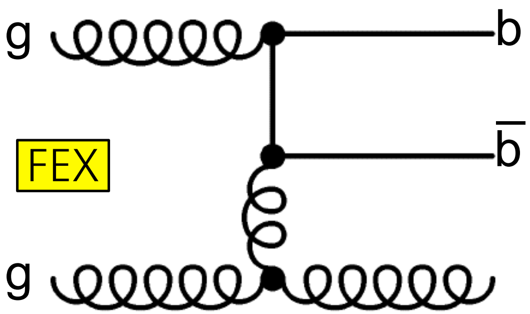


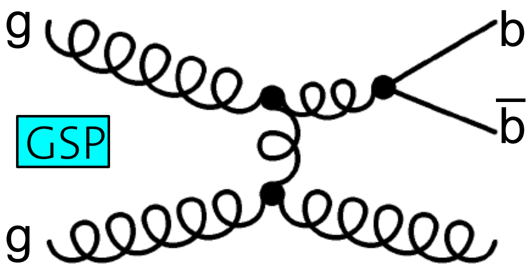
Heavy Quark Production

- LO
  - Flavor creation (FCR): gg fusion (dominant) and $q\bar{q}$ annihilation
- Large NLO contributions
  - Flavor excitation (FEX): $b\bar{b}$ from the sea, only one b participates in hard scattering
  - Gluon splitting (GSP): g → $b\bar{b}$ in initial or final state
- Production mechanism not separated in analyses presented here



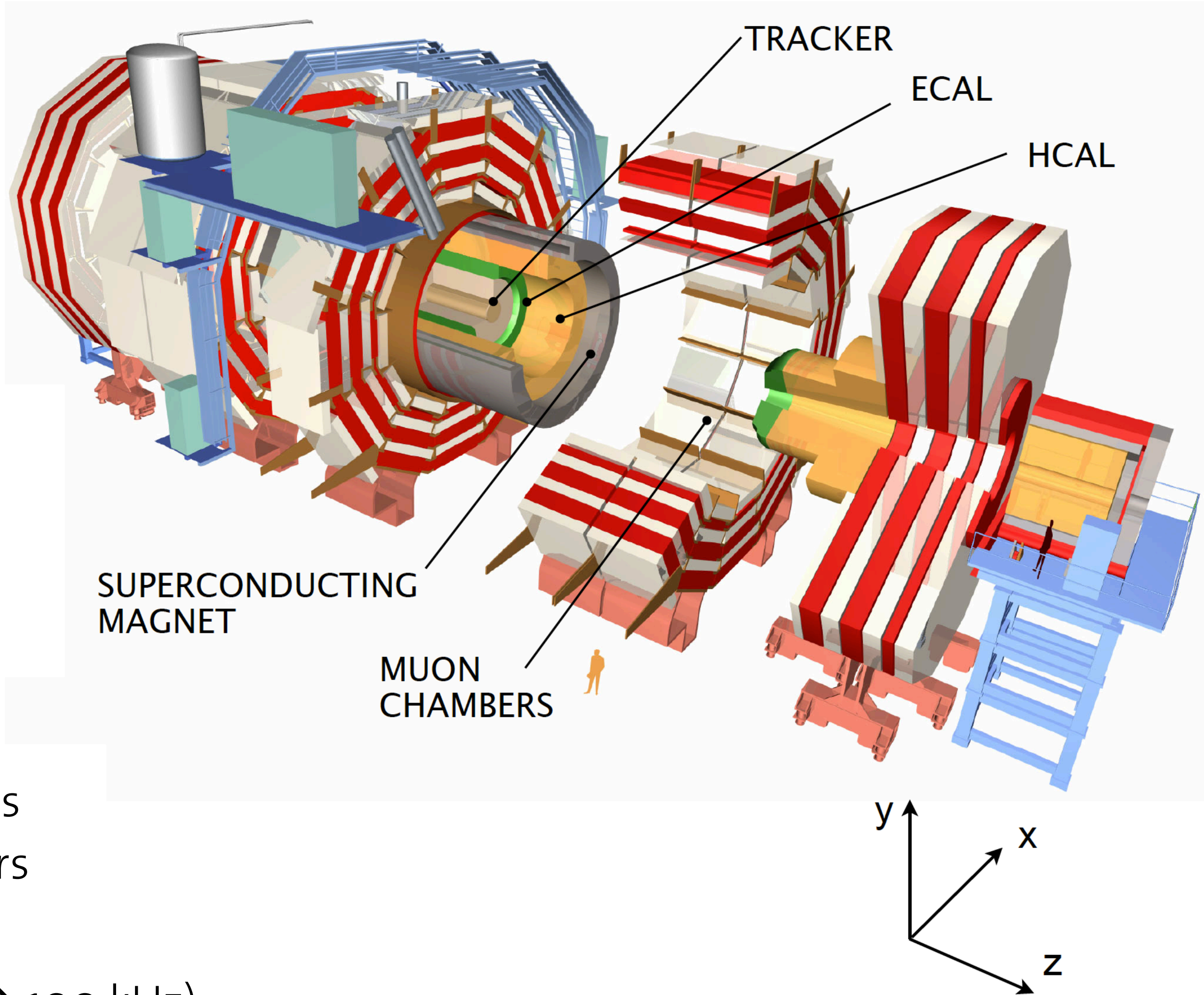






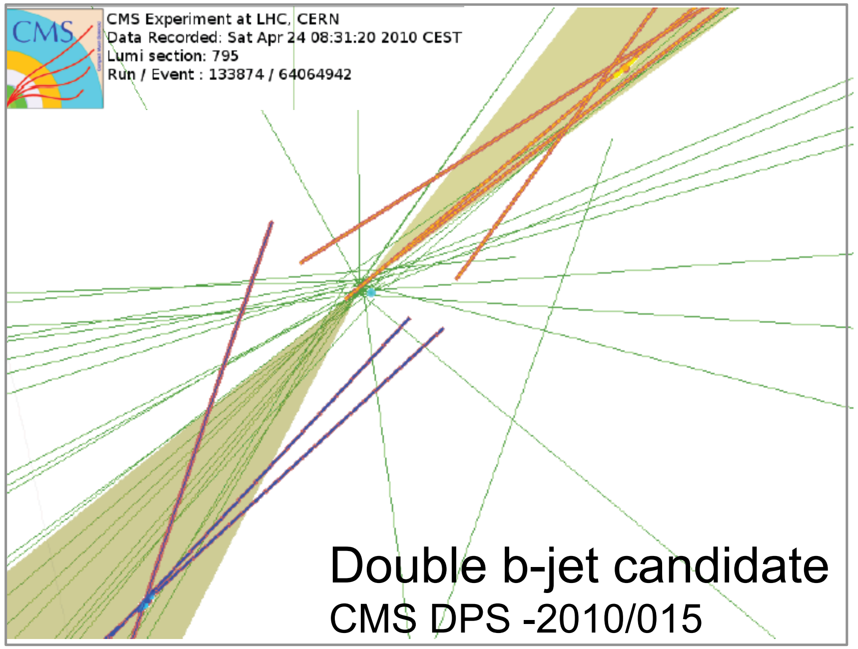
The CMS Detector

- Magnet
  - 3.8 T
- Tracking
  - 200 m² silicon
  - pixels and strip
- Calorimeter
  - ECAL: 76 000 $PbWO_4$ crystals
  - HCAL: brass absorbers and scintillators
- Muon System
  - Drift Tube Chambers
  - Cathode Strip Chambers
  - Resistive Plate Chambers
- Trigger System
  - L1: hardware (40 MHz → 100 kHz)
  - HLT: software (100 kHz → 100 Hz)

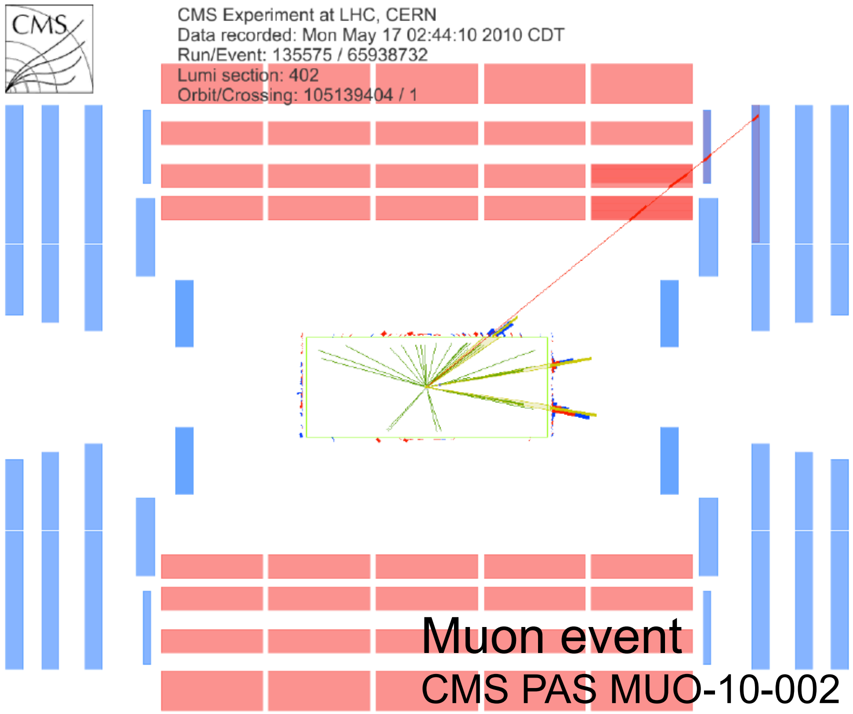


b Identification at CMS

- Use of distinct properties of b quarks
  - long lifetime, large mass, hard fragmentation
- Semi-leptonic and hadronic decays
- Tracking and muon detectors are main subdetectors for early heavy flavor physics
  - Pixel detector for precise reconstruction of secondary vertices
  - Muon system with ability to trigger on low p_T muons ($p_T > 3$ GeV)



Double b-jet candidate
CMS DPS -2010/015

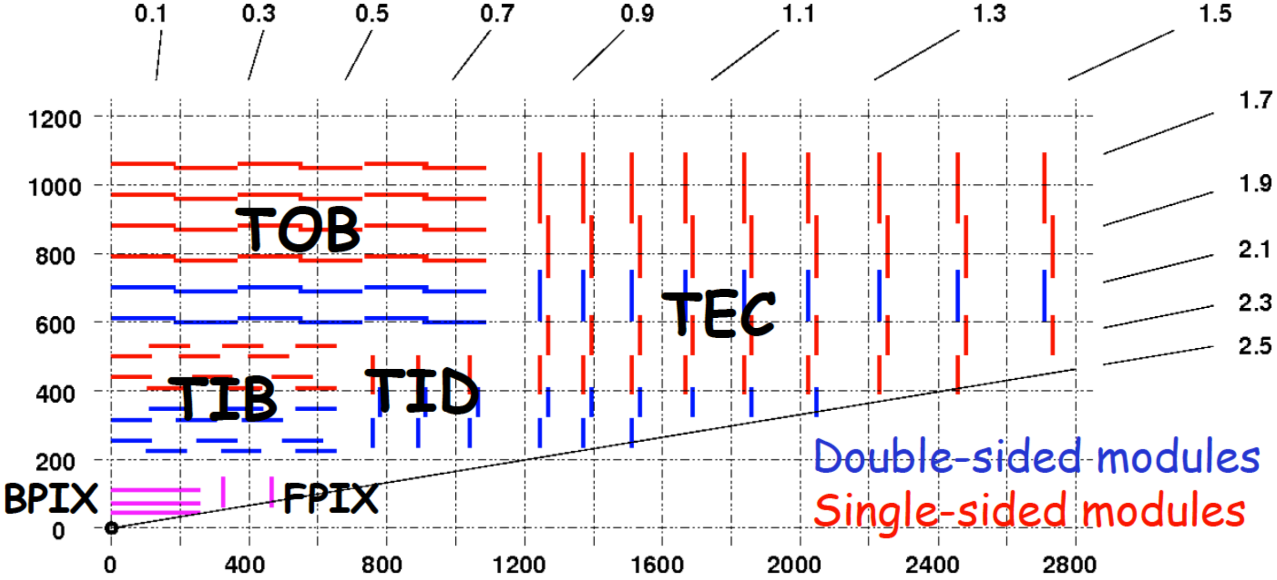


Muon event
CMS PAS MUO-10-002

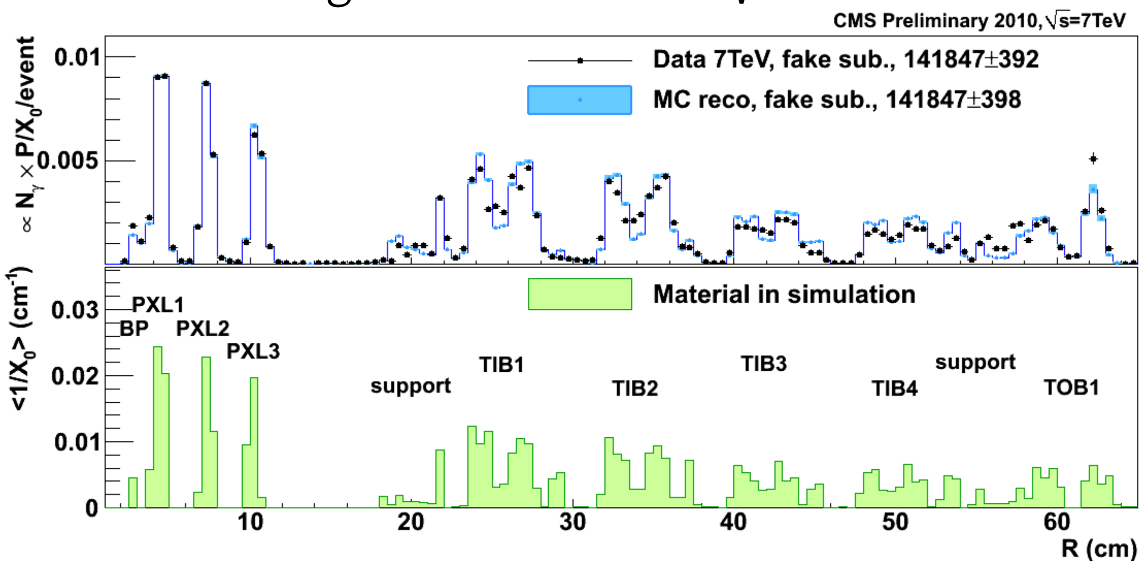
CMS Tracker

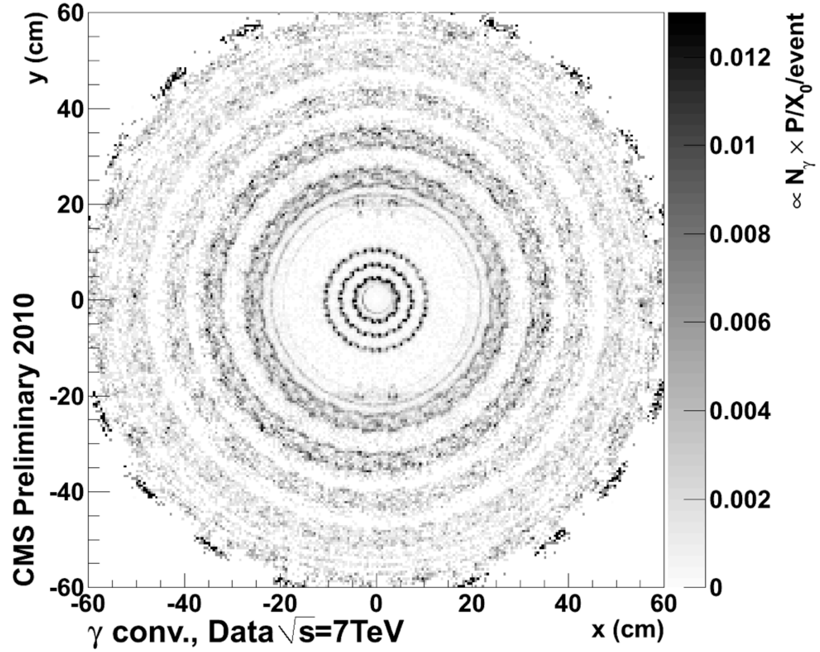
10 M strips

60 M pixels



Material budget estimate from γ conversion

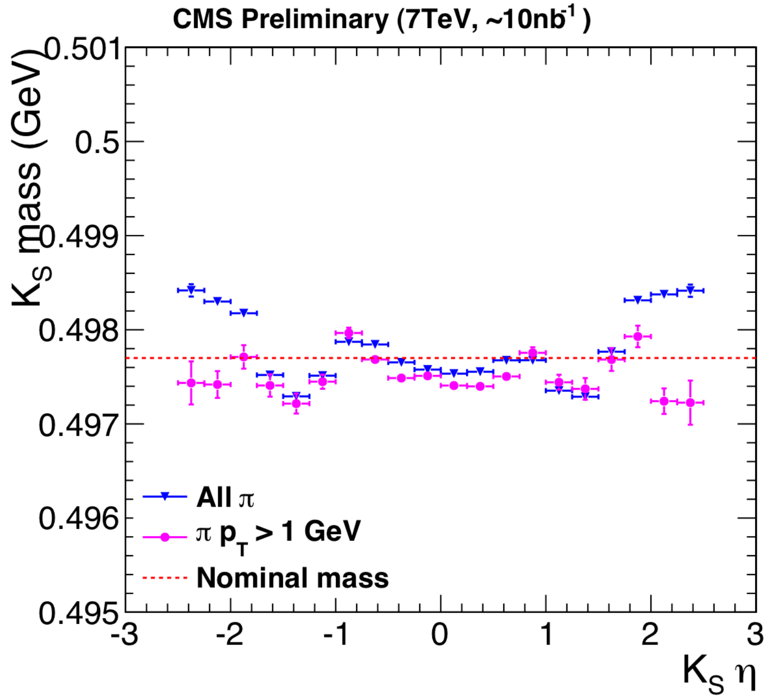


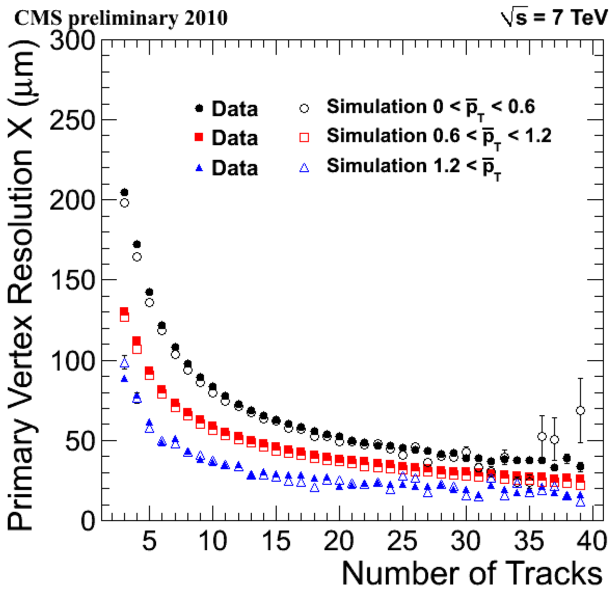


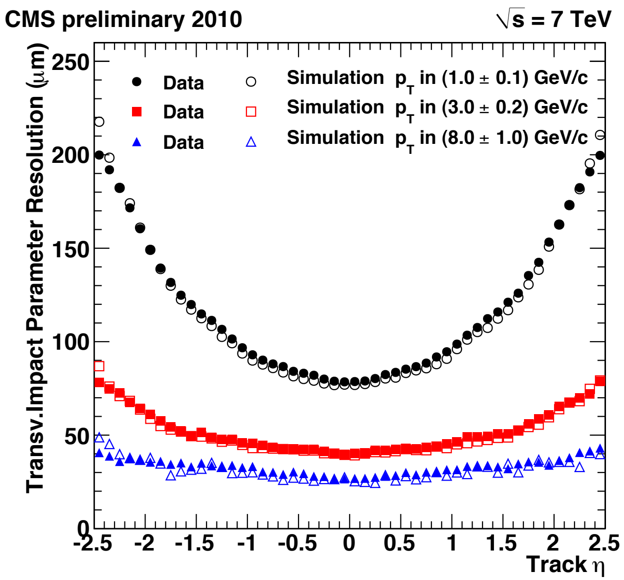
=> Data and simulation agree within 10%

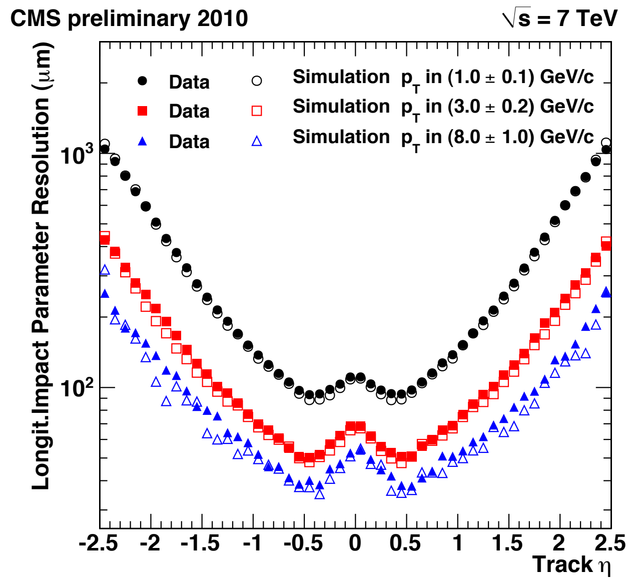
Tracker Performance

- CMS Tracker is well understood and performing as expected from simulation
  - Momentum scale measurement using K_S mass
  - Primary vertex resolution
  - Track impact parameter resolution

