Heavy flavor physics with the CMS experiment

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On behalf of the CMS Collaboration

PH/LHC CERN Seminar

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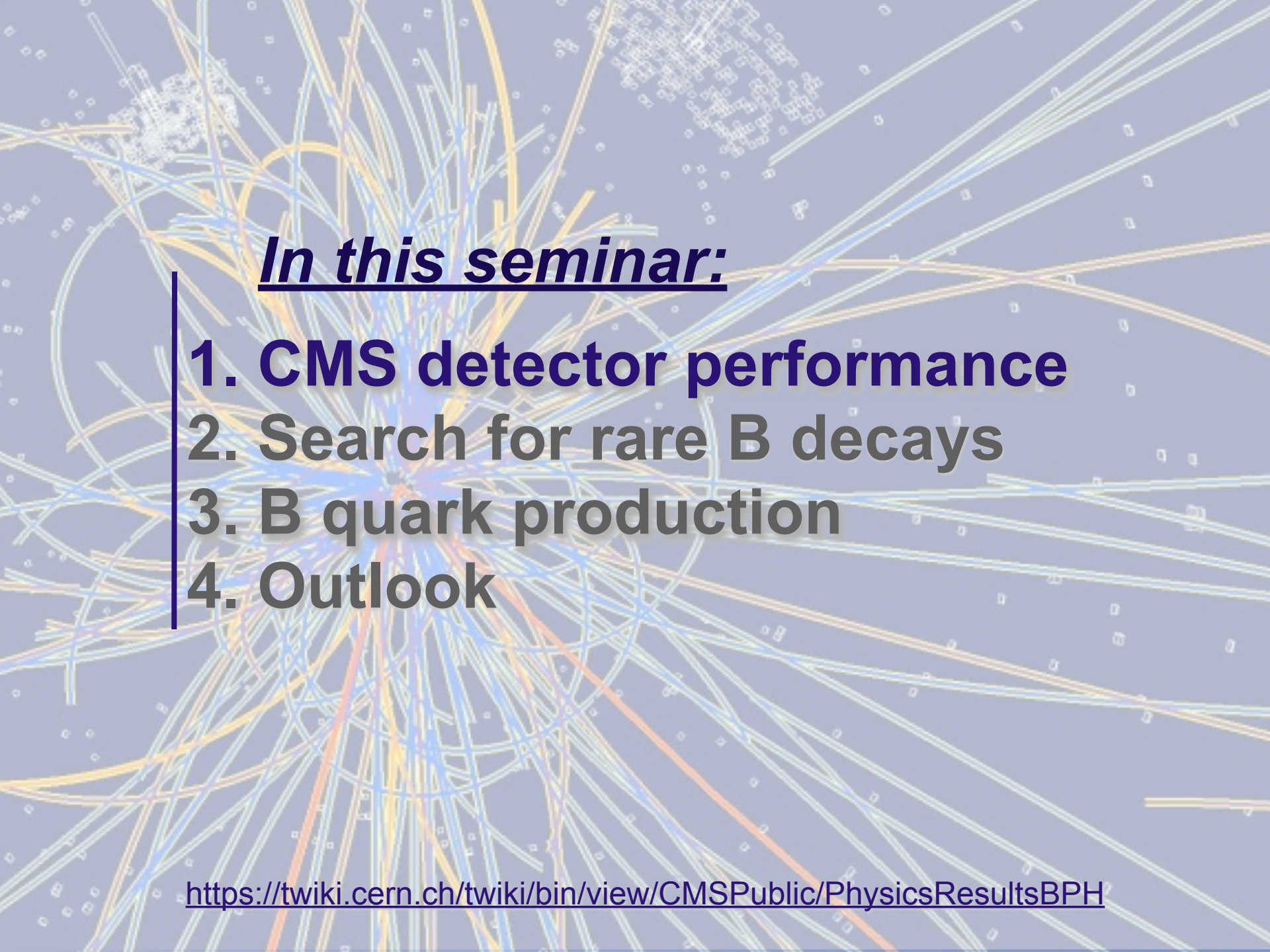
CERN, Geneva

Switzerland

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



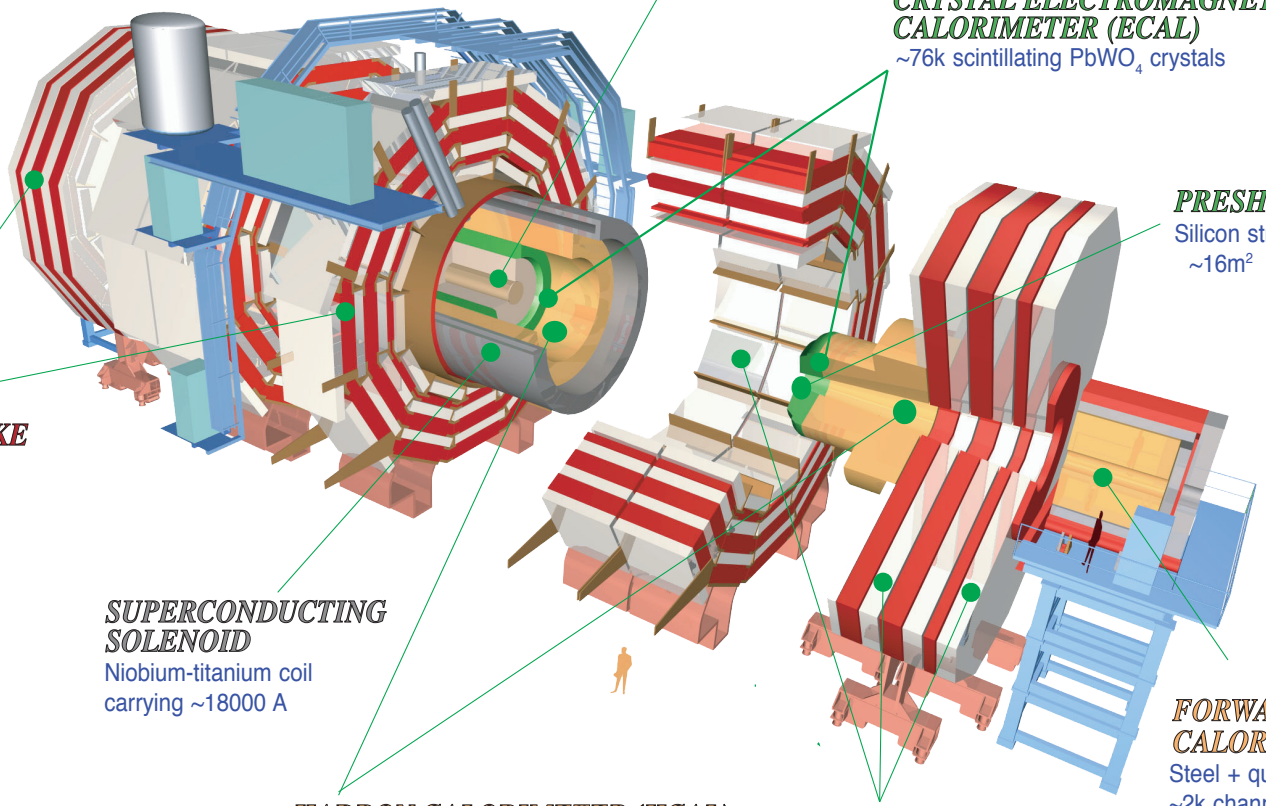
In this seminar:

1. **CMS detector performance**
2. **Search for rare B decays**
3. **B quark production**
4. **Outlook**

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

CMS Detector

Pixels
Tracker
ECAL
HCAL
Solenoid
Steel Yoke
Muons



SILICON TRACKER
Pixels (100 x 150 μm²)
~1m² ~66M channels
Microstrips (80-180μm)
~200m² ~9.6M channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76k scintillating $PbWO_4$ crystals

PRESHOWER
Silicon strips
~16m² ~137k channels

STEEL RETURN YOKE
~13000 tonnes

SUPERCONDUCTING SOLENOID
Niobium-titanium coil
carrying ~18000 A

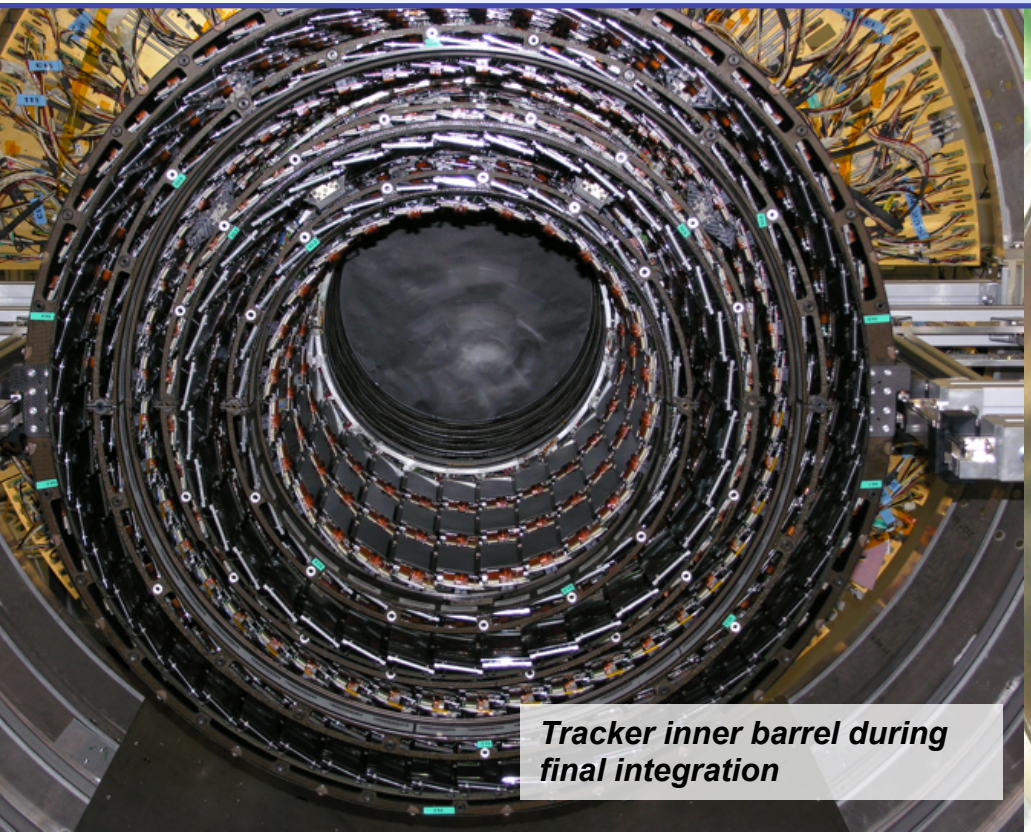
FORWARD CALORIMETER
Steel + quartz fibres
~2k channels

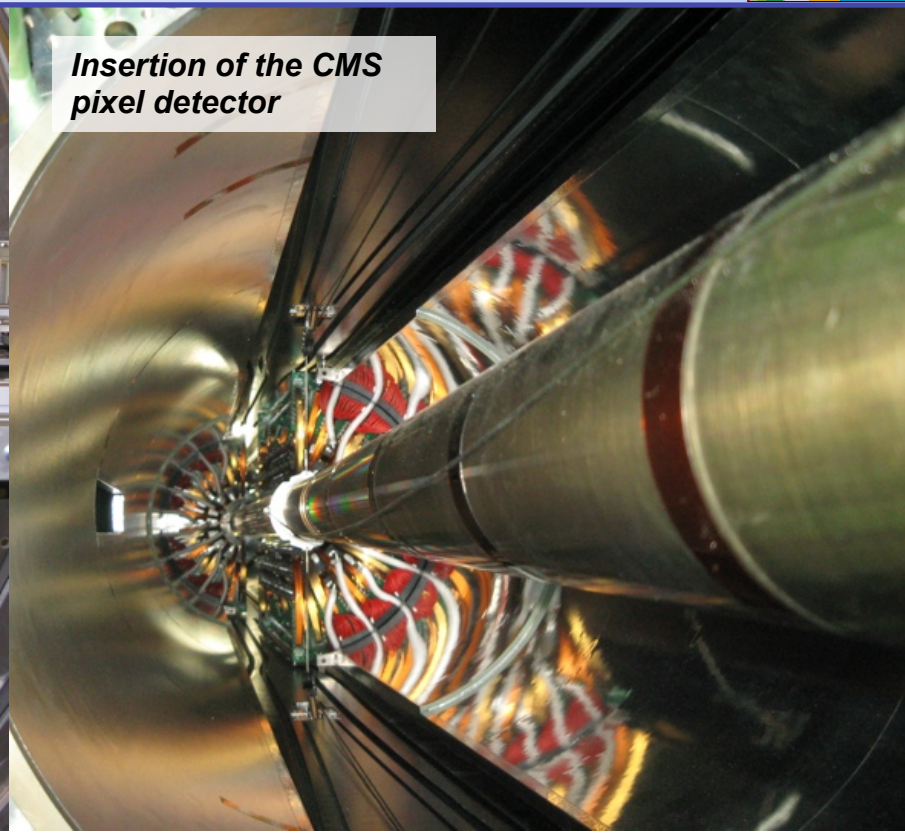
HADRON CALORIMETER (HCAL)
Brass + plastic scintillator
~7k channels