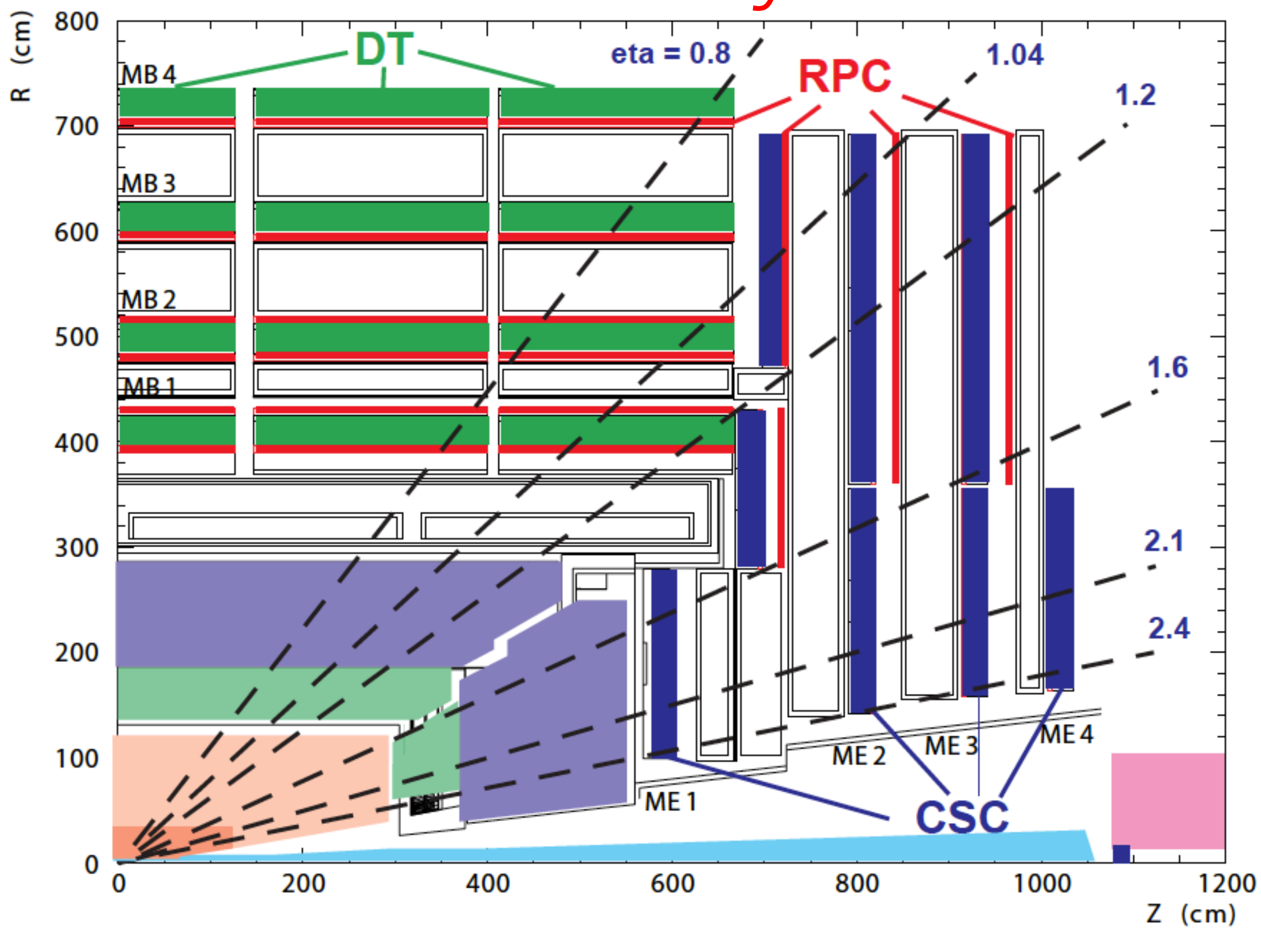








CMS Muon System



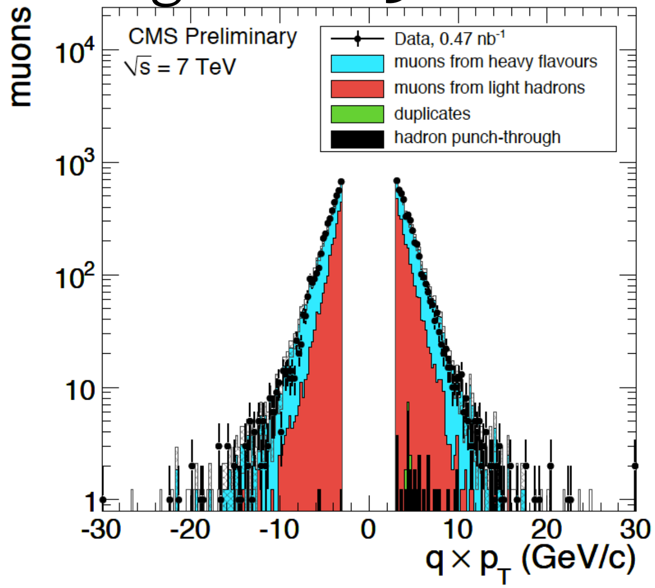
- Three different algorithms for muon reconstruction:
  - Standalone muons
  - Tracker muons
  - Global muons (combined fit of hits in tracker and muon system)

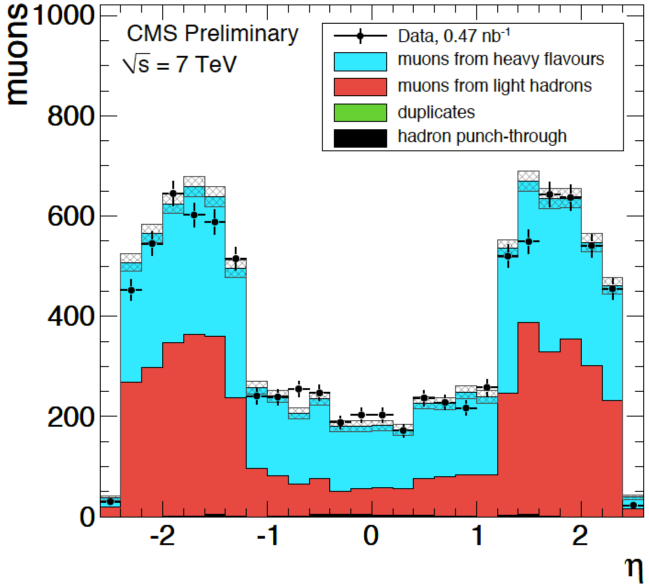
    ↘ used in the analyses presented here

Performance of Global Muon Reconstruction

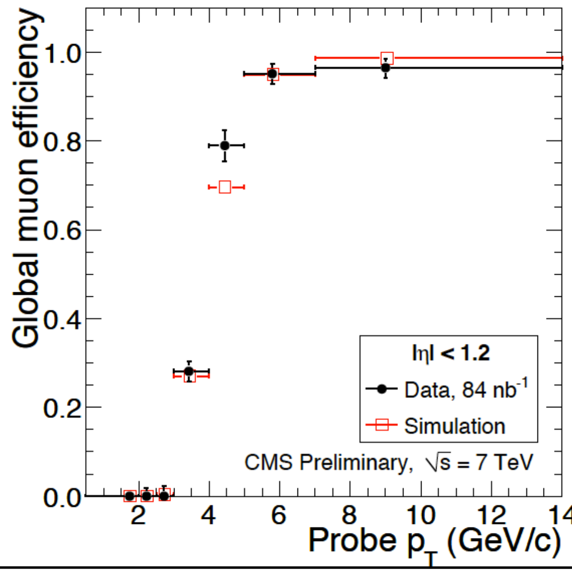
- Muon system well commissioned in cosmic runs 2008/09 and early collision data taking in 2009/10

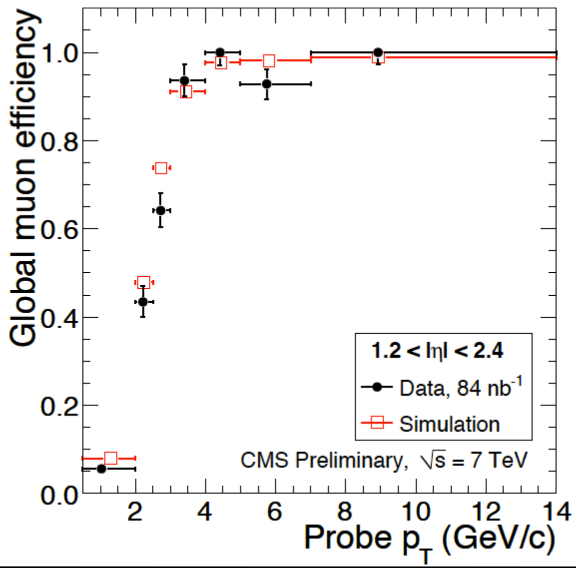
Kinematic distributions in minimum bias events





Global muon reconstruction efficiency (measured from data using J/Ψ resonance)





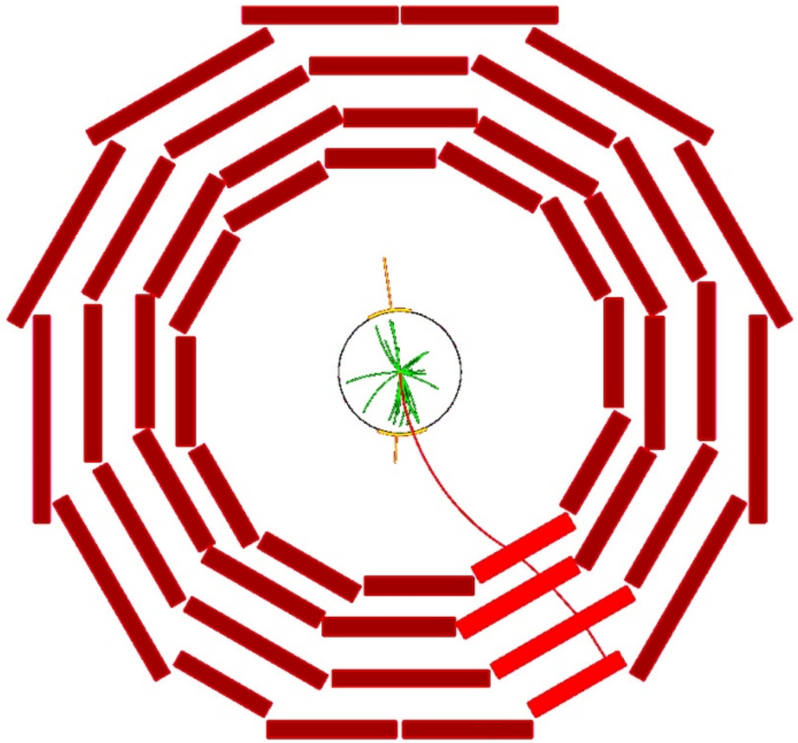
Measurements of Inclusive b Production at CMS

- Based on LHC data collected by the CMS experiment between March and July 2010
- Presented at ICHEP 2010

- Open beauty production cross section with muons in pp collisions at $\sqrt{s}$ = 7 TeV ($L = 8\ nb^{-1}$)
  CMS PAS BPH-10-007
- Measurement of the inclusive b-jet production in pp collisions at $\sqrt{s}$ = 7 TeV ($L = 60\ nb^{-1}$)
  CMS PAS BPH-10-009

- Two independent measurements with their own systematic uncertainties and covering different regions in phase space

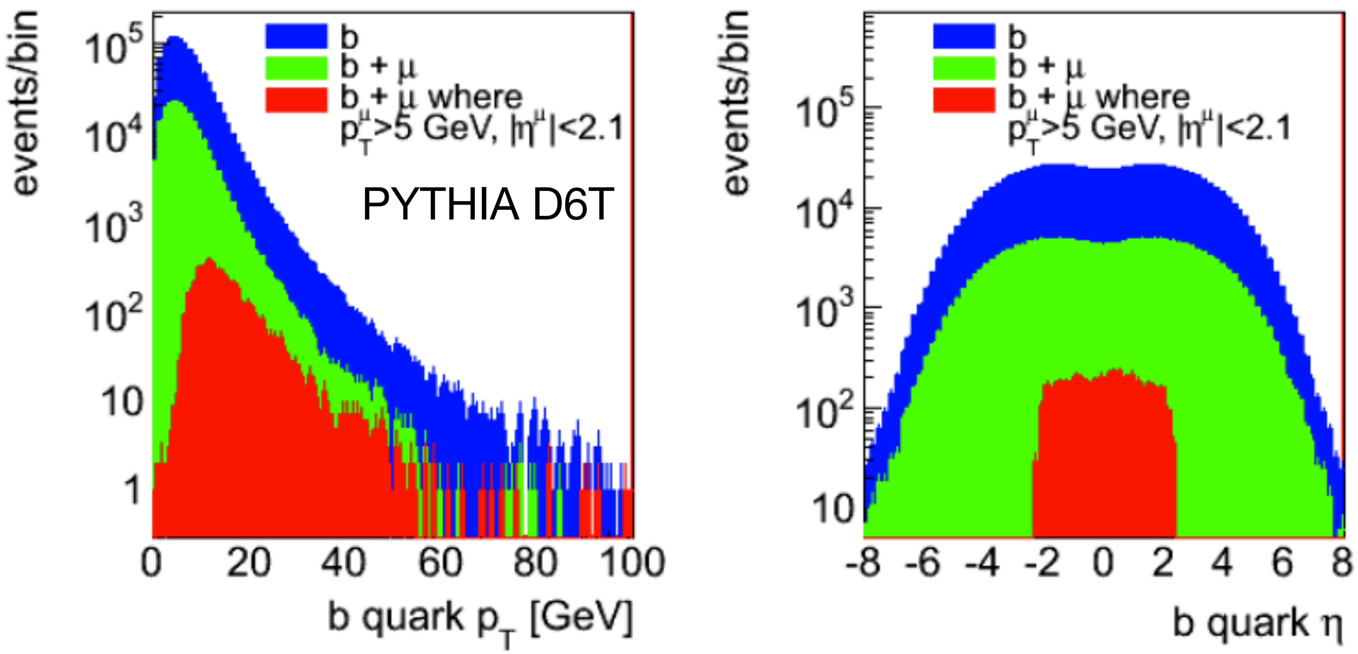
Open Beauty Production with Muons



Open Beauty Production with Muons

- Semi-leptonic b decays into muons
  - Direct ($b \rightarrow \mu X$) and cascade ($b \rightarrow c \rightarrow \mu X$) decays
  - Kinematic selection: muon $p_T > 6$ GeV, $|\eta| < 2.1$
  - $\Rightarrow$ Acceptance ≈ 1%

- Background
  - Charm decays to muons
  - Fake muons from π/K in-flight decays and hadronic punch through

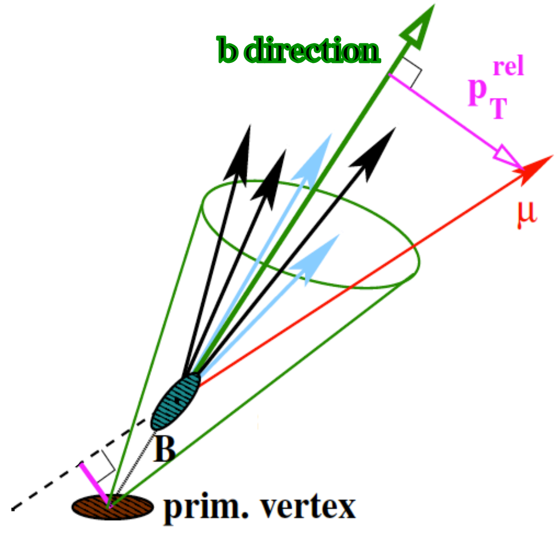


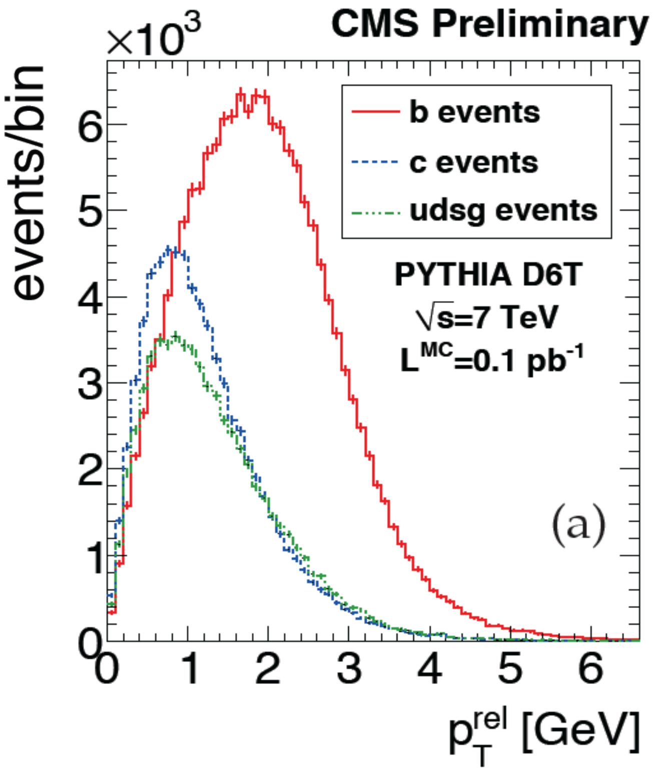
Methodology

- Signal events discriminated from background based on muon p_T^{rel}
  - harder in b-events than in background events due to larger mass of b-quark

- Binned maximum likelihood fit to measured p_T^{rel} distribution based on simulated template distributions

- Measurement of total cross section and differential cross section as a function of muon p_T and pseudo-rapidity



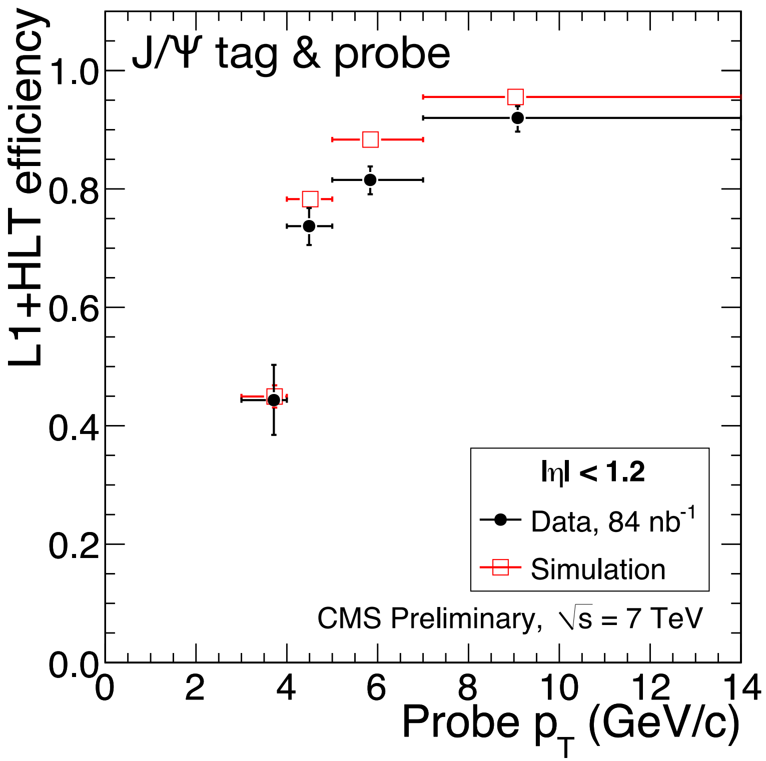


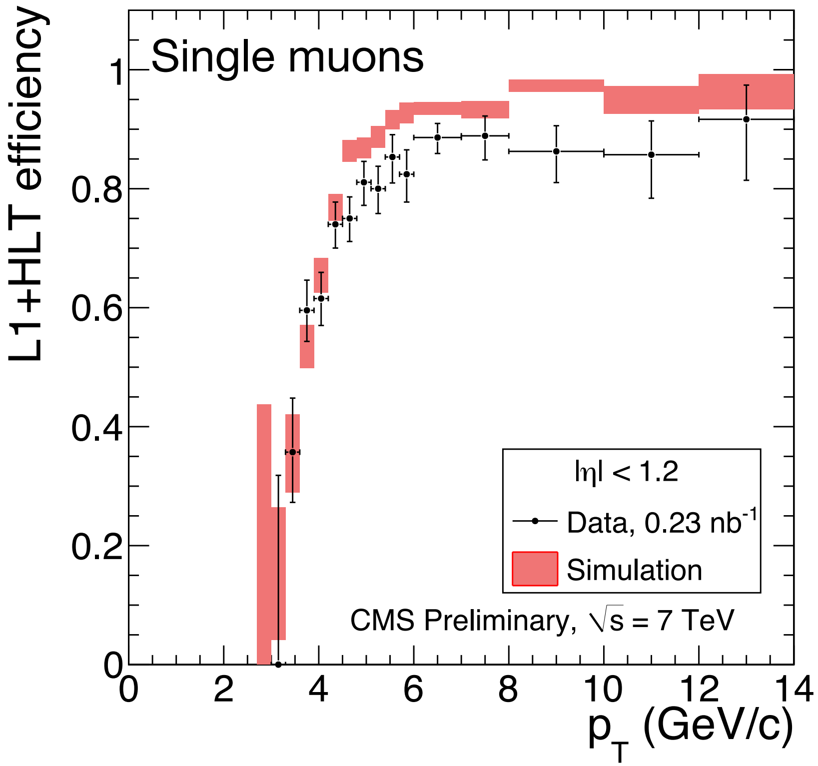
Event Selection

- Data collected in April/May 2010 ($L = 8\ nb^{-1}$)
- Single muon trigger ($p_T > 3$ GeV)
- Primary vertex with >= 3 tracks
- Muon $p_T > 6$ GeV, $|\eta| < 2.1$
  - Efficiency: trigger ~82%, reconstruction ~97%
- b direction reconstructed from tracks only
  - Tracks clustered by anti-k_T (D=0.5) algorithm (→ TrackJets)
  - Muon momentum subtracted from TrackJet momentum
  - p_T^{rel} between muon and closest TrackJet
  - TrackJet provide very good angular resolution (2-8%)
  - Efficiency of 74% to almost 100% depending on muon p_T

Muon Trigger Efficiency

- Derived from data using two independent methods
  - Tag & probe on di-muons from J/Ψ
  - Single muons in minimum bias events
- Efficiency turn-on curve well described by simulation, plateau few percent lower in data
- Efficiency as measured from data is used in analysis

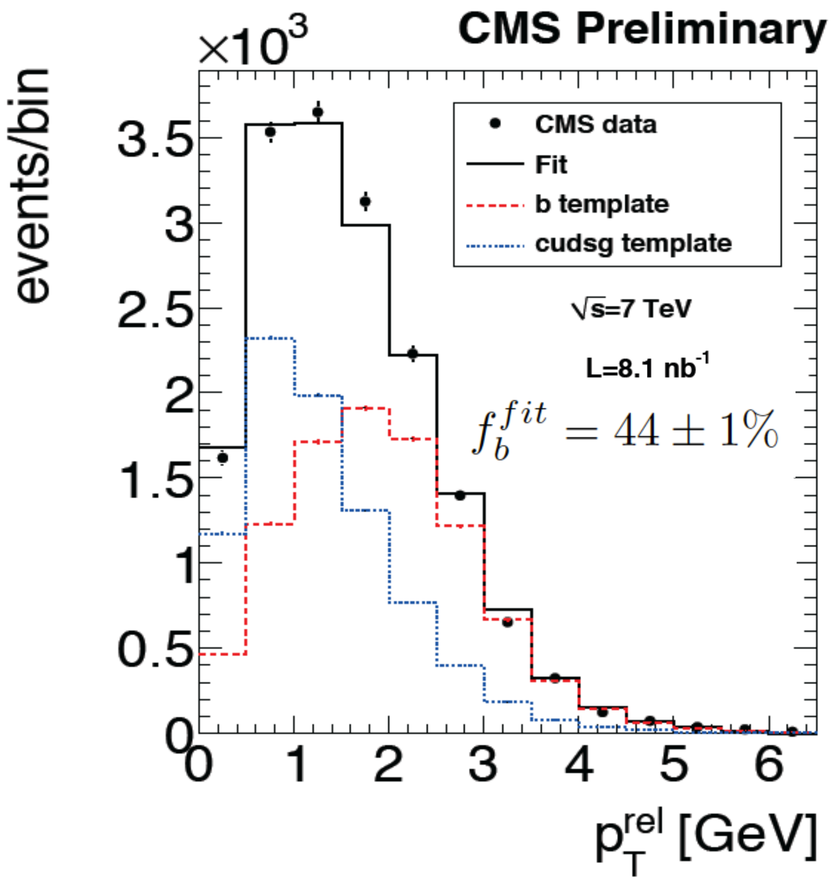




Binned Maximum Likelihood Fit

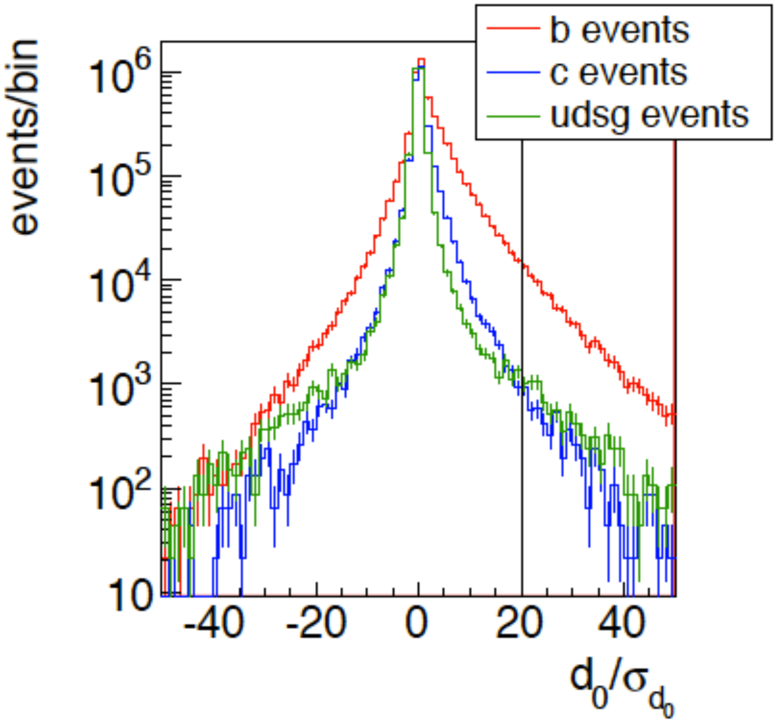
- Binned maximum likelihood fit to measured p_T^{rel} distribution
  - b and c templates from MC (signal validated in b-enriched data)
  - Data-driven template for muons from light quarks and gluons (measurement of in-flight decays)
  - Background combined in fit
  - c-to-udsg background composition treated as systematic uncertainty
  - Different templates for each bin in muon p_T and η

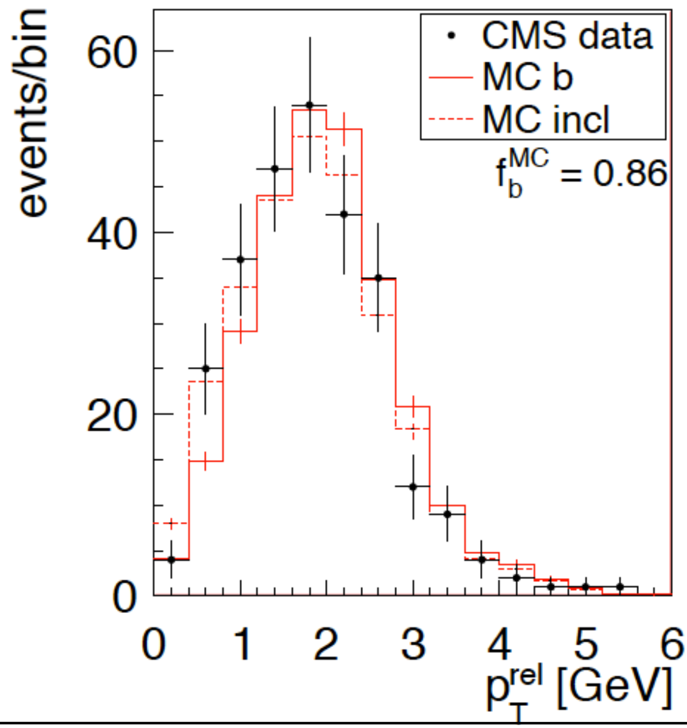
$$N_b^{data} = f_b^{fit} N^{data}$$



Validation of signal p_T^{rel} templates

- Systematic uncertainty of p_T^{rel} shape in b-events
  - due to modelling of b production mechanism, b-quark fragmentation and decay
  - ~7% (determined by comparing different MC tunes and generators)
- Data-driven validation in b-enriched sample obtained by cut on muon impact parameter significance
  - b purity of 86% for $d_0/\sigma_d > 20$
  - Data and MC agree within limited statistics





Determination of background p_T^{rel} templates

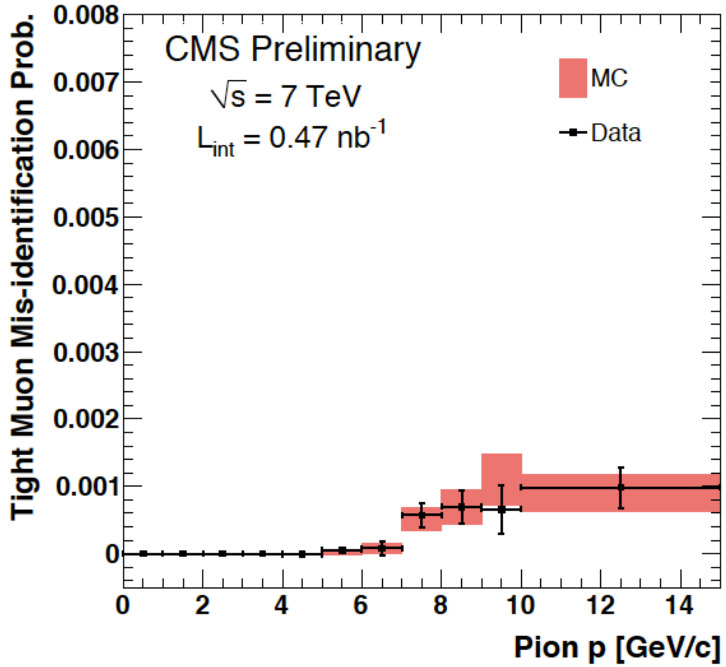
- Muon fake probability measured using low mass resonances

$$K_S{}^0 \rightarrow \pi^+\pi^-, \Lambda \rightarrow p\pi^- \text{ and } \phi \rightarrow K^+K^-.$$

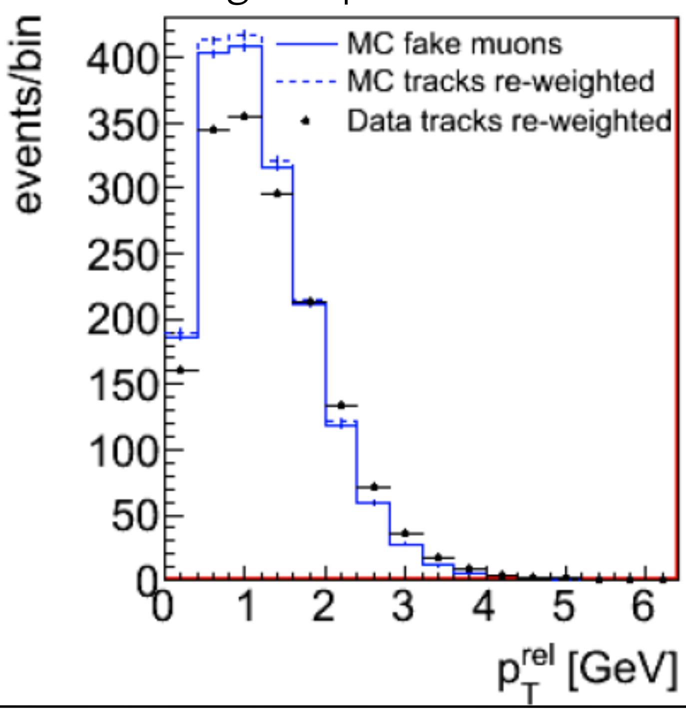
- Data-driven udsg template obtained by re-weighting the hadronic track spectrum in minimum bias events by the muon fake probability and measuring the p_T^{rel} between any track and the closest TrackJet

- p_T^{rel} distribution in data significantly harder (covered by systematics)

Fake probability for pions



udsg template



Cross Section Measurement

- Visible cross section defined by muon kinematic range

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

  - N_b^{data} : number of b events in data determined by the fit
  - ε : trigger and reconstruction efficiency
  - $\mathcal{L}$: integrated luminosity

- Result

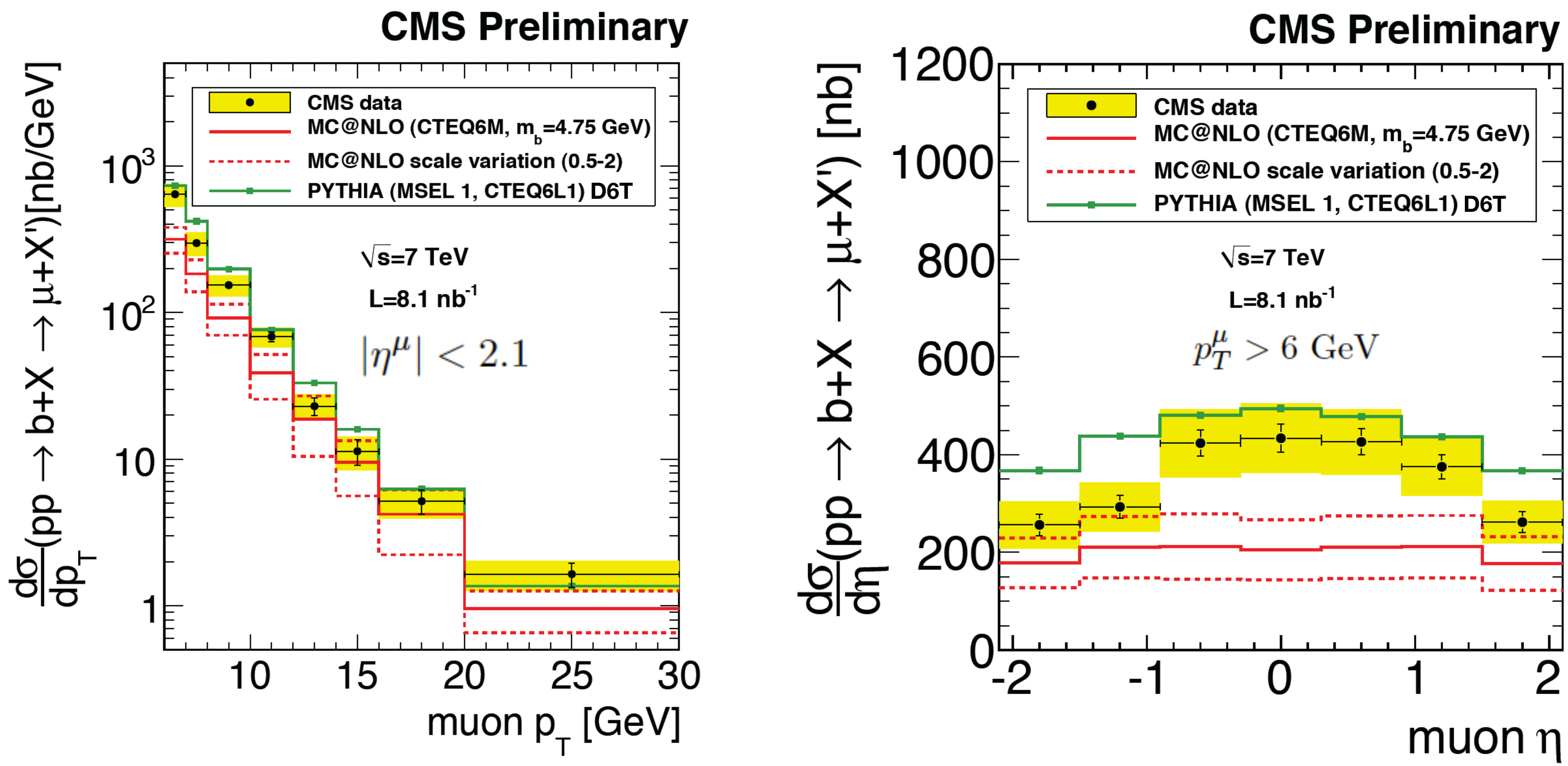
$$\sigma = (1.48 \pm 0.04_{\mathrm{stat}} \pm 0.22_{\mathrm{syst}} \pm 0.16_{\mathrm{lumi}})\,\mu\mathrm{b}$$

- Compared to

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

MC@NLO+HERWIG
CTEQ6M PDF
m_b = 4.75 GeV
$\mu_F = \mu_R = p_T$

Differential b Cross Section at √s = 7 TeV



- Measurement in agreement with MC@NLO for muon $p_T > 12$ GeV, while data is above the prediction in the central region at low p_T

Systematic Uncertainties

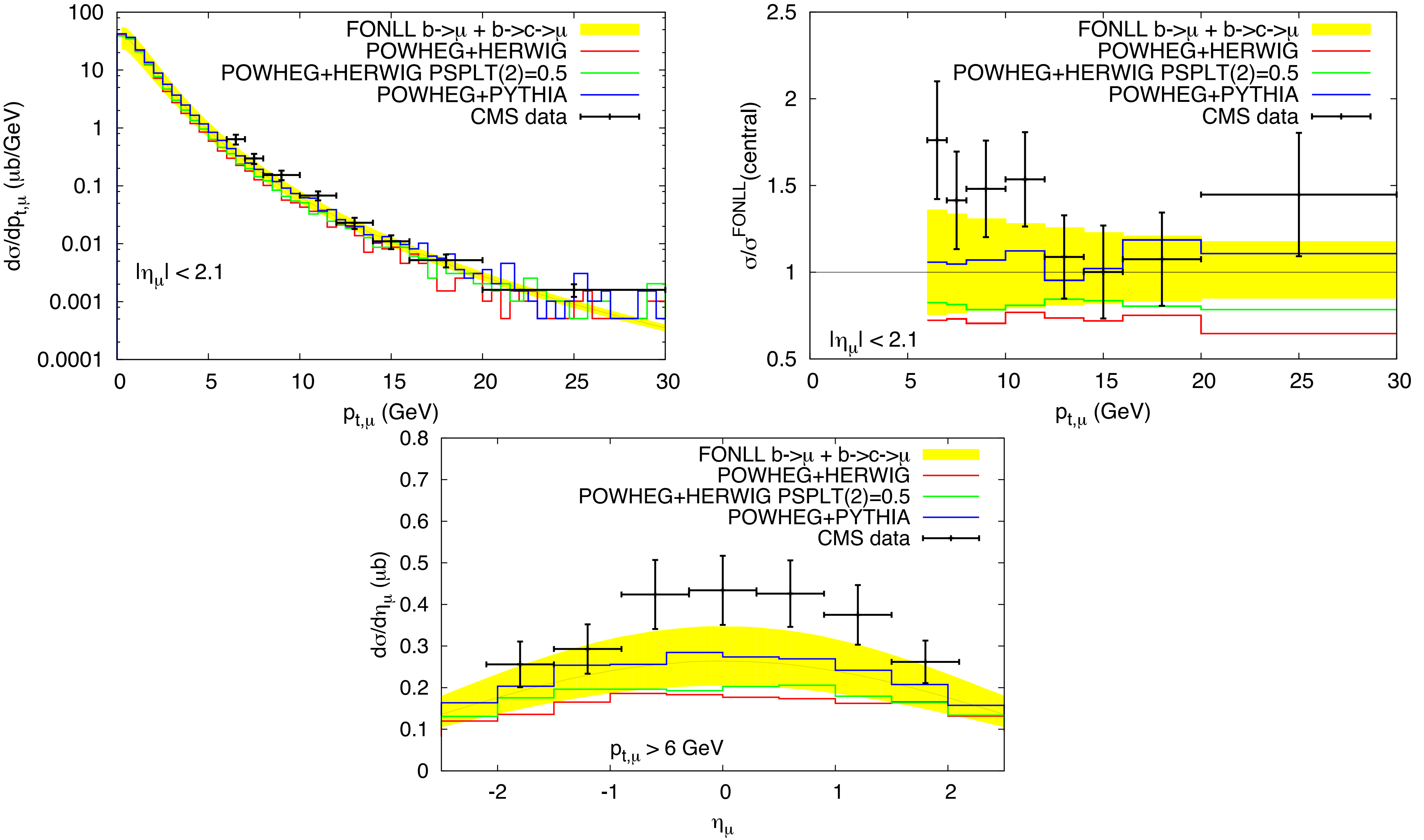
- Systematic uncertainty dominated by the description of the light quark background template and the underlying event as well as the luminosity uncertainty
- Modelling of b production and decay are better understood and have less impact

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 %

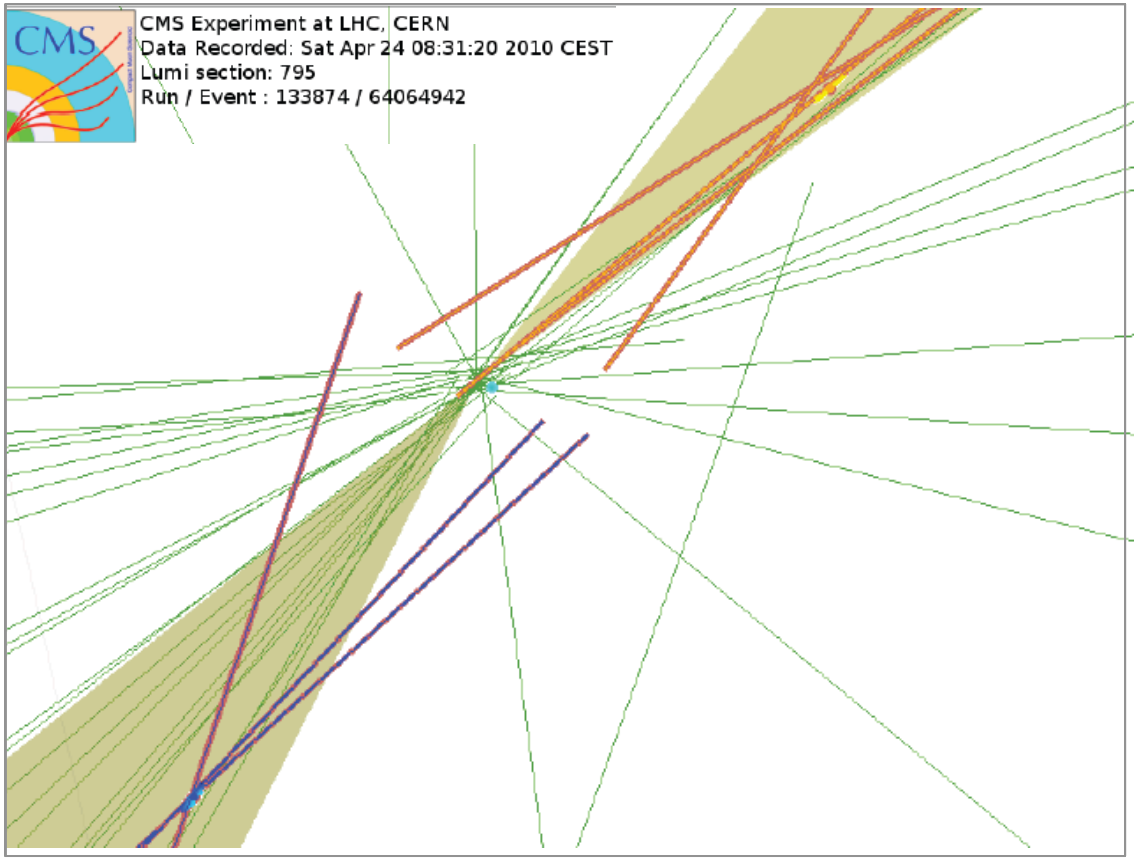
Recent Data/Theory Comparison

(Cacciari and Nason)