MUON CHAMBERS
Barrel: 250 Drift Tube & 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip & 432 Resistive Plate Chambers

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

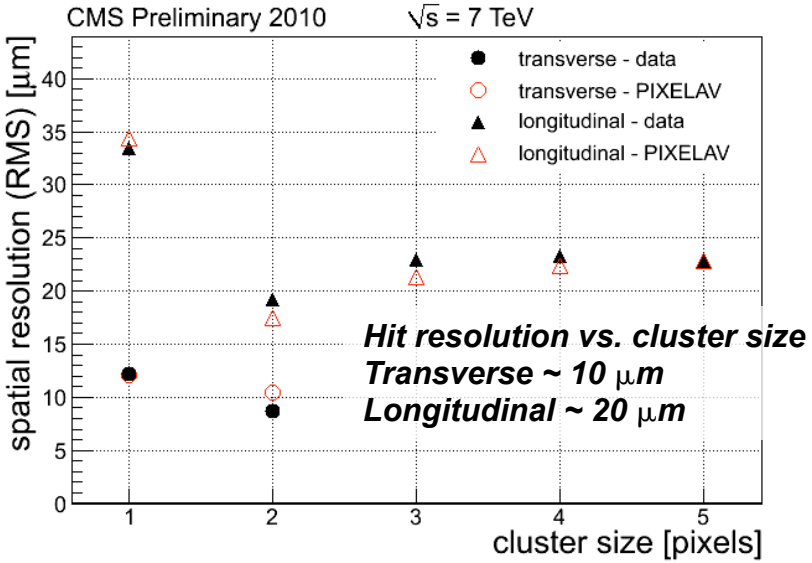
CMS Tracker





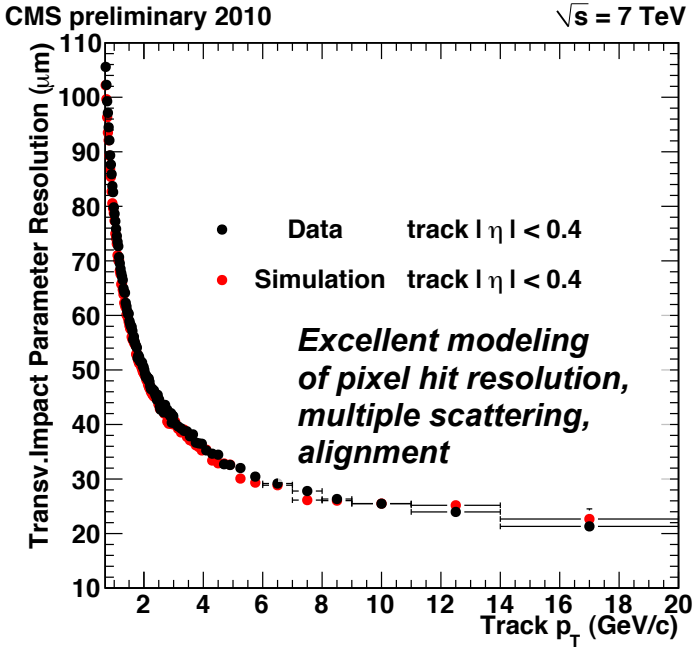
- **CMS is equipped with a full-silicon tracking detector**
  - Three layers and two disks of **pixel sensors** (~66M channels)
  - Ten barrel layers and 3+9 endcap wheels of **strip sensors** (~10M channels)
  - Pseudorapidity coverage up to 2.4. Transverse momentum resolution 2-3%.

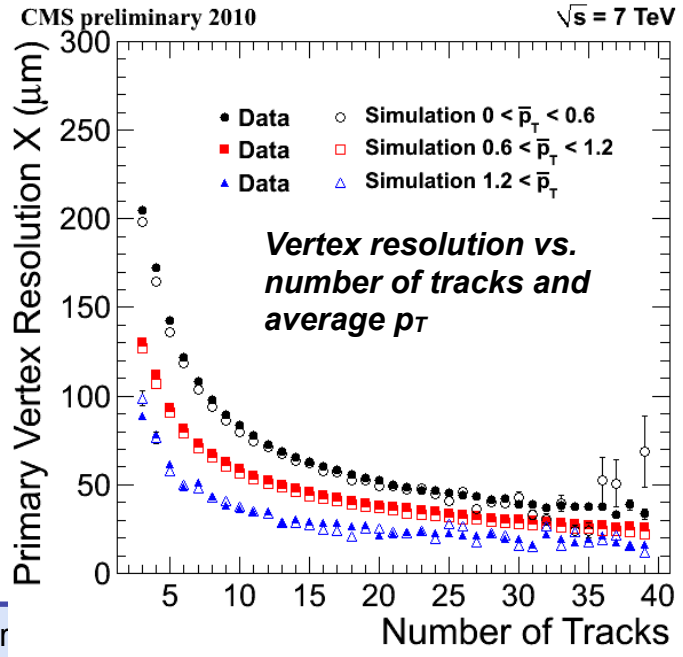
Silicon pixel detector



- ~98% operational during data taking. Hit efficiency >99%
- Excellent understanding of detector resolution:
  - Hit, impact parameter, vertices

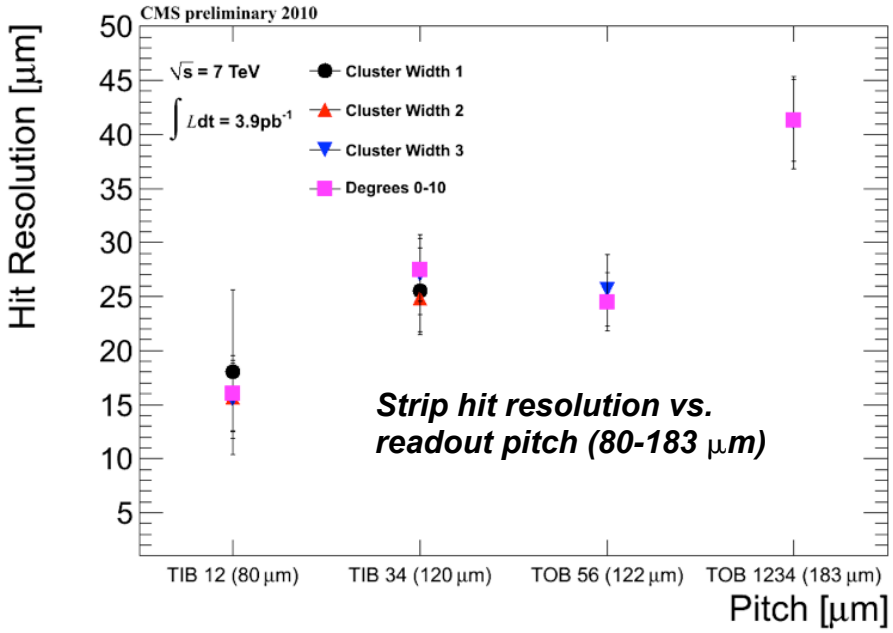
CMS-PAS-TRK-10-005
Eur.Phys.J. C70 (2010) p.1165