- CMS data compared to FONLL calculation



Inclusive b-Jet Production

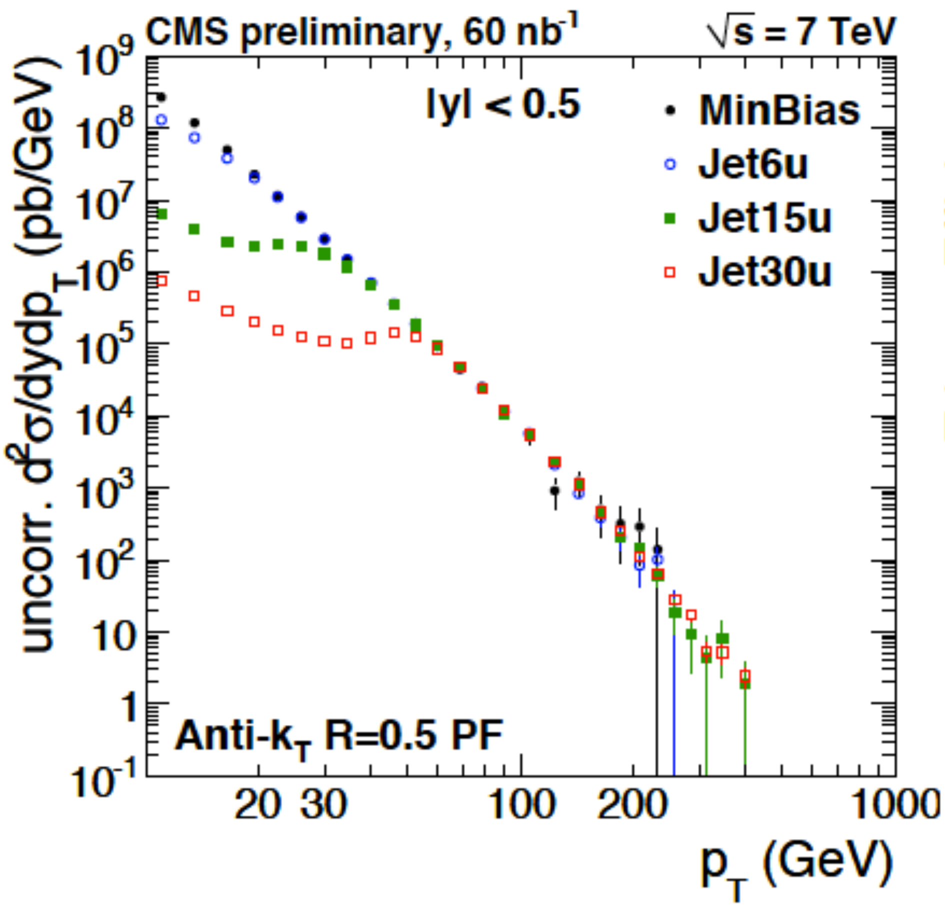


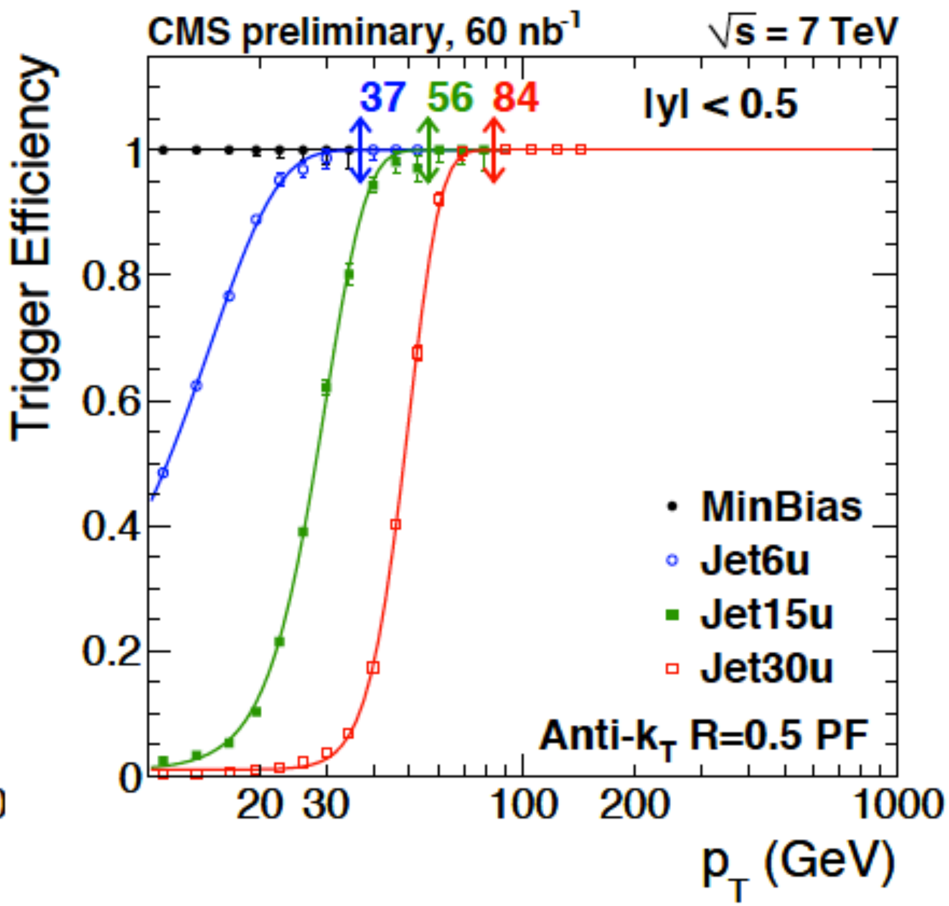
Inclusive b-Jet Production

- Measurement of the inclusive b-jet cross section and ratio to the inclusive jet production with L = 60 nb^{-1}
- Events collected with a combination of minimum bias and jet triggers
- Jets ($18 < p_T < 300$ GeV, $|y| < 2$) reconstructed by anti-k_T algorithm (D=0.5) using tracker and calorimeter information (Particle Flow) to extend measurement to low p_T
- B-tagging based on secondary vertex reconstruction
- Data-driven techniques to control b-tagging efficiency and purity
- Unfolding technique to correct p_T bin migration

Minimum Bias and Jet Trigger

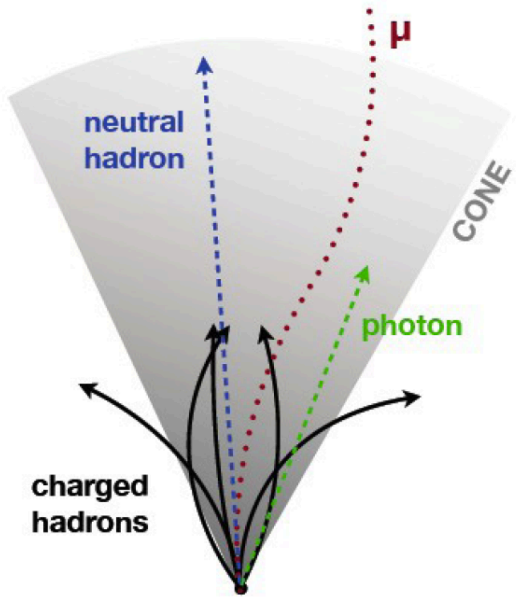
- Minimum bias and single jet triggers p_T > 6, 15, 30 GeV
- Combined exclusively at ~99% turn-on
- Low p_T results limited to run periods with negligible pile-up (10 nb^{-1})

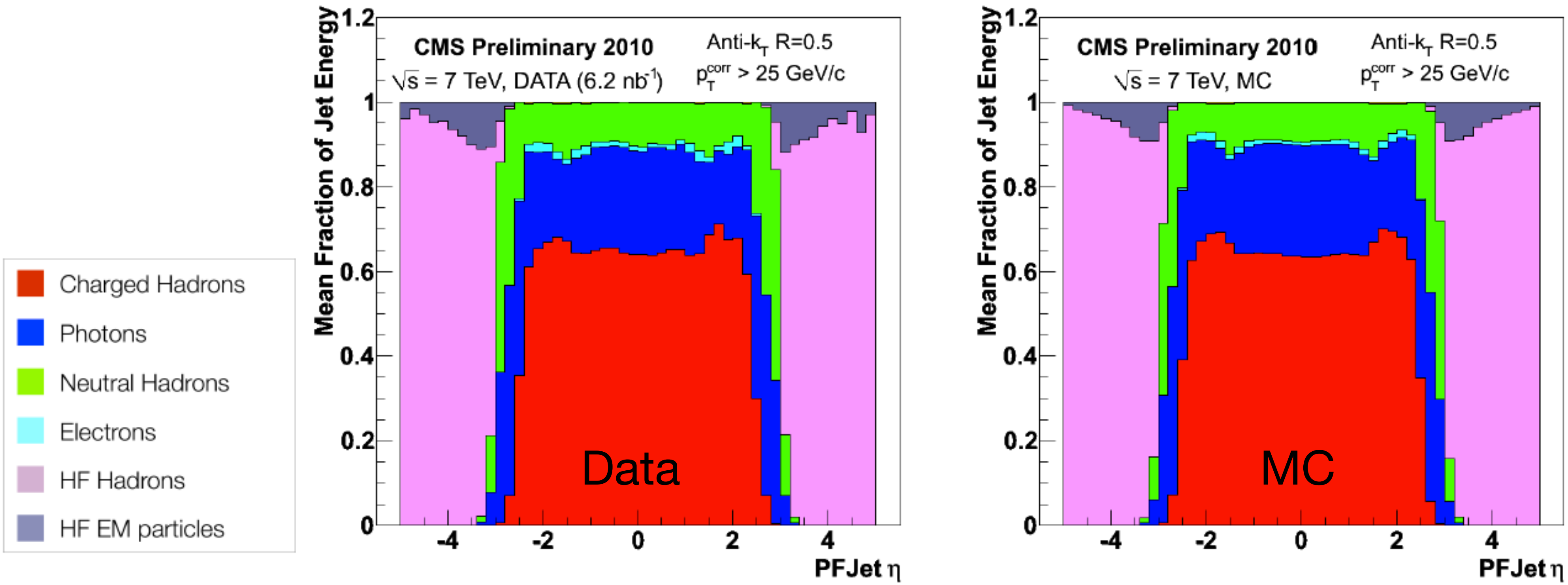




Particle Flow

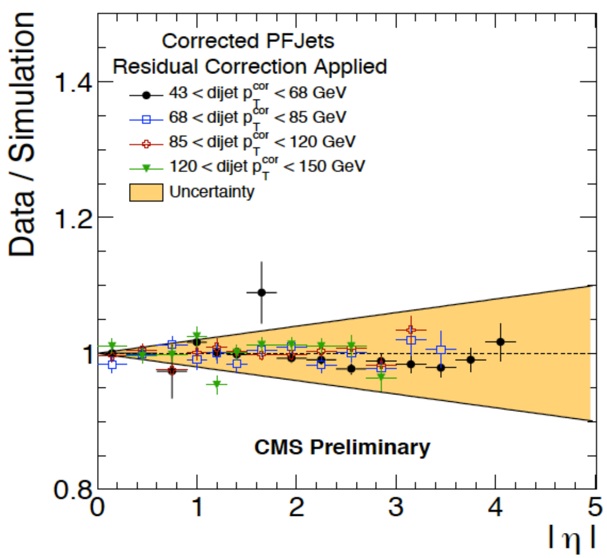
- Particle Flow algorithm combines information from all subdetectors to create a unique list of reconstructed particles
- This list is then used as input to the jet clustering algorithm
- Significant improvement of jet response and resolution at low p_T

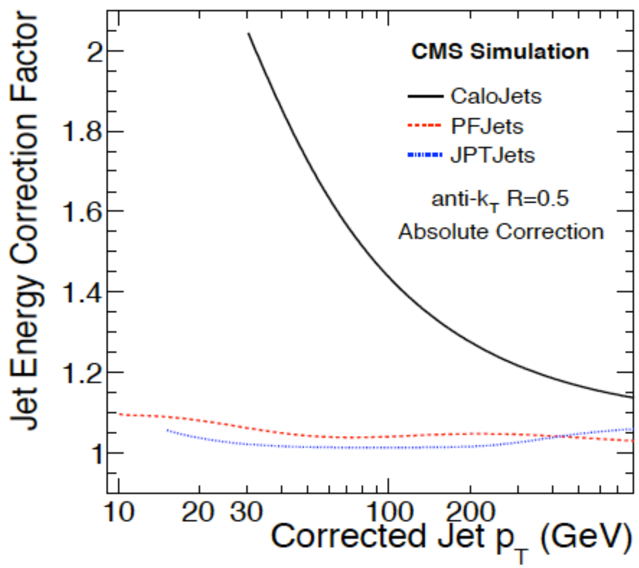


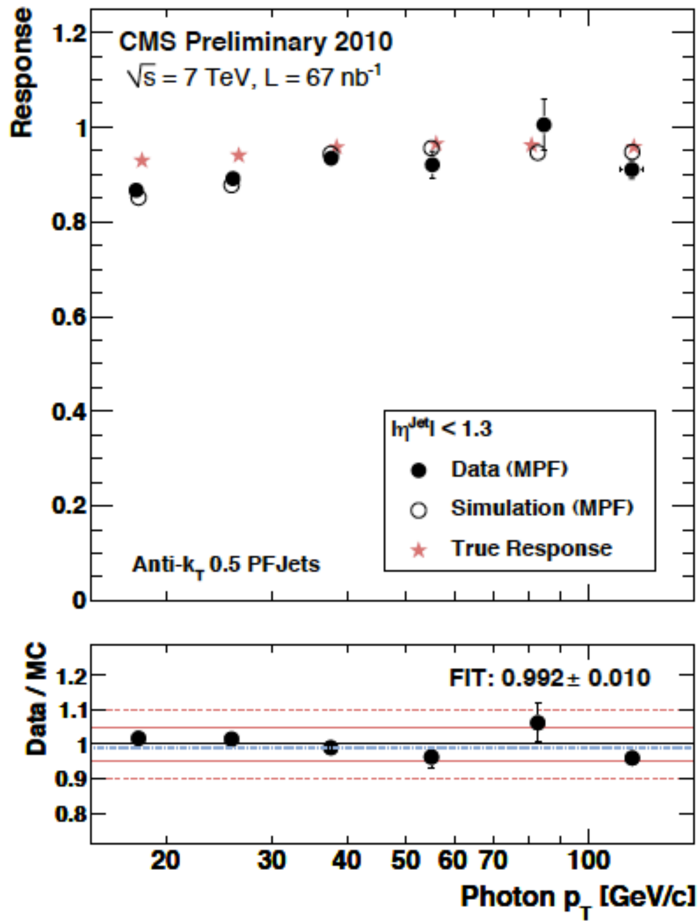


Jet Energy Corrections

- JEC currently derived from MC, cross-checked by in-situ jet calibration studies using di-jet and γ+jet events
- Relative η
  - Residual corrections determined from di-jet balance (with reference jet in central region)
- Absolut p_T
  - 5% JEC uncertainty for tracking-based jets
  - Supported by missing E_T projection fraction method in γ+ jet events

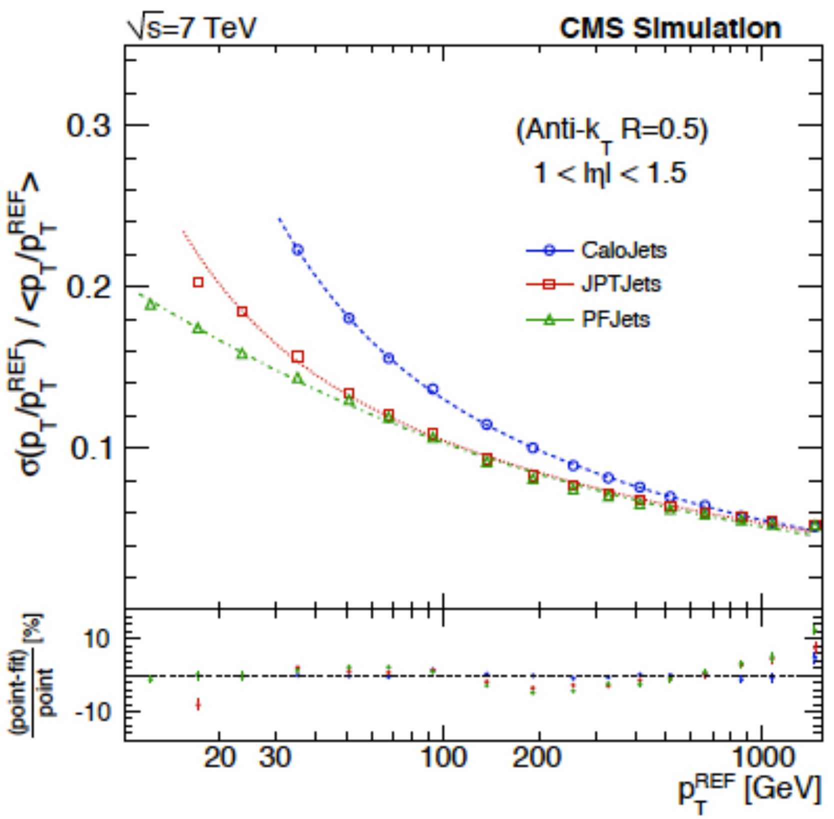


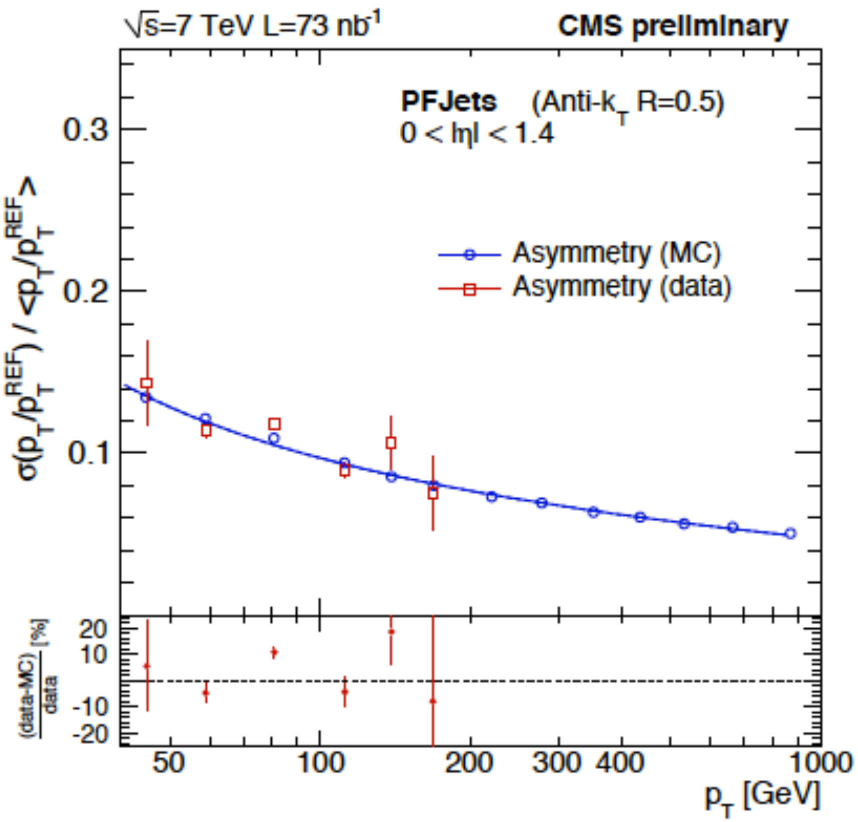




Jet p_T Resolution

- Jet resolution estimated from di-jet asymmetry $A = \frac{p_T^{jet1} - p_T^{jet2}}{p_T^{jet1} + p_T^{jet2}}$
- For approximately equal values of jet p_T: $\frac{\sigma(p_T)}{p_T} = \sqrt{2}\sigma_A$
- Resolution in data and MC agree within 10%





Unfolding

- Ansatz method to correct jet p_T back to particle level
- Phenomenological power law motivated by parton model (Feynman, Field, Fox), extended at the Tevatron and updated at CMS for low p_T and b-jets

$$f(p_T) = \underbrace{N_0 p_T^{-\alpha}\left(1 - \frac{2p_T\cosh(y_{\min})}{\sqrt{s}}\right)^{\beta}}_{\text{high } p_T} \underbrace{\exp(-\gamma/p_T)}_{\text{low } p_T \text{ and b-jets}}$$