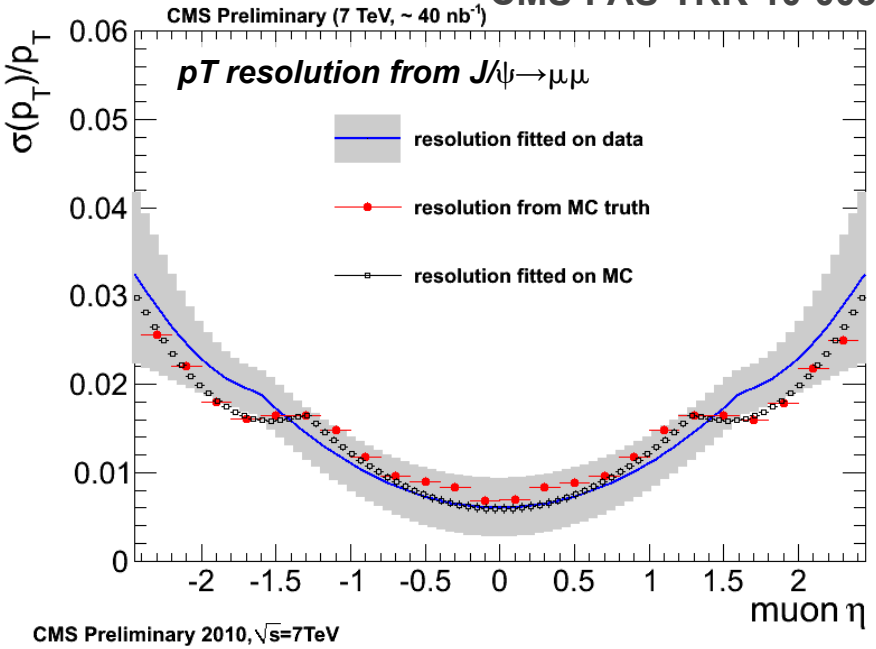


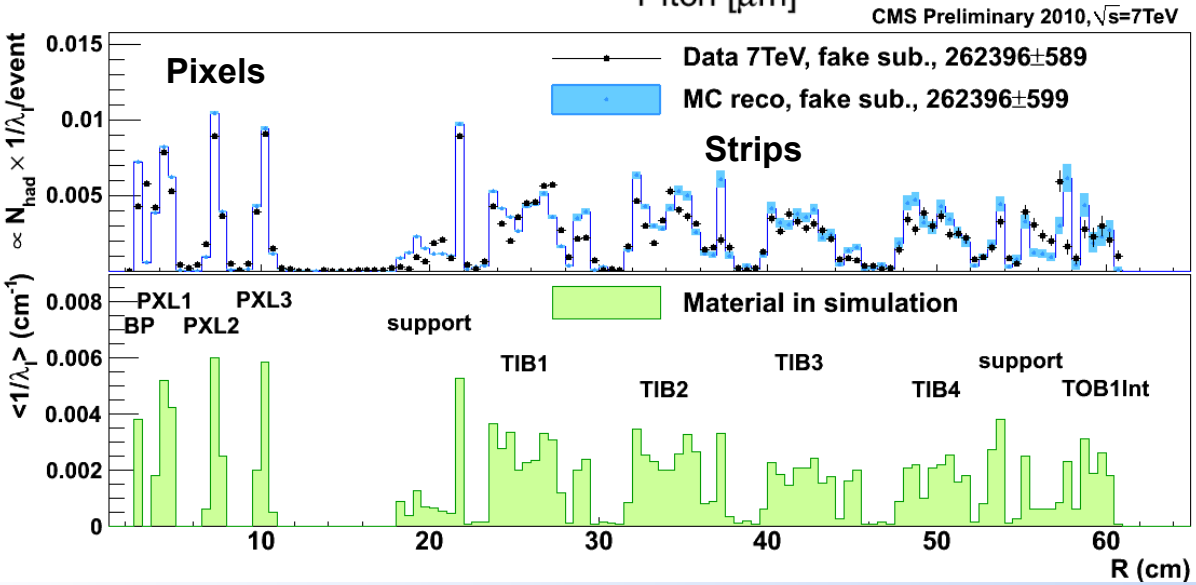


Silicon micro-strips

CMS-PAS-TRK-10-003/4



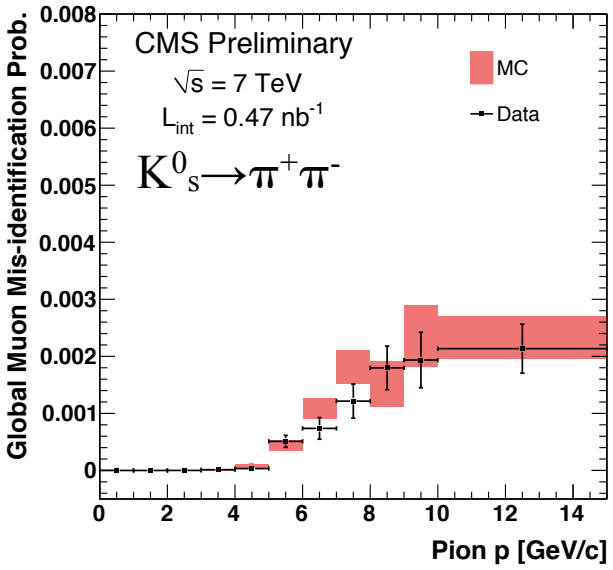


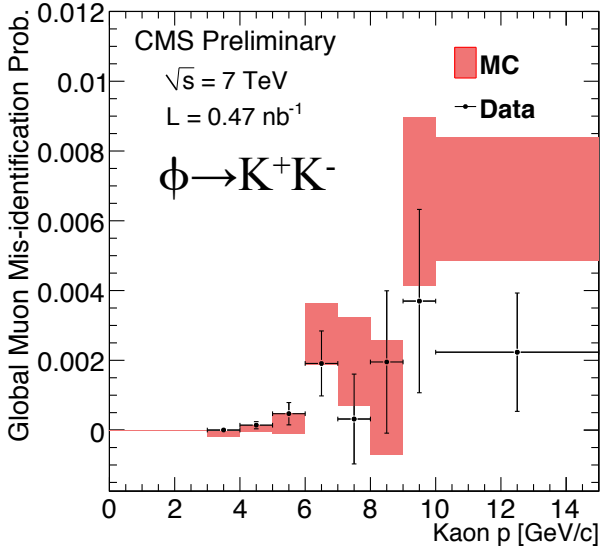


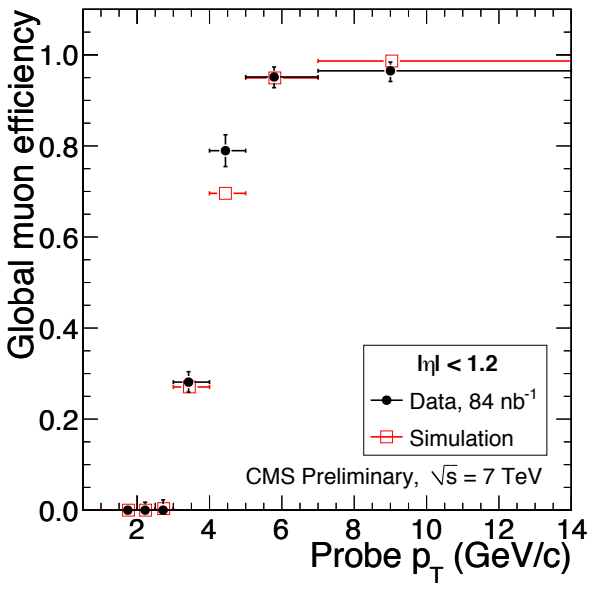
Distribution of the silicon tracker material as function of the radius