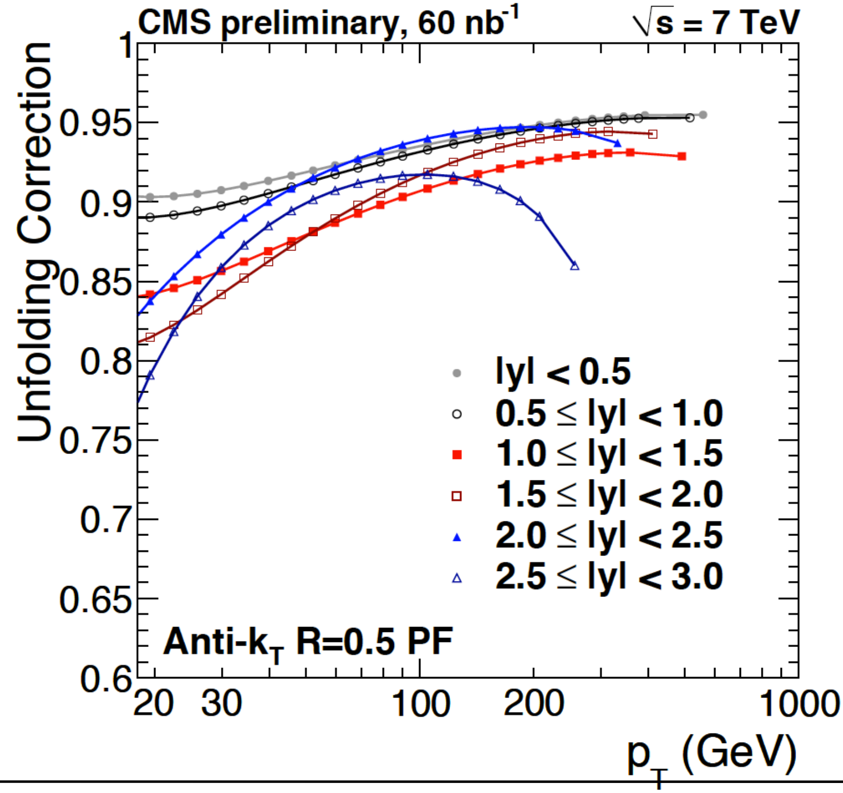
new

$f(p_T)$: Ansatz function to parametrize true jet p_T spectrum

$$F(p_T) = \int_0^{\infty} f(p'_T) R(p'_T - p_T;\sigma) dp'_T$$

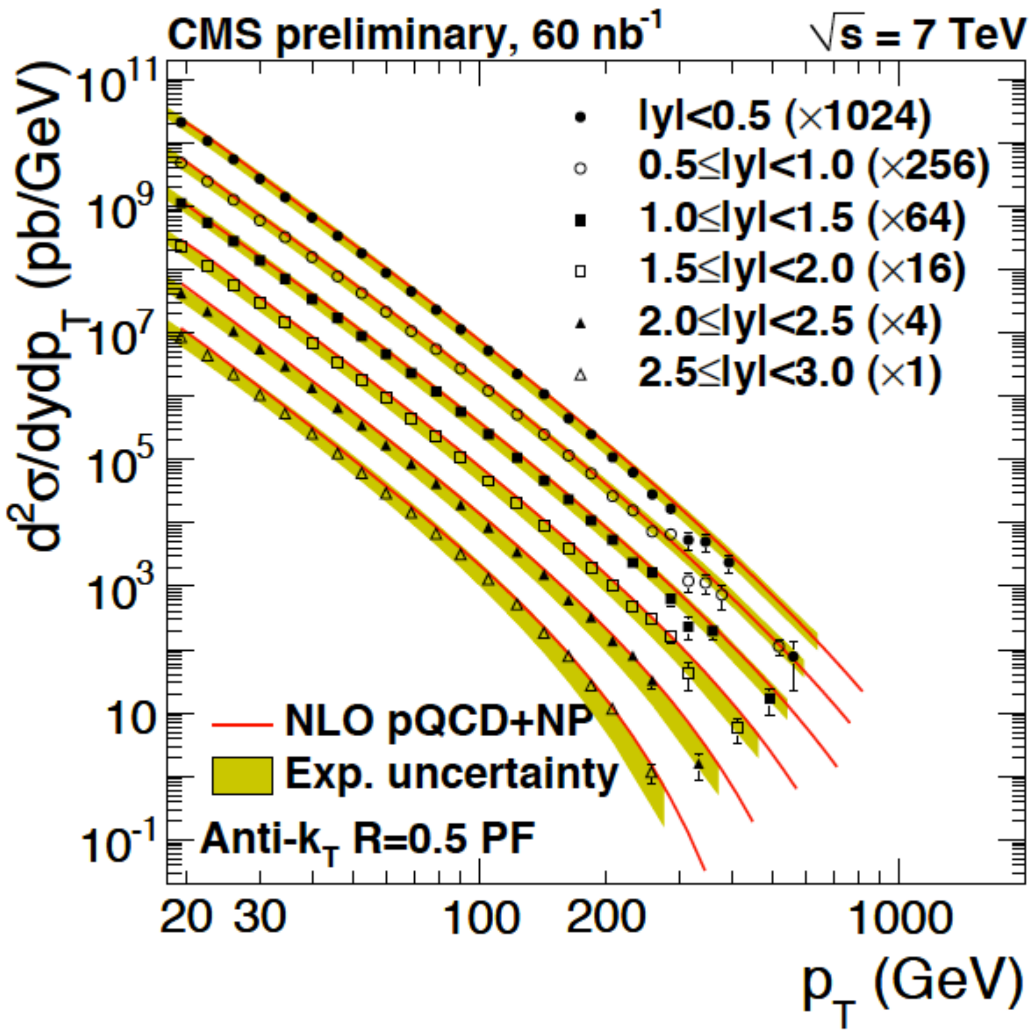
$R(p'_T - p_T;\sigma)$: smearing function

$$C_{res} = f(p_T)/F(p_T)$$



Inclusive Jet Cross Section

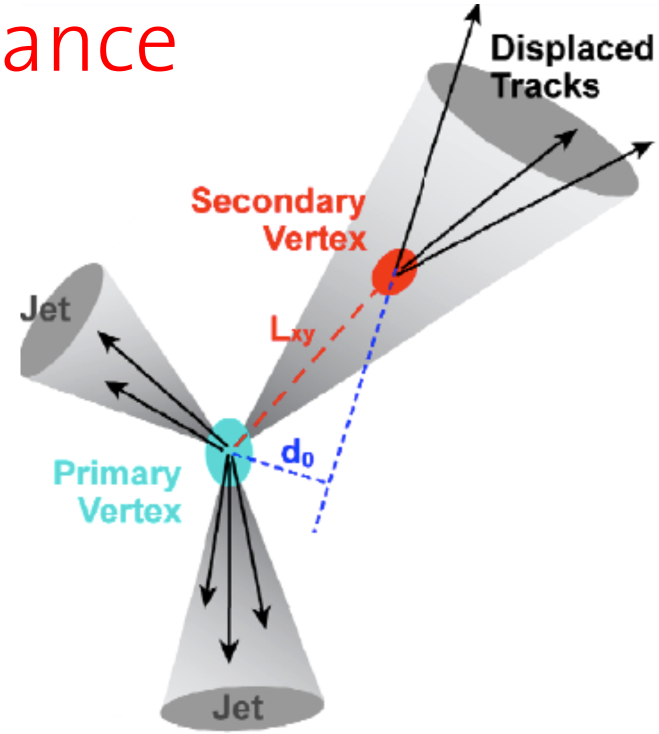
- Inclusive jet p_T spectrum in good agreement with NLO theory
- Main systematic uncertainties from jet energy scale (5%), jet resolution (10%) and luminosity (11%)

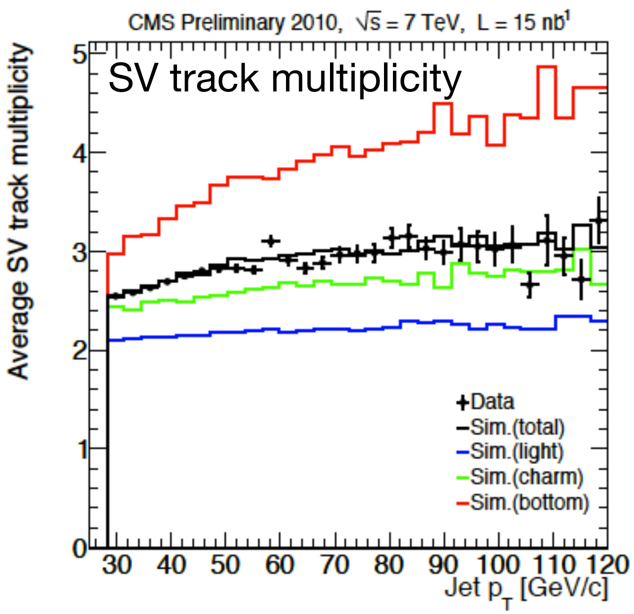


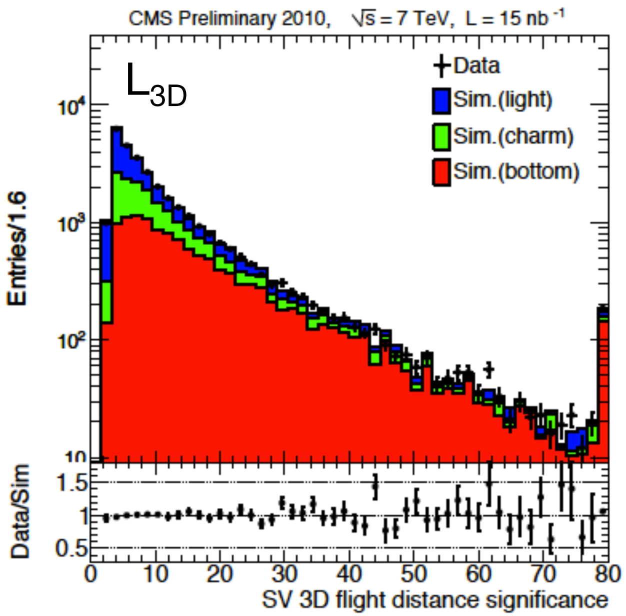
B-tagging Performance

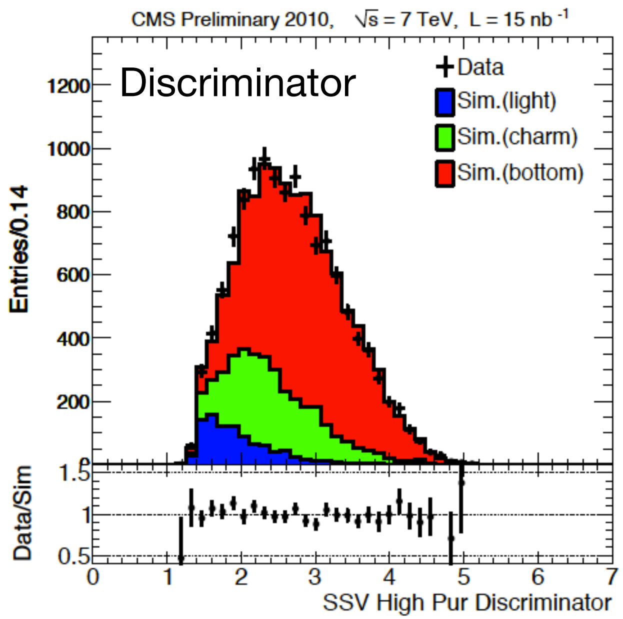
- Based on reconstruction of secondary vertices (SV)
- SV with at least 3 tracks and large flight length significance
- SV tagging commissioned with first lumi

  => MC simulation well reproduces the measured b-tagging observables





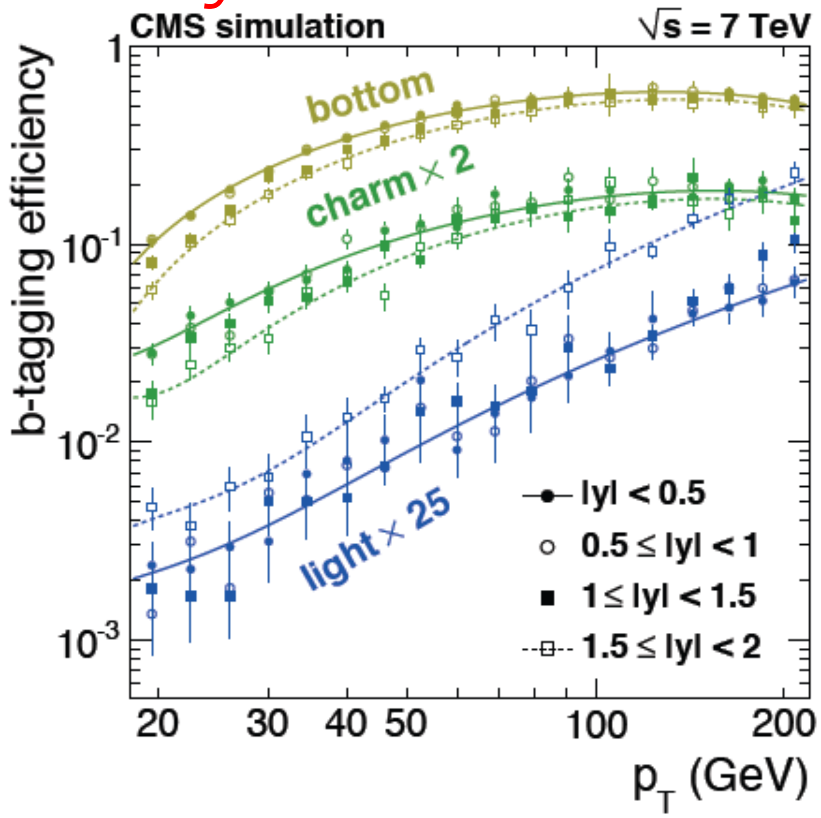


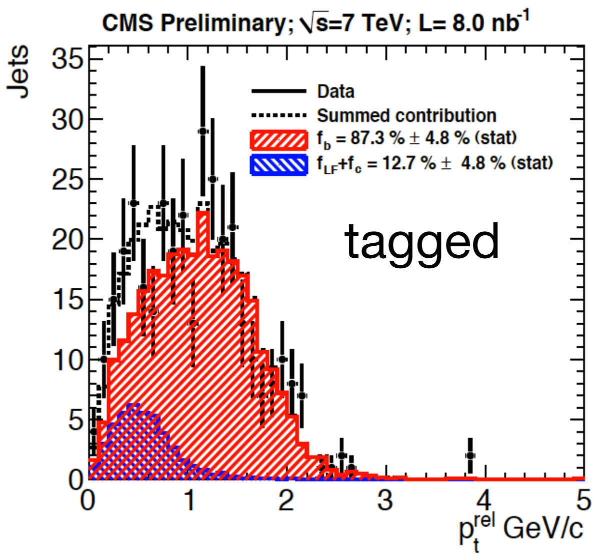


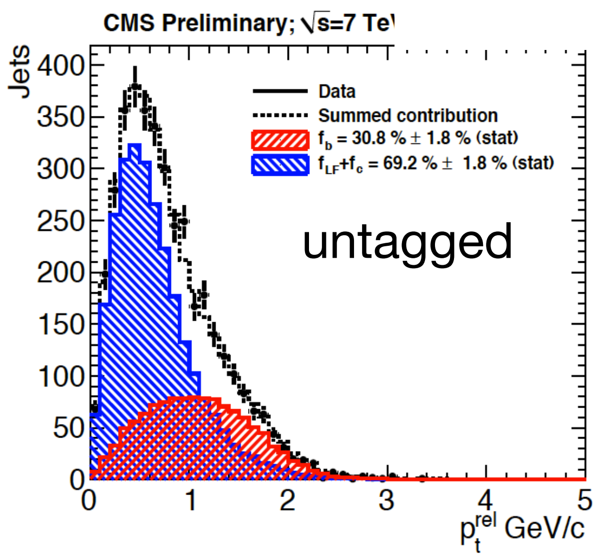
B-tagging Efficiency

- b-tagging efficiency as a function of p_T and y is taken from MC
- Verified in subsample by measurement of data/MC scale factors based on p_T^{rel}:

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



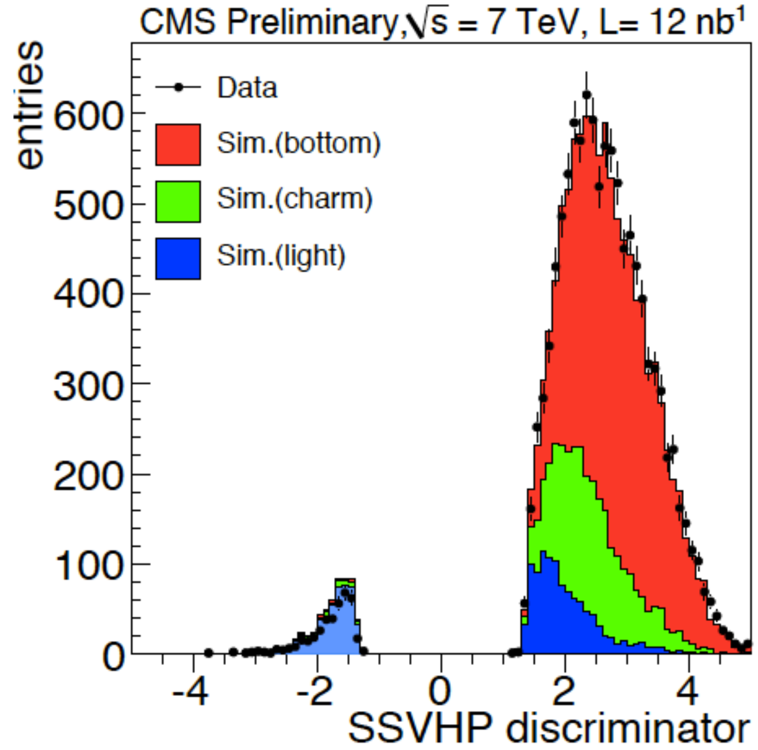




=> Measured scale factors are compatible with 1 within the systematic uncertainty (20%)

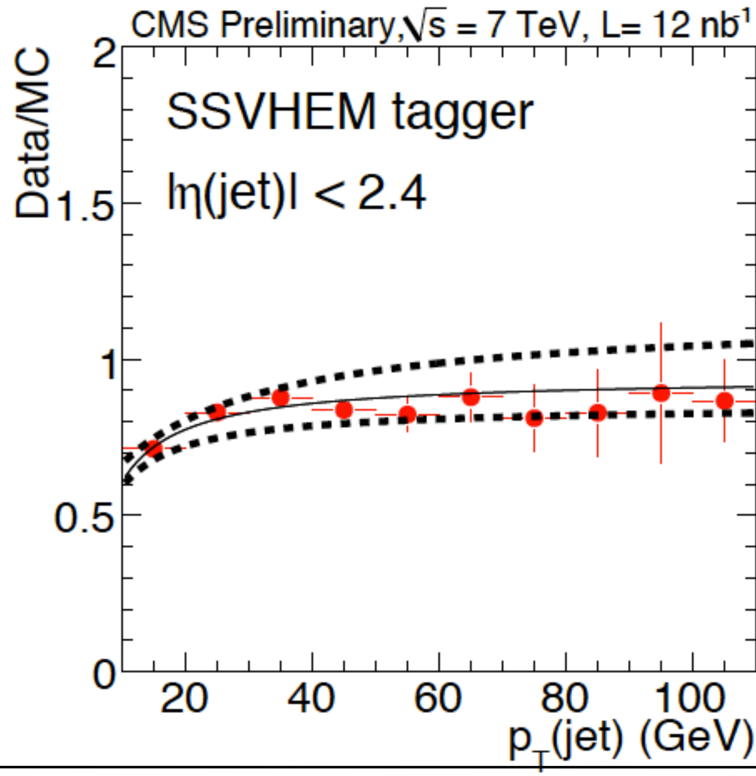
B-tagging Mistag Rate

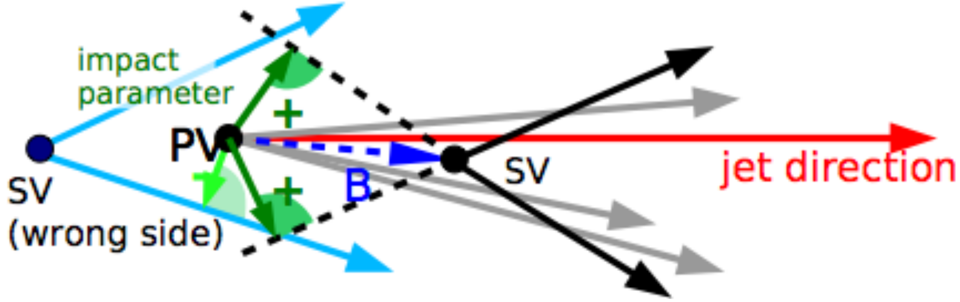
- Mistag rate constrained by data-driven study using negative tag discriminators



$$\varepsilon_{data}^{mistag} = \varepsilon_{data}^{-} \cdot R_{light},$$

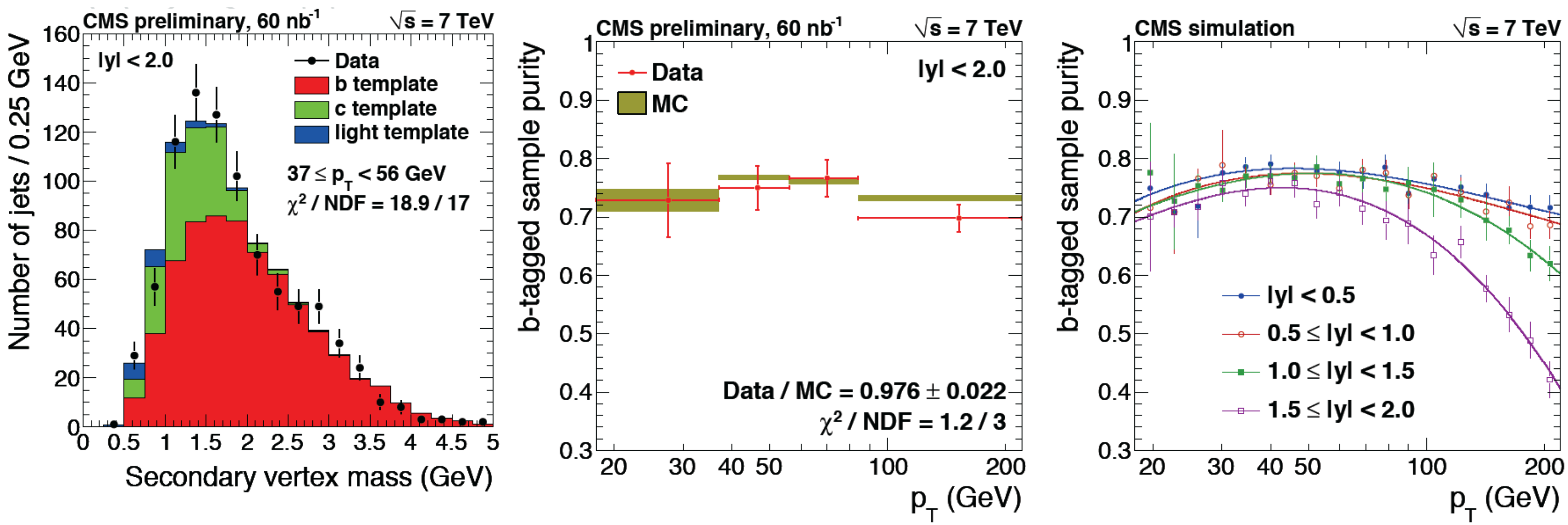
where $R_{light} = \varepsilon_{MC}^{mistag} / \varepsilon_{MC}^{-}$





B-tagged Sample Purity

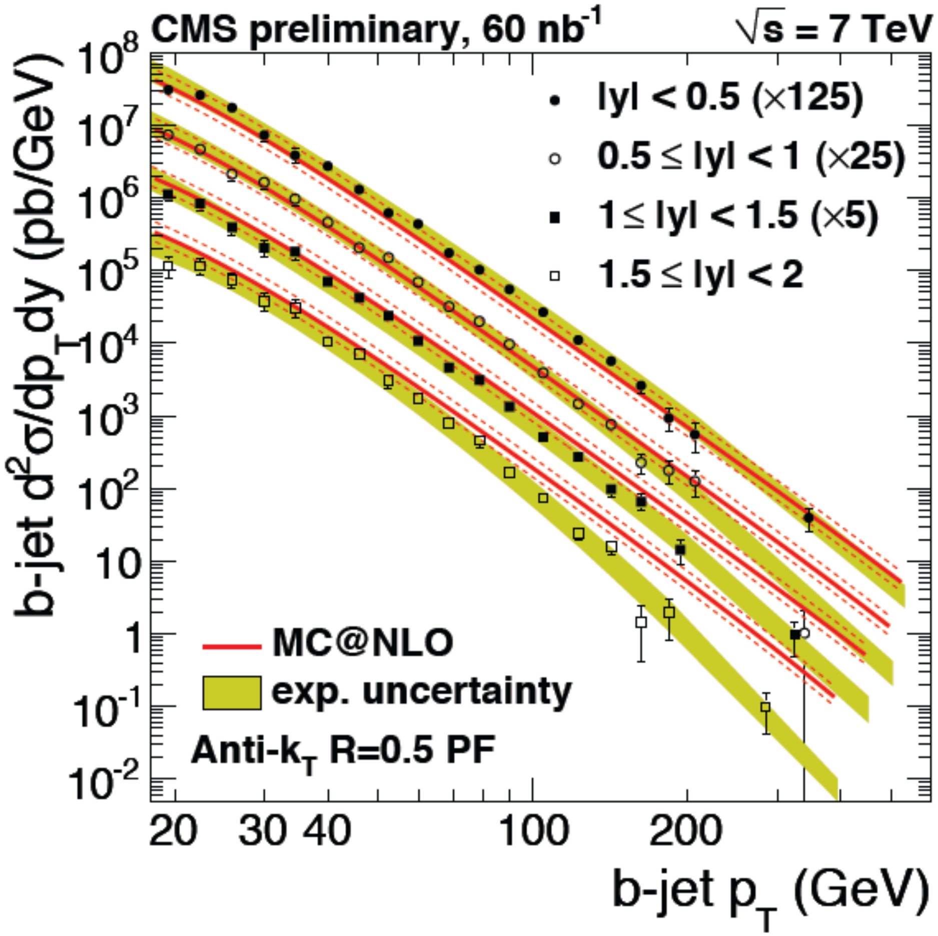
- Estimated using two complementary approaches
  1) Data-based: Fit to secondary vertex mass
  2) MC-based: $f_b = \dfrac{F_b \epsilon_b}{F_b \epsilon_b + F_c \epsilon_c + F_l \epsilon_l}$ (F: flavor fraction)
- Good agreement between data and MC: $Data/MC = 0.976 \pm 0.022$
- Central values taken from MC for proper treatment of p_T and y dependence

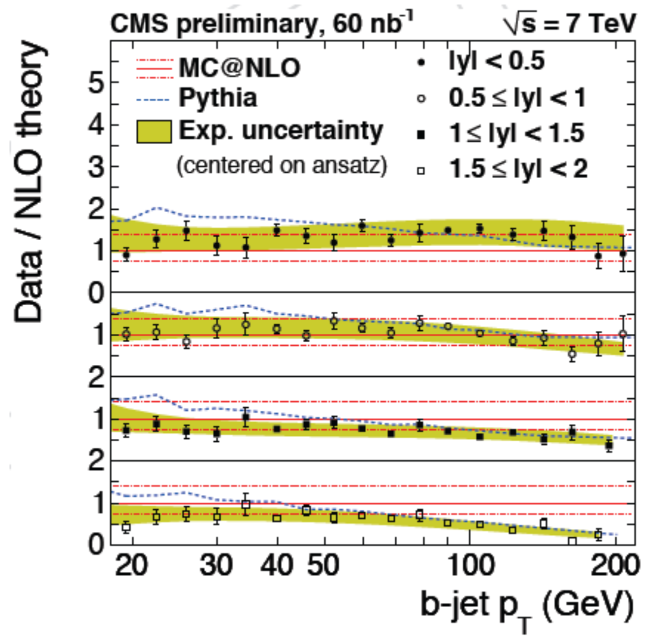


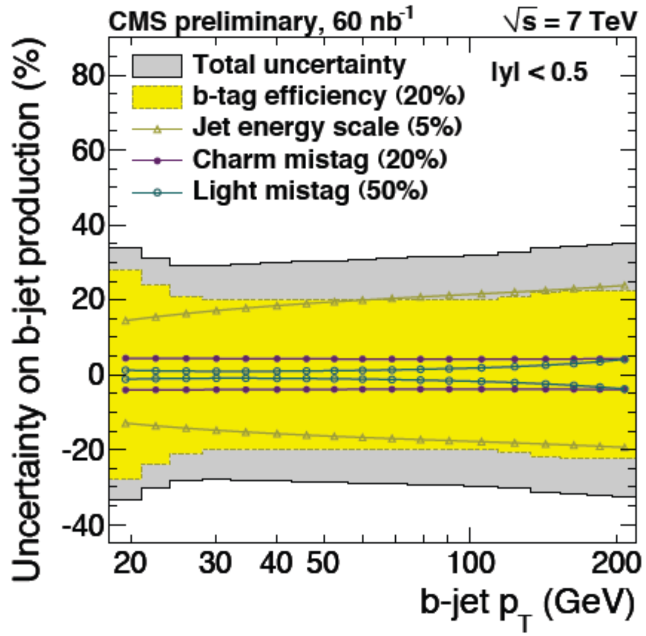
b-Jet Cross Section at √s = 7 TeV

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

with C_{smear} : unfolding correction
ϵ_{jet} : jet reconstruction efficiency
ϵ_b : b-tagging efficiency

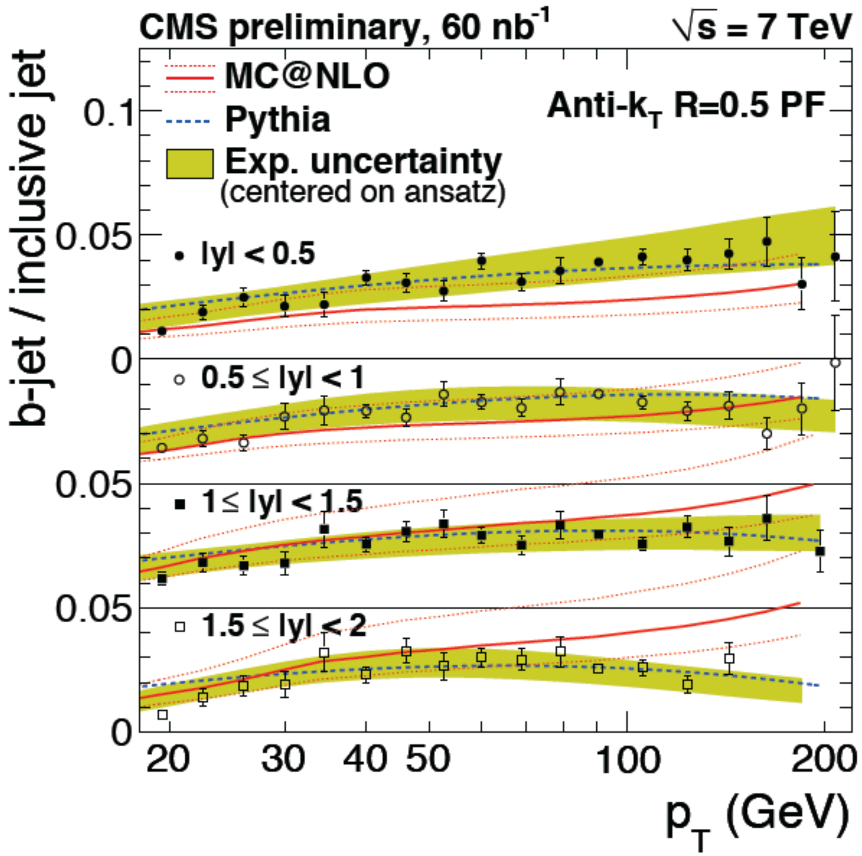


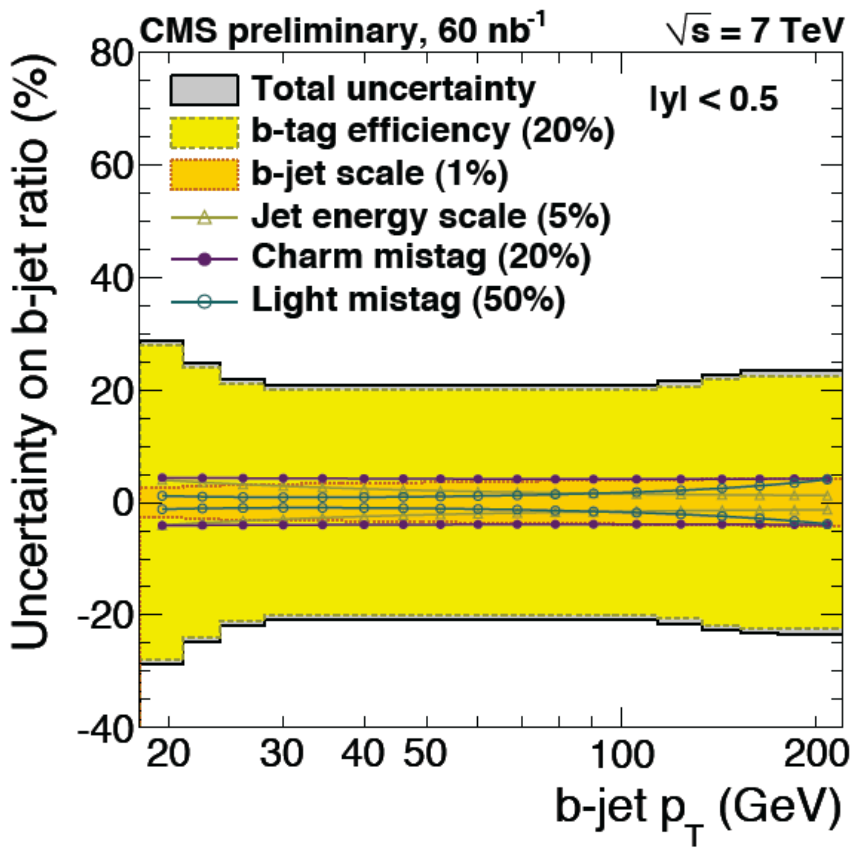




Ratio to Inclusive Jet Cross Section

- Measurement of ratio reduces experimental uncertainty from jet energy reconstruction and luminosity
- Fit of measured ratio of data and PYTHIA for $30 < p_T < 150$ GeV and |y| < 2 yields scale factor of $0.99 \pm 0.02(\mathrm{stat}) \pm 0.21(\mathrm{syst})$





Conclusions

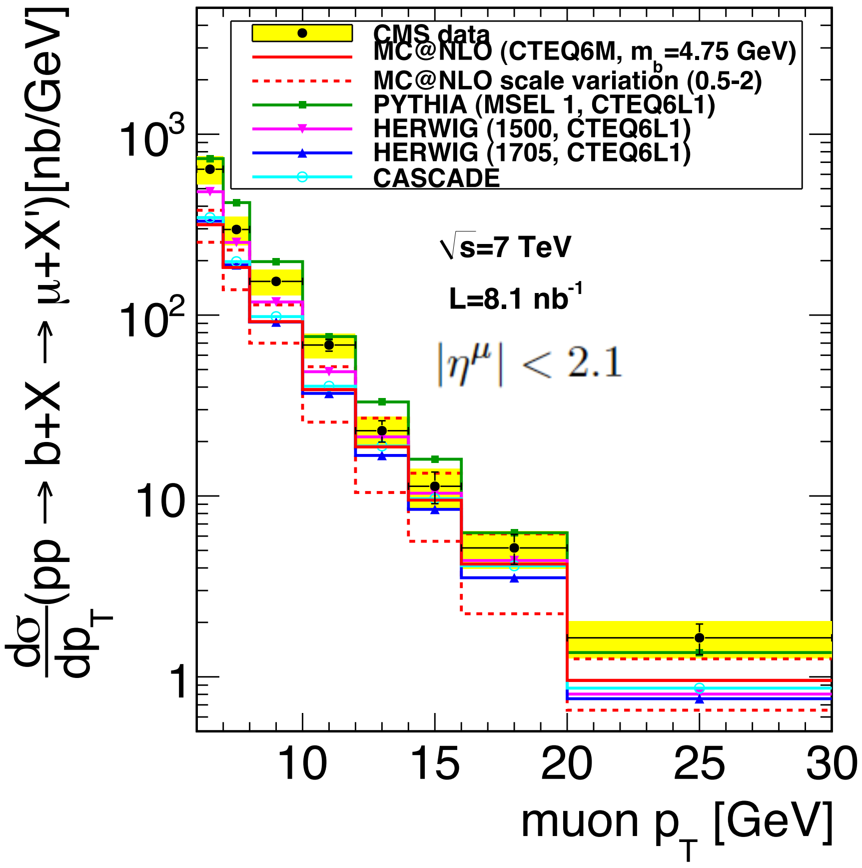
- CMS detector is working very well which made the first measurements of the inclusive b production possible

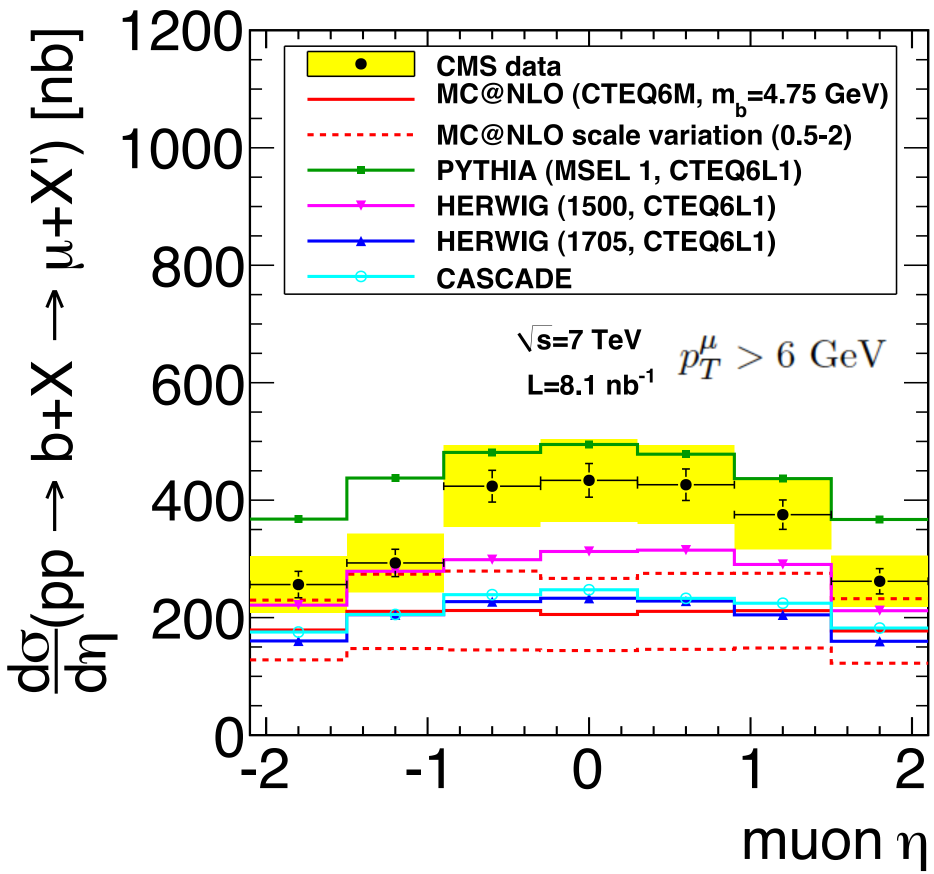
- Open b production with muons:
  - Measurement for muon p_T = 6-30 GeV, $|\eta| < 2.1$ with statistical error of 5-20% and systematic uncertainty of 16-20%
  - Good agreement with MC@NLO at muon $p_T > 12$ GeV, while data are above the prediction in the central region at low p_T
  - Recent comparison to FONLL

- Inclusive b-jet production:
  - Measurement for jet p_T = 18-300 GeV, $|y| < 2$
  - Overall good agreement with PYTHIA within ~2% statistical and 21% systematic uncertainty
  - Reasonable agreement with MC@NLO for overall cross section, but shape differences in p_T and y