Muon ID performance

CMS-PAS-MUO-10-002

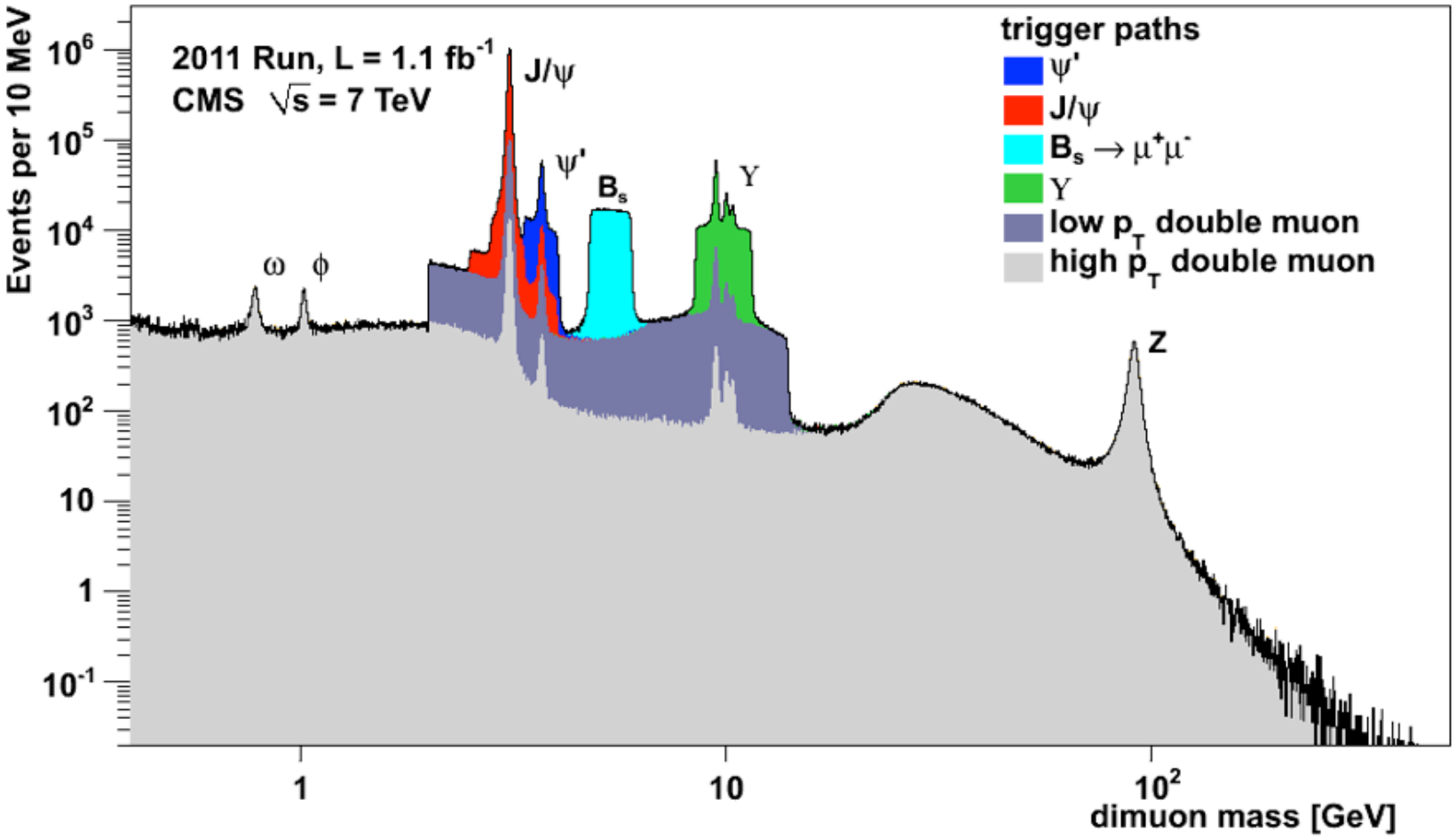




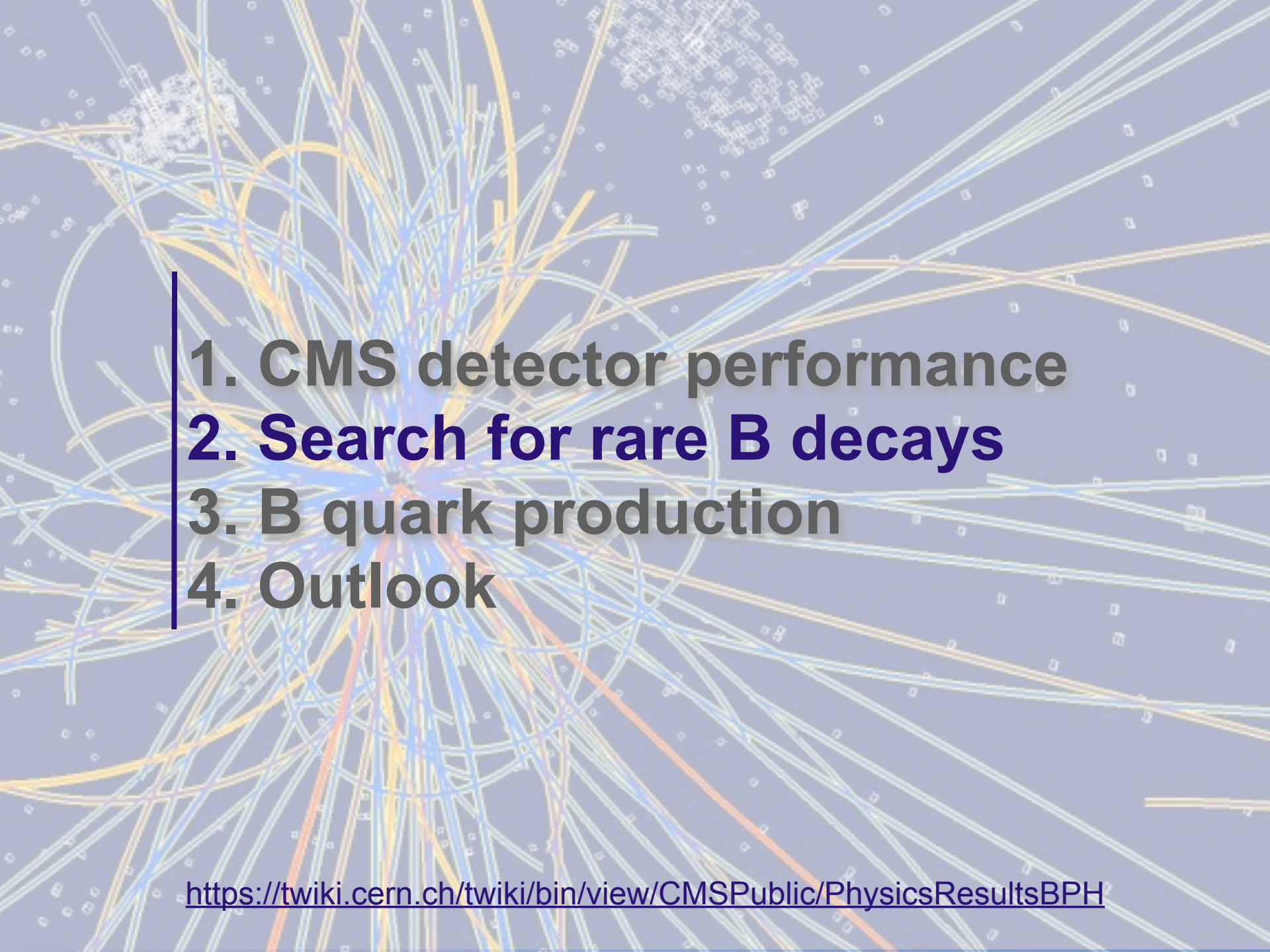


- Muon identification based on outside-in matching of muon segments with tracks in the inner tracks, "*Global muons*"
- Fraction of muons from Pions, Kaons and Protons verified with resonance decays
- Muon efficiency reconstruction verified with a "tag-and-probe" technique on J/ψ decays