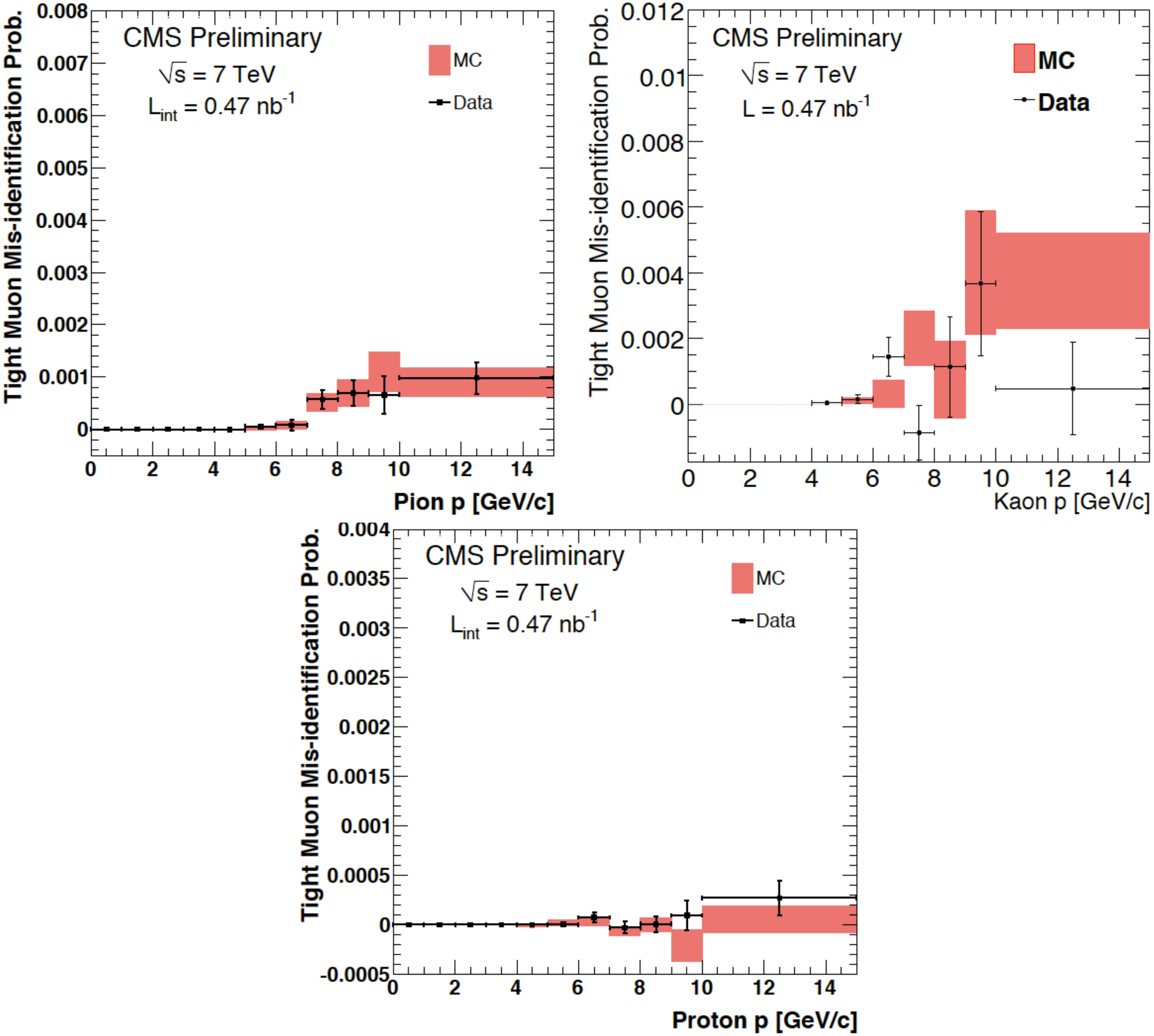
Backup

Differential b Cross Section

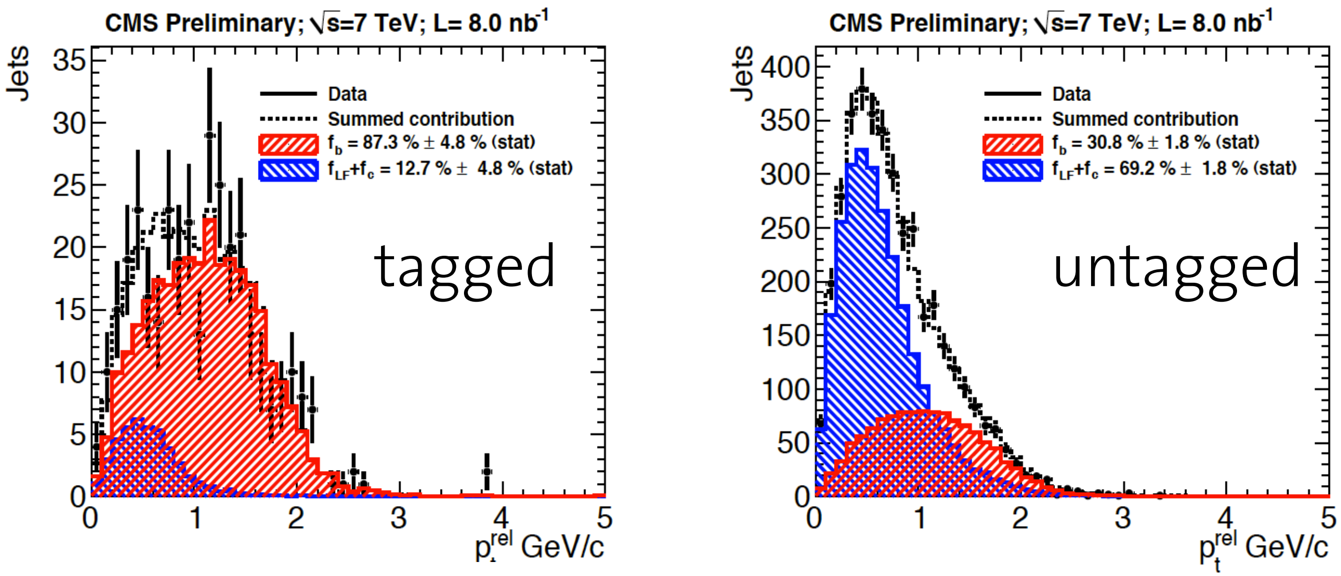




Fraction of pions, kaons and protons mis-identified as muons



B tagging Efficiency

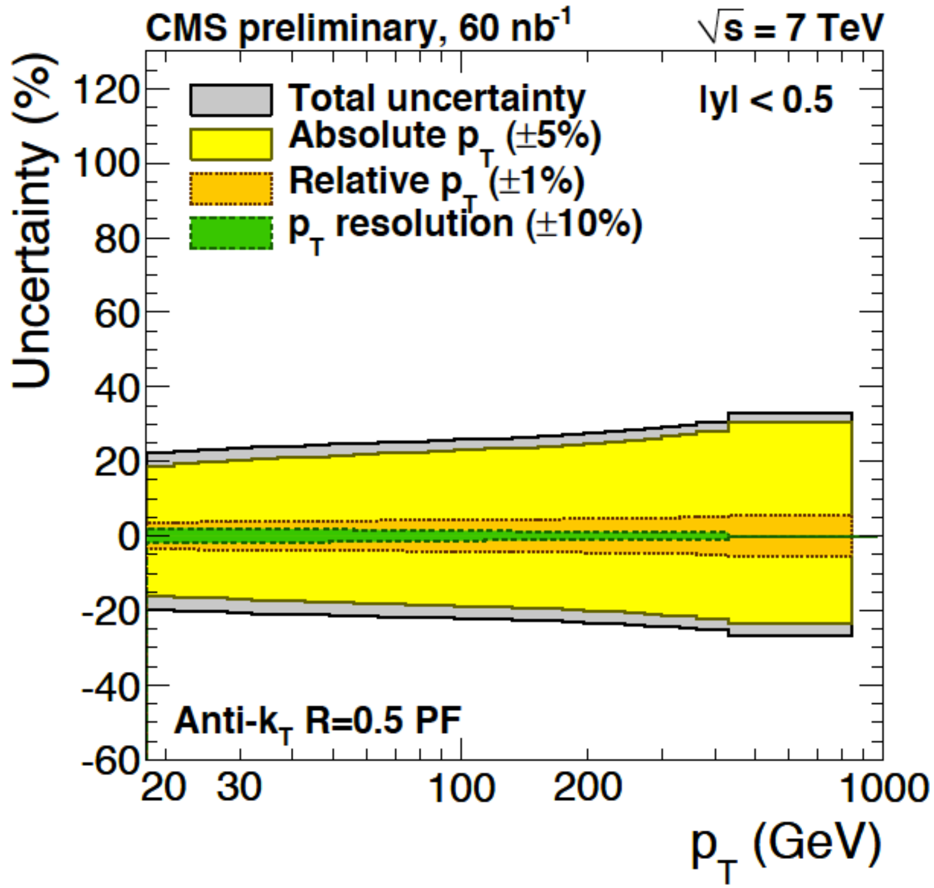


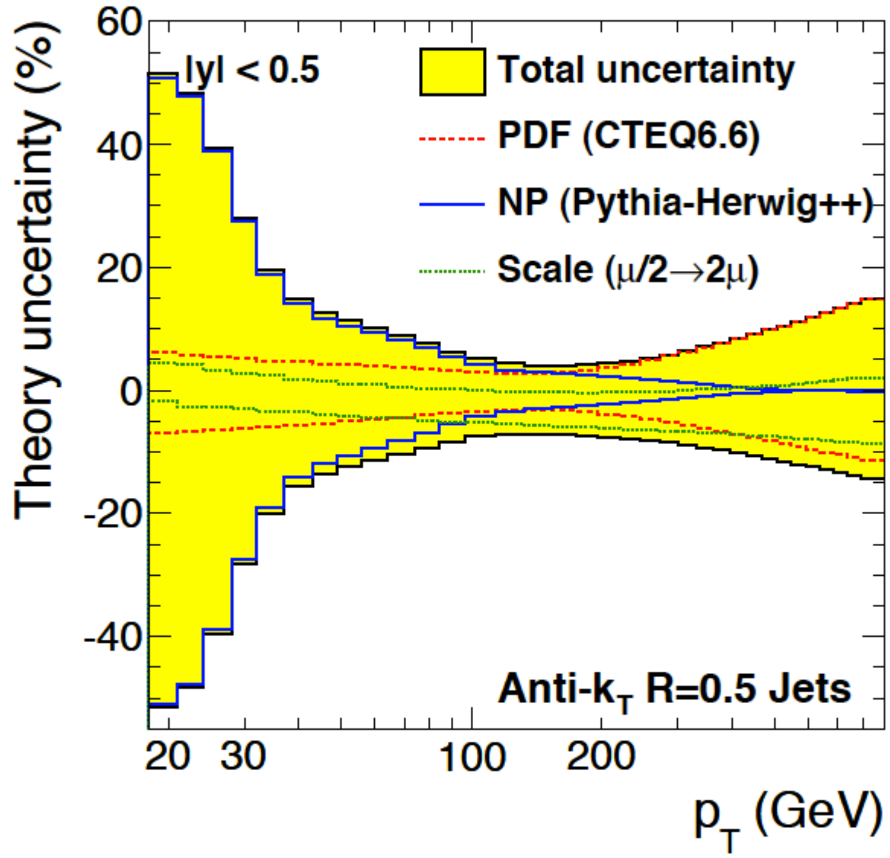
$$\epsilon_b^{\text{data}} = \frac{f_b^{\text{tag}} \cdot N_{data}^{\text{tag}}}{f_b^{\text{tag}} \cdot N_{data}^{\text{tag}} + f_b^{\text{untag}} \cdot N_{data}^{\text{untag}}}$$

Tagger+Operating Point	ϵ_b^{data}	ϵ_b^{MC}	SF_b
SSVHPT	0.203 ± 0.015	0.207 ± 0.002	$0.98 \pm 0.08 \pm 0.18$

- 12% systematic uncertainty derived from study of jet p_T and η modelling (4-8%), muon selection (2-8%), jet flavor assignment (2%), pile-up (3%), shape of light quark background (3-5%)
- Additional systematic uncertainty of 15% to effects not yet studied(p_T^{rel} shape for b and non-b jets, fragmentation, effect of trigger, jet energy scale uncertainty)

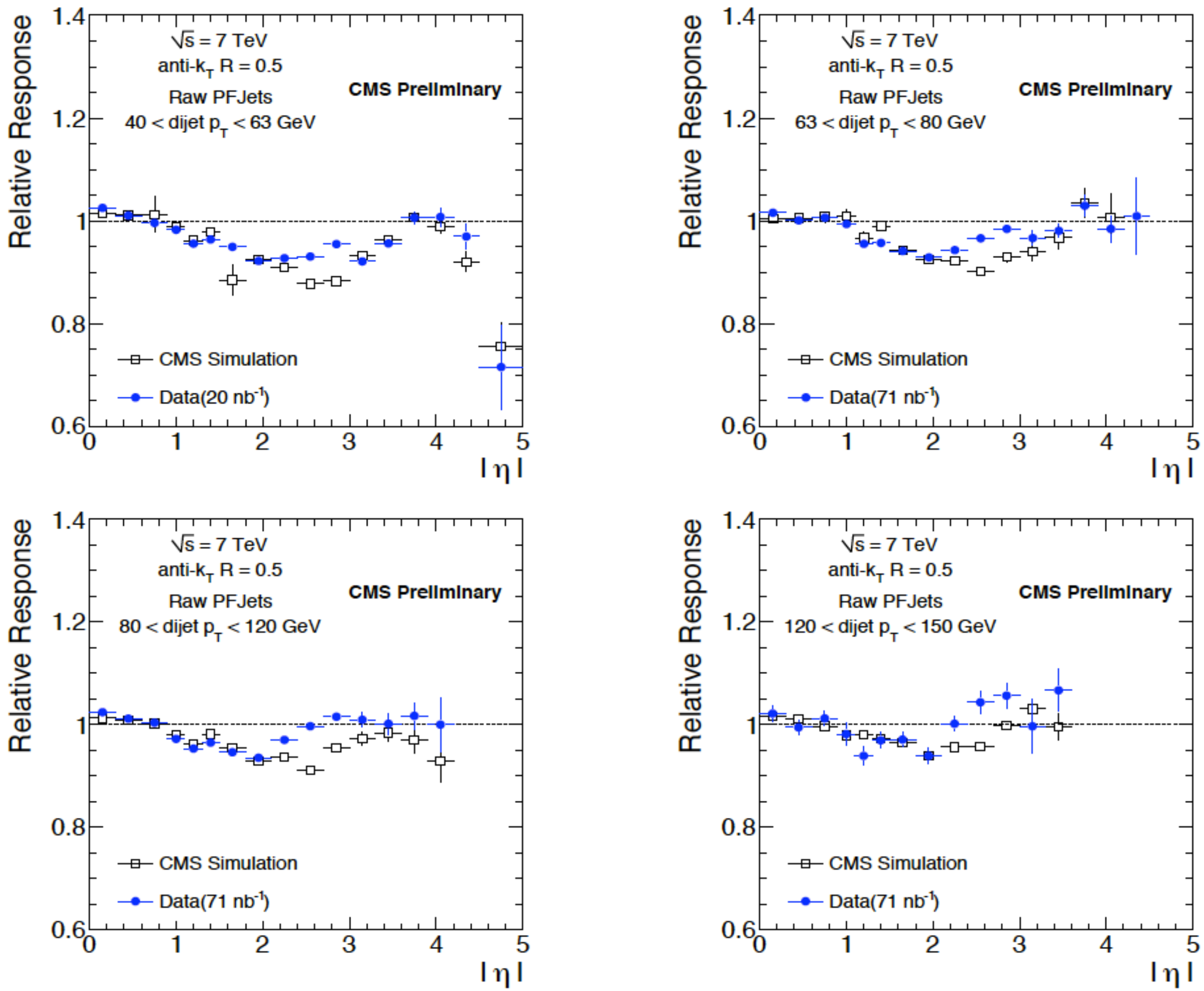
Inclusive Jet Cross Section: Systematic



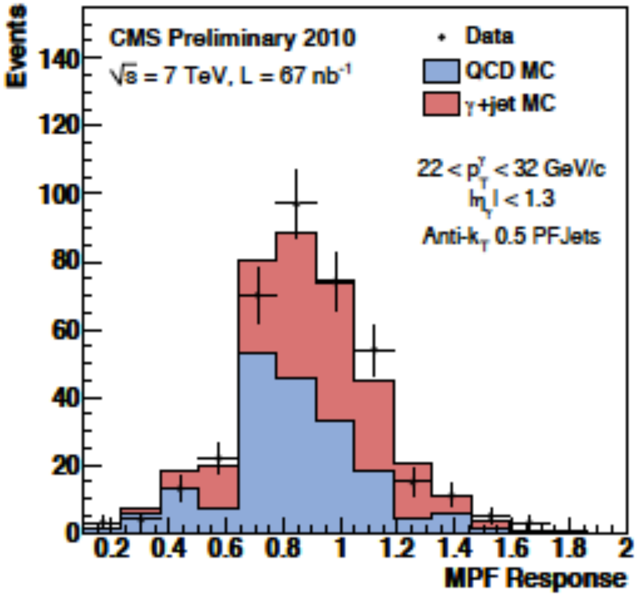


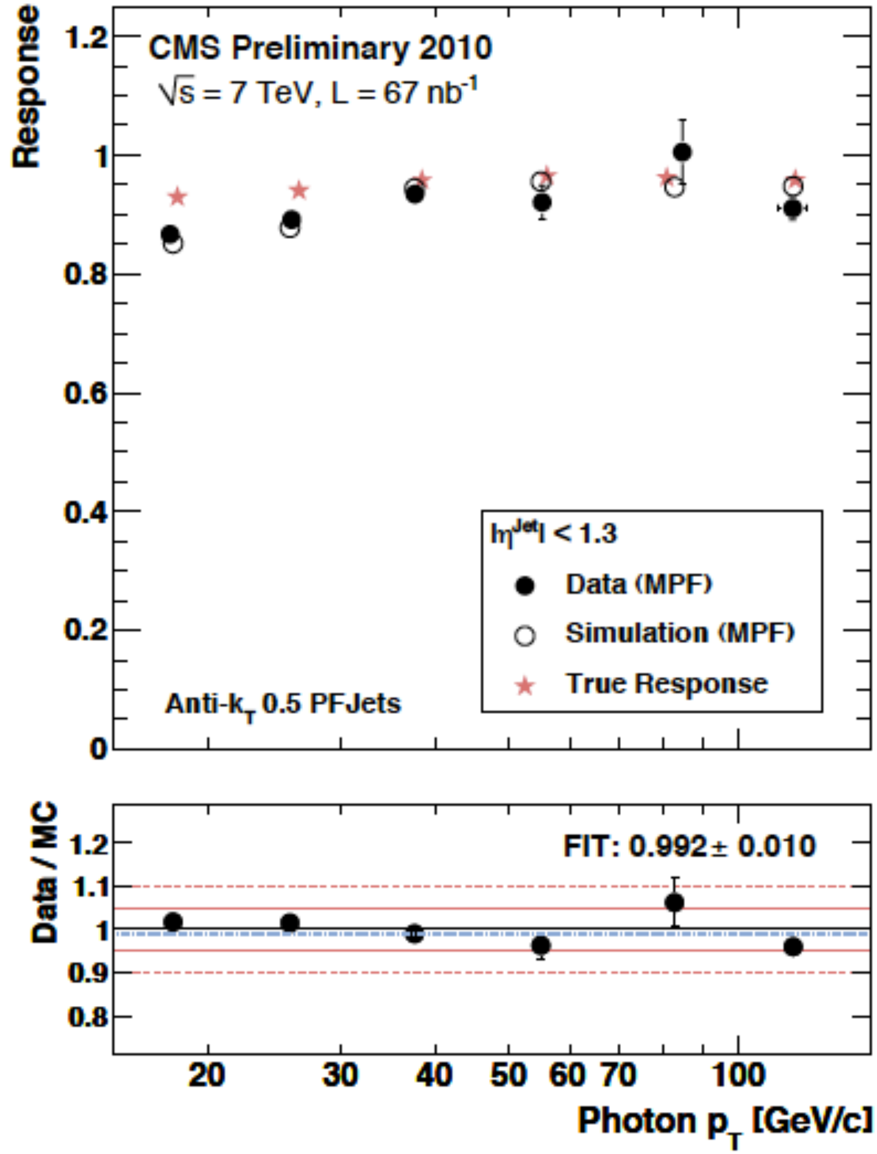
Jet Relative Response

$$R(\eta^{probe}, p_T^{dijet}) = \frac{2+ < B >}{2- < B >} \quad \text{where} \quad B = \frac{p_T^{probe} - p_T^{barrel}}{p_T^{dijet}}$$



Jet Response





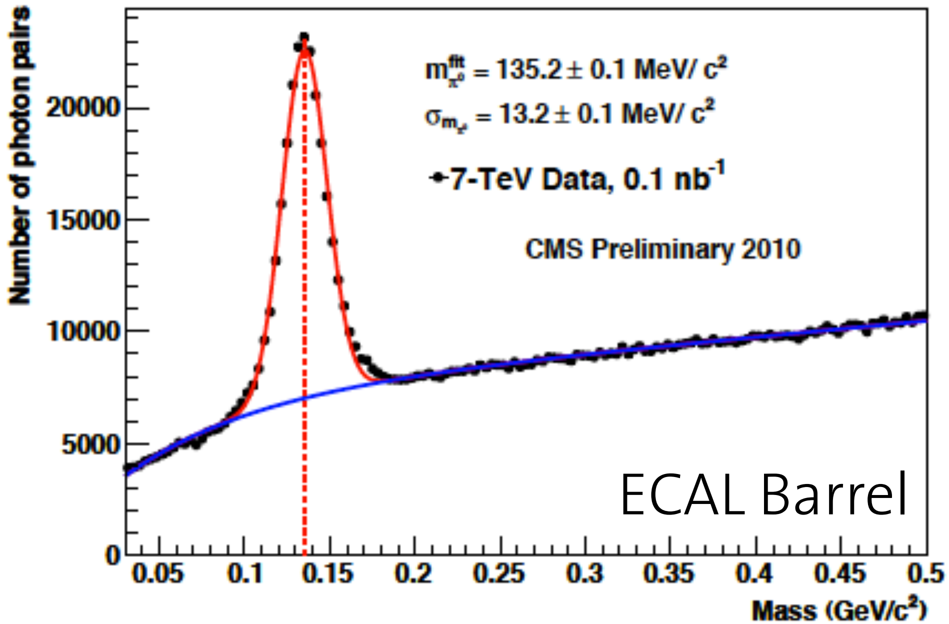
$$\vec{p_T}^{\gamma} + \vec{p_T}^{recoil} = 0$$

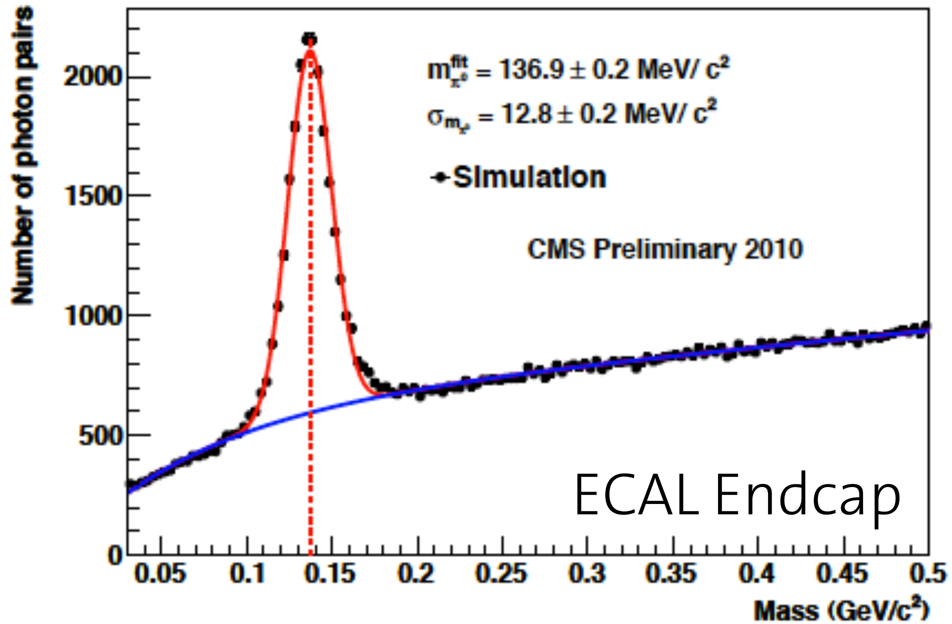
$$R_\gamma \vec{p_T}^{\gamma} + R_{recoil} \vec{p_T}^{recoil} = -\vec{E}_T^{miss}$$

$$R_\gamma = 1$$

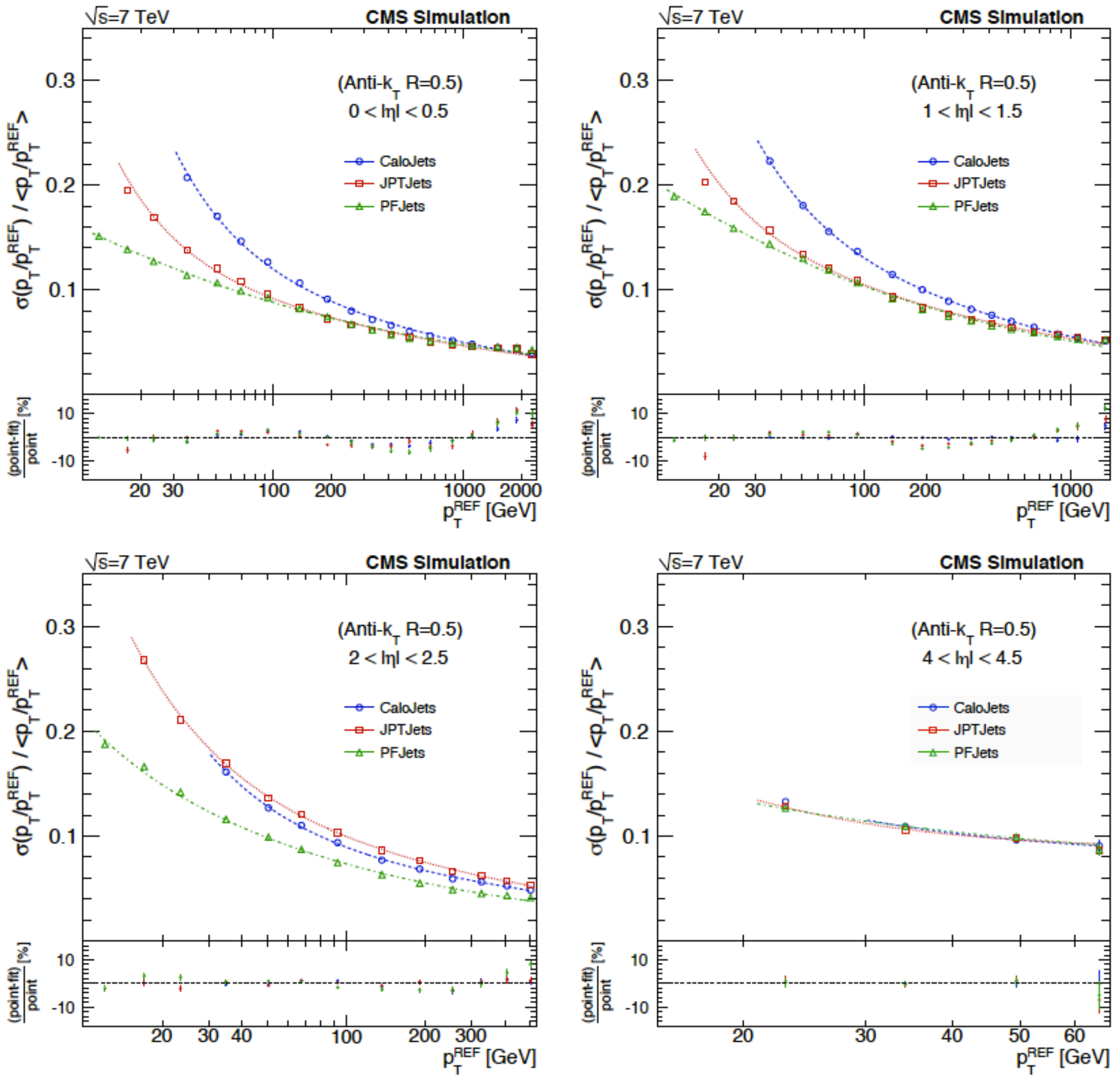
$$R_{recoil} = 1 + \frac{\vec{E}_T^{miss} \cdot \vec{p_T}^{gamma}}{(p_T^{\gamma})^2} \equiv R_{MPF}$$

Photon Pair Invariant Mass Distribution

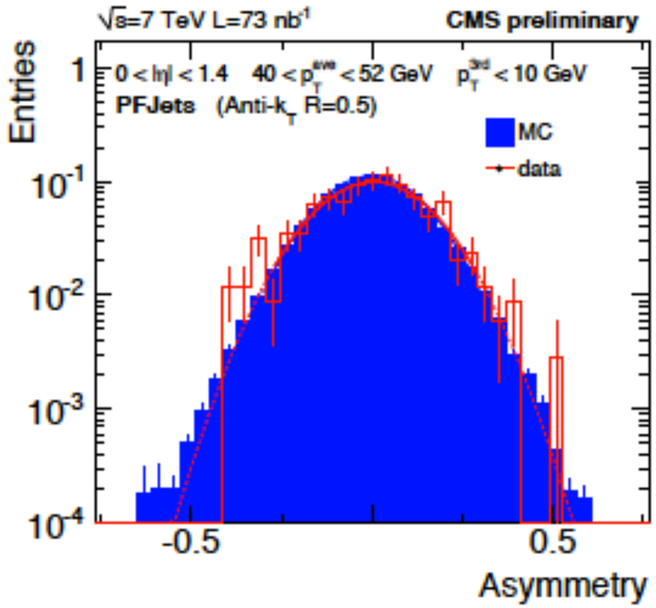




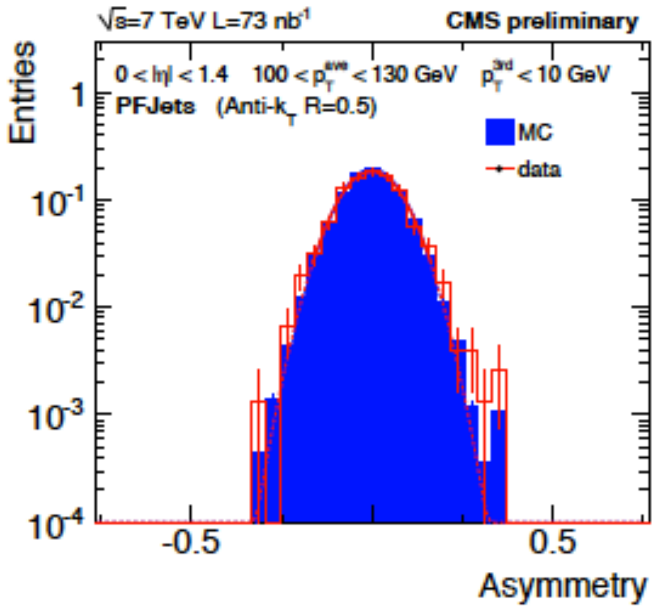
Jet p_T Resolution

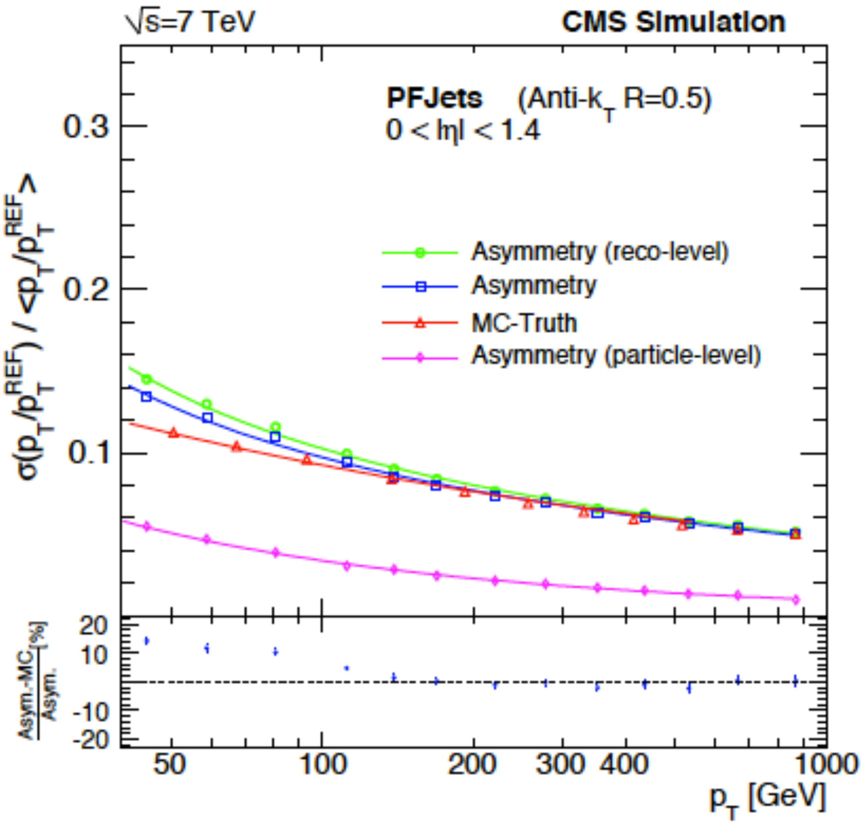


Jet p_T Resolution: Asymmetry Method

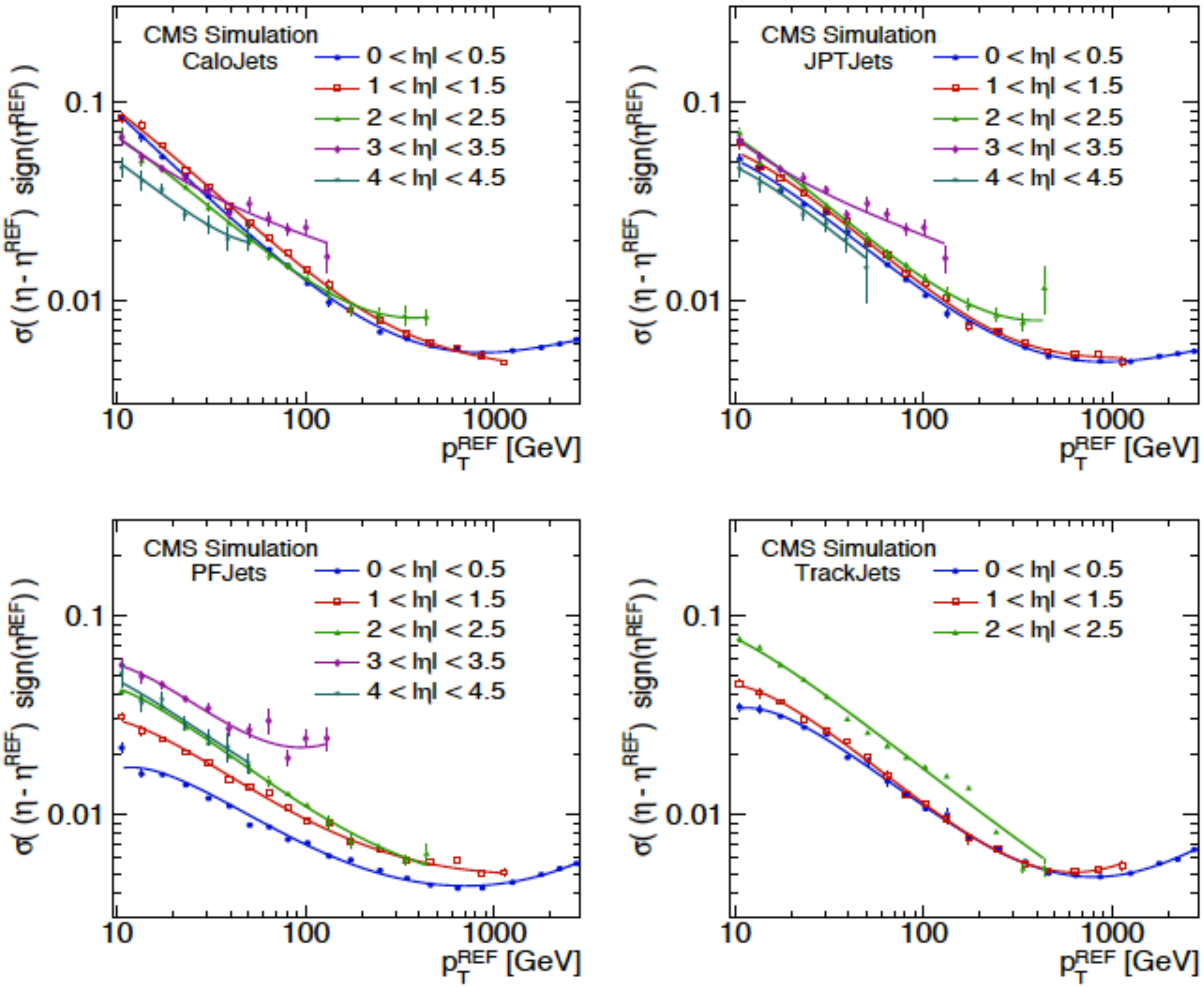


$$A = \frac{p_T^{\text{jet1}} - p_T^{\text{jet2}}}{p_T^{\text{jet1}} + p_T^{\text{jet2}}}$$

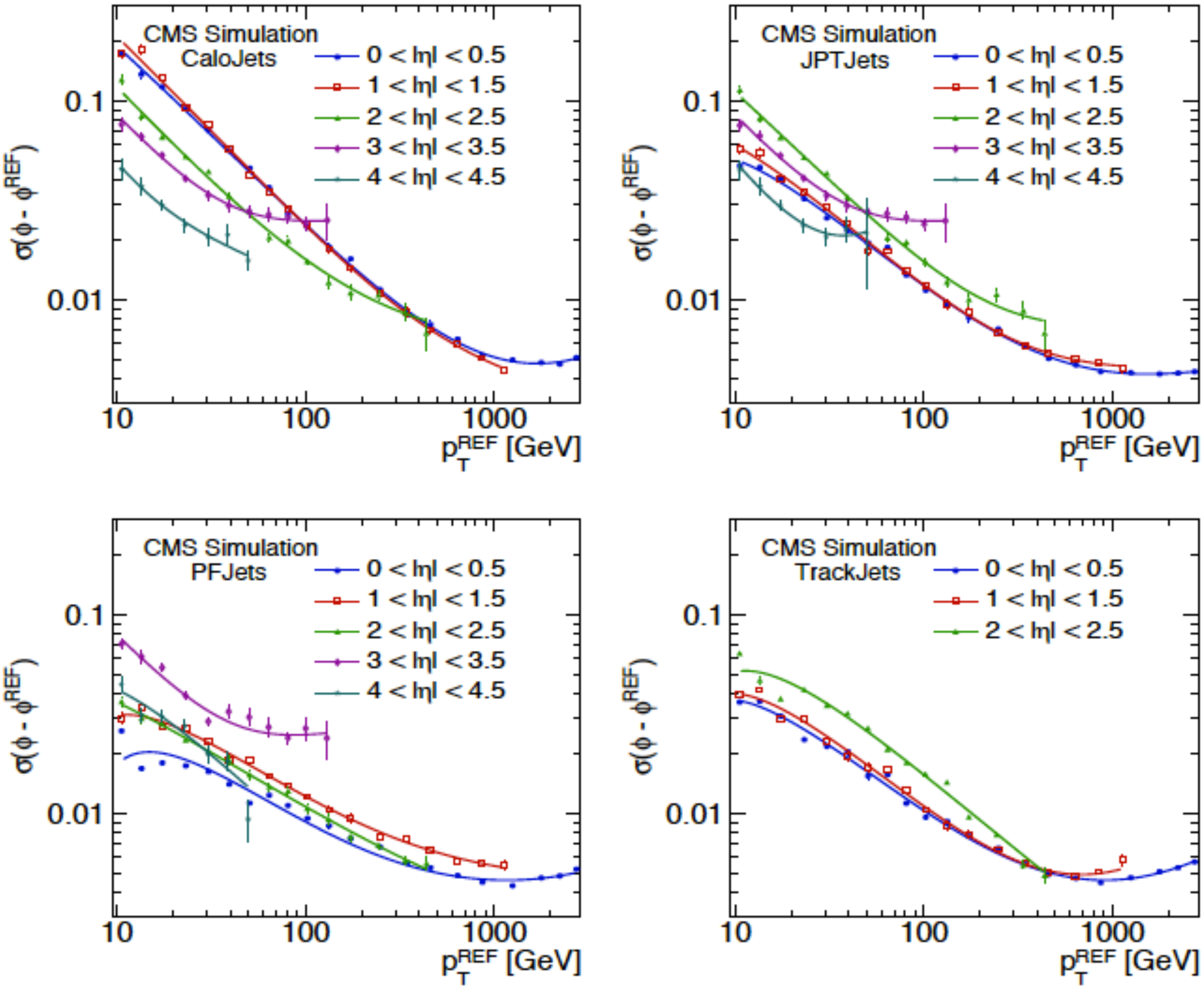




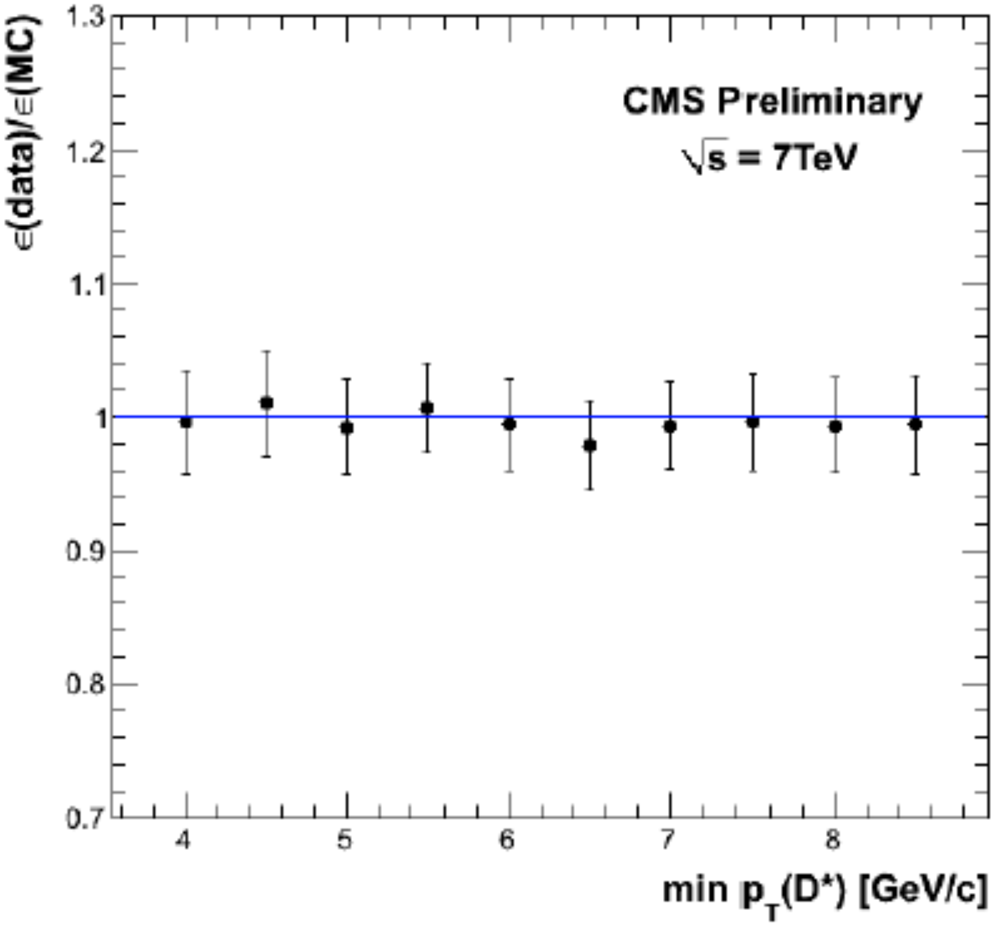
Jet Position Resolution (η)



Jet Position Resolution (Φ)



Tracking Efficiency for Pions



$$D^0 \to K^-\pi^+\pi^-\pi^+ \text{ ("}K3\pi\text{")}$$

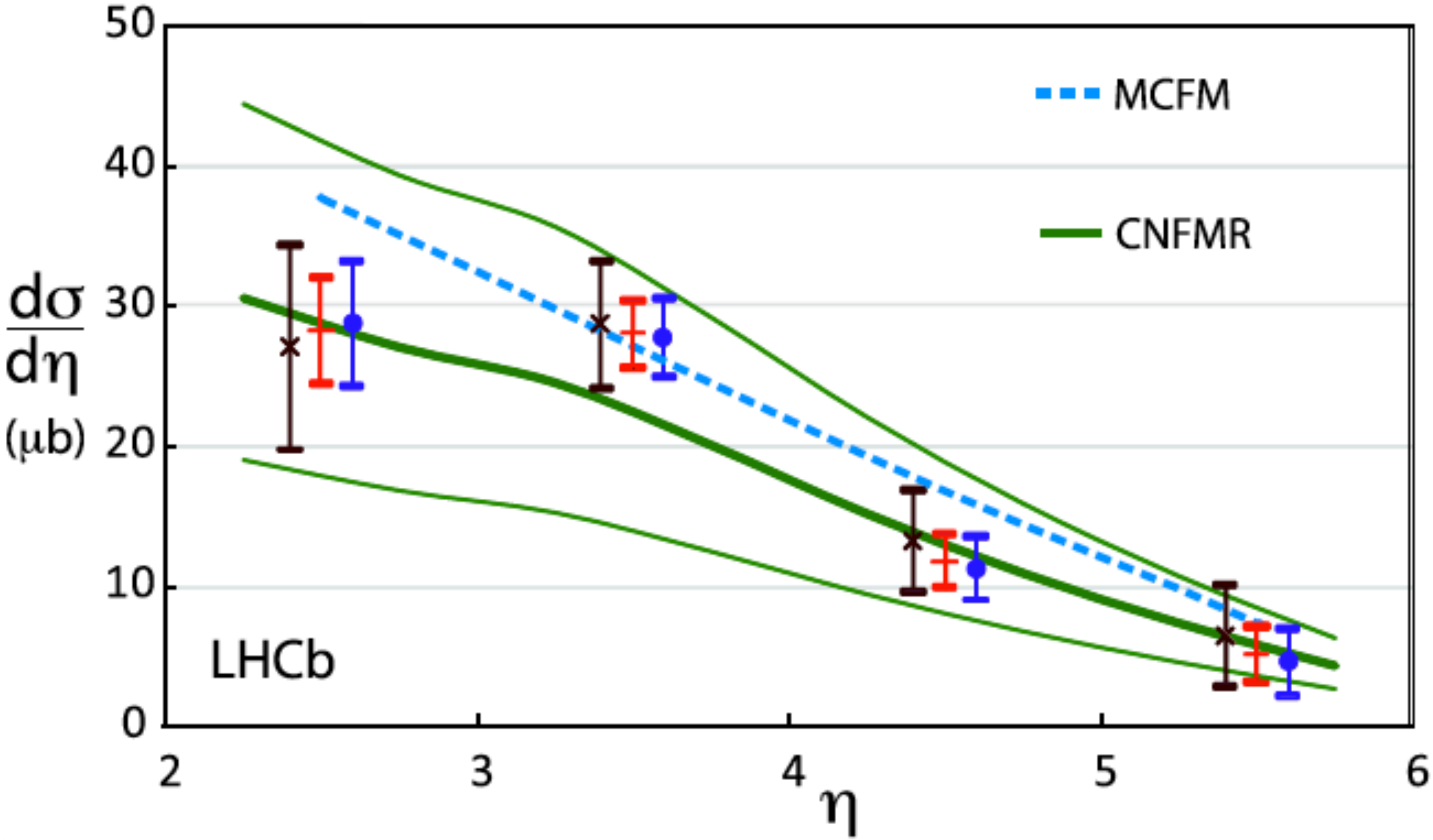
$$D^0 \to K^-\pi^+ \text{ ("}K\pi\text{")}$$

$$\mathcal{R} = \frac{N_{K3\pi}}{N_{K\pi}} \cdot \frac{\epsilon_{K\pi}}{\epsilon_{K3\pi}}$$

$$\mathcal{R}(\mathrm{PDG}) = 2.08 \pm 0.05$$

$$\frac{\epsilon(\mathrm{data})}{\epsilon(\mathrm{MC})} = \sqrt{\frac{\mathcal{R}}{\mathcal{R}(\mathrm{PDG})}}$$

Measurement of $\sigma(pp \rightarrow b\bar{b}X)$ at LHCb



CMS Measurement of non-prompt J/Ψ Production