Trigger



- Specialized muon triggers deployed for heavy flavor measurements
- Exploit mass, vertex and momentum constraints

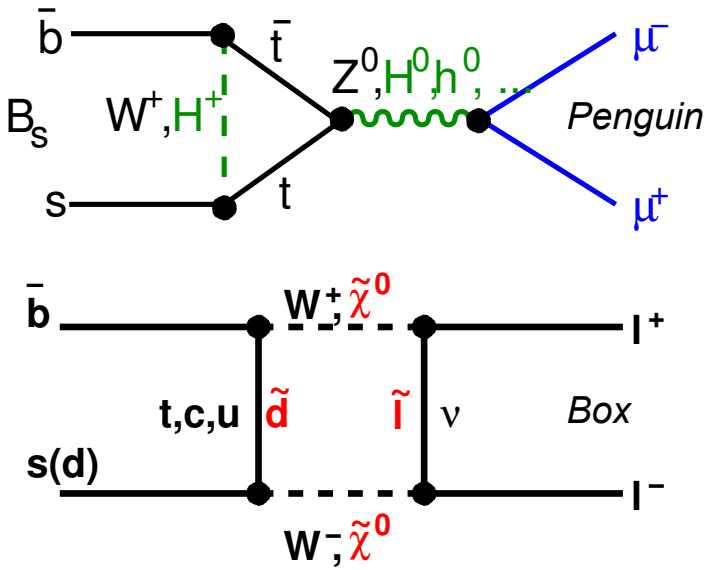


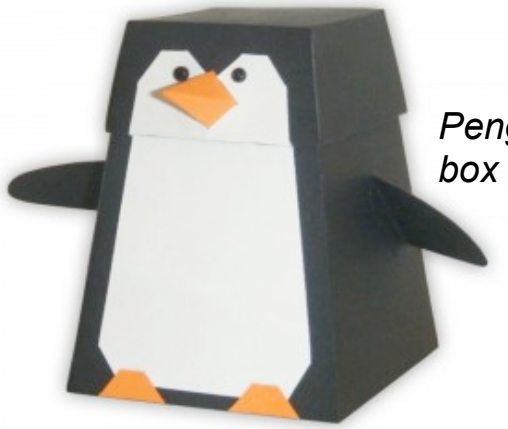
1. CMS detector performance
2. **Search for rare B decays**
3. B quark production
4. Outlook

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

Why searching for $B_{s,d} \to \mu^+\mu^-$?

- **Decays highly suppressed in SM**
  - Forbidden at tree level
  - b →s(d) FCNC transitions only through *Penguin* or *Box* diagrams
  - Helicity suppressed by factors of $(m_\mu/m_B)^2$
- **Standard Model predictions**
  - $\mathcal{B}(B_s \to \mu\mu) = (3.2 \pm 0.2) \times 10^{-9}$
  - $\mathcal{B}(B^0 \to \mu\mu) = (1.0 \pm 0.1) \times 10^{-10}$
- **Sensitivity to new physics**
  - MSSM Br proportional to $(\tan\beta)^6$

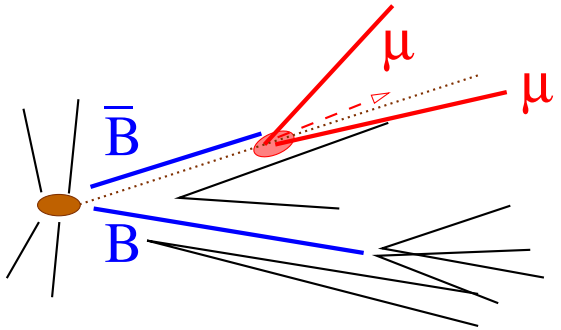




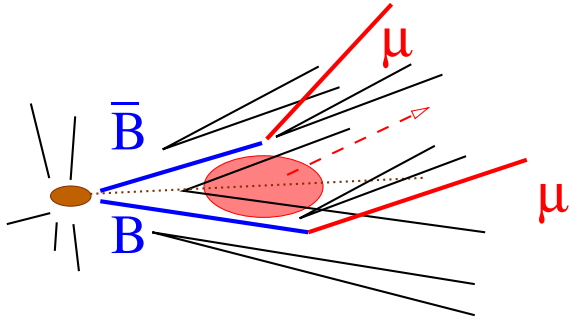
Penguin box

Event characteristics

- **Signal characteristics:**
  - Two muons from a single decay vertex
  - Mass compatible with B_s (or B^0)
  - Well reconstructed secondary vertex
  - Dimuon momentum aligned with flight direction



- **Background sources:**
  - Two semi-leptonic B decays (gluon splitting)
  - One semi-leptonic B decay + misidentified hadron
  - Rare B decays (e.g. $B_s \to KK$, $B_s \to K^- \mu^+ \nu$)

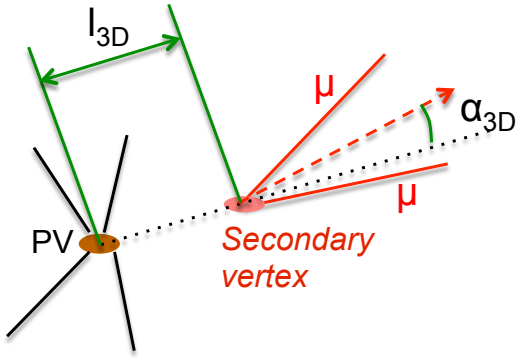


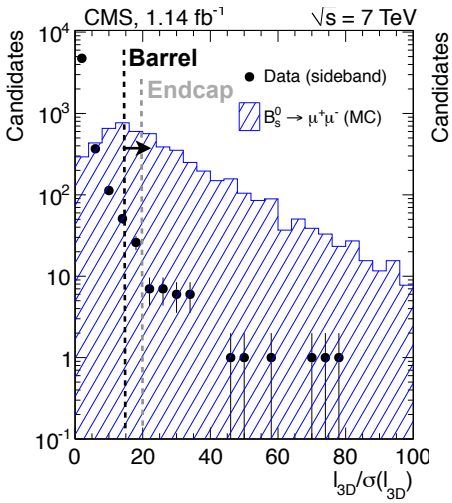
Key ingredients:
Good di-muon vertex, correct B mass assignment, momentum pointing to interaction point

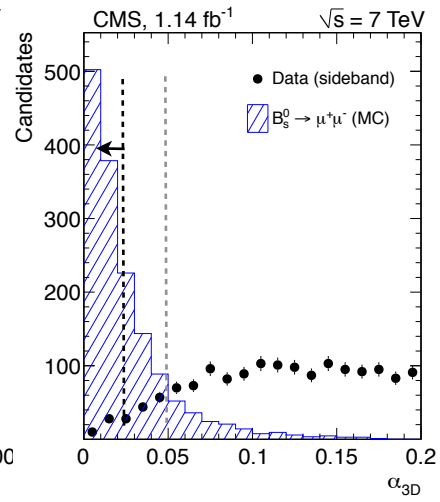
Signal event selection

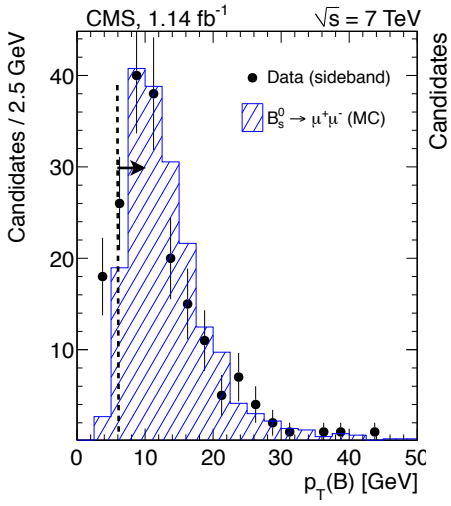
All selection criteria optimized for limit sensitivity <u>before</u> <u>unblinding</u> of signal window

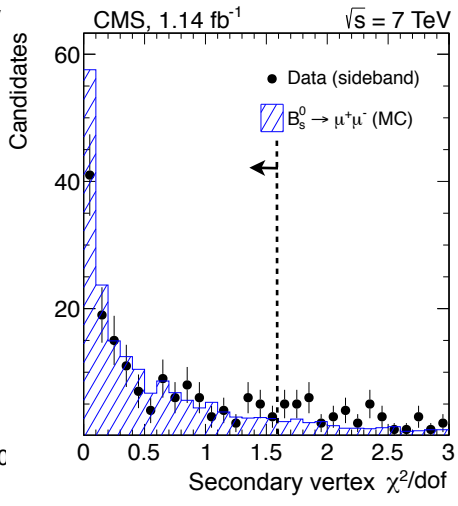
- Mass window requirement:
  - Resolution: **36 (85) MeV** in barrel (endcap)
  - **5.3-5.45 (5.2-5.3) GeV** for B_s (B^0)
- Selection cuts differentiated for **barrel** (both $|\eta(\mu)|<1.4$) and **endcap** region (all other μ pairs)
- Primary vertex consistent with **p**(B) direction
- Secondary vertex fit χ^2/dof<1.6
- Decay length and flight direction:
  - $l_{3D}/\sigma(l_{3D})>15$ (20), $\alpha_{3D}<50$ (25) mrad
- Single muon and B candidate selection:
  - $p_T(\mu)>4.5$ or 4.0 GeV, $p_T(B)>6.5$ GeV





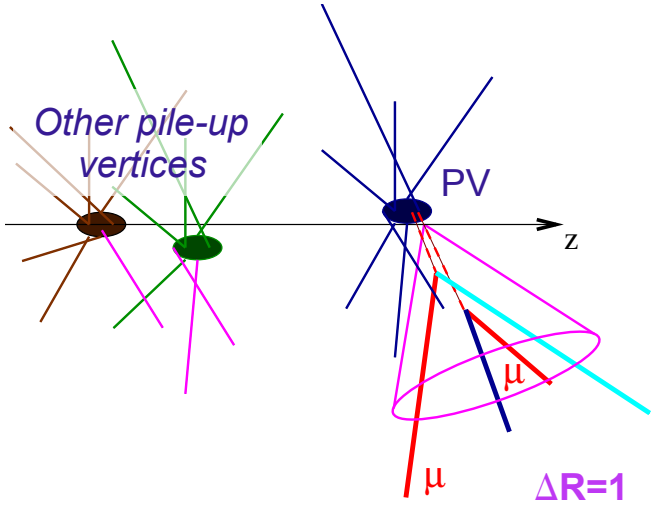




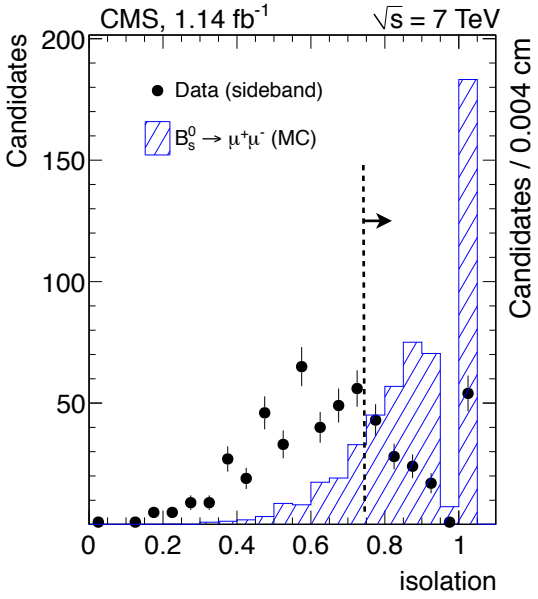


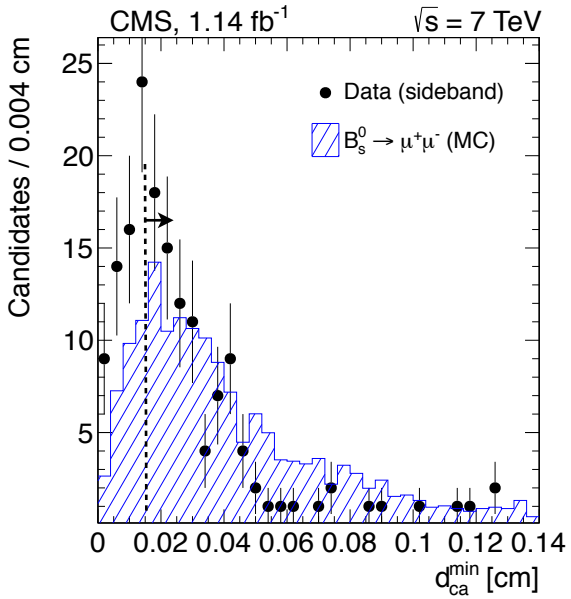
Signal event selection: isolation

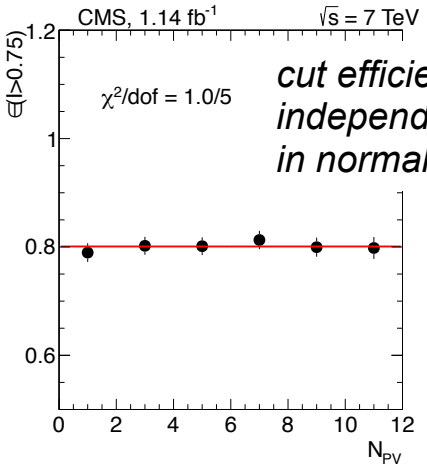
- **Relative isolation of muon pairs**
  - Cone with $\Delta R=1$ around di-muon momentum
  - Include all tracks with $p_T>0.9$ GeV from same PV or $d_{CA}<500$ μm from B vertex
  - Require isolation larger than 75%
- Distance of closest approach of any track w.r.t. B vertex larger than 150 μm (endcap region only)



$$\text{Isolation} = \frac{p_T(\mu^+\mu^-)}{p_T(\mu^+\mu^-) + \sum_{\Delta R<1} p_T} > 75\%$$







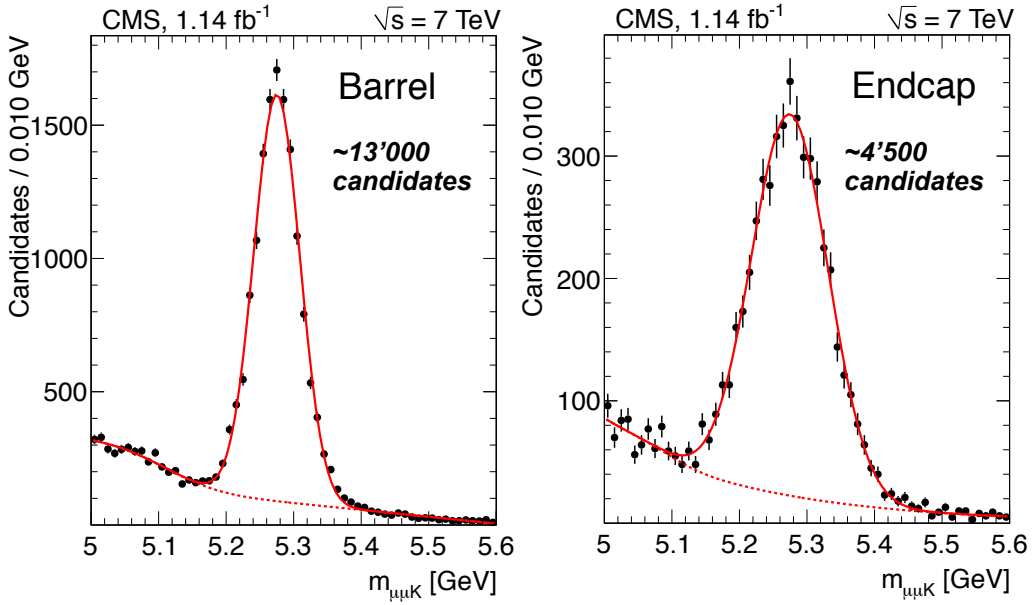
cut efficiency independent on pile-up in normalization sample

Branching ratio calculation

- **Branching ratios calculated w.r.t. normalization channel $B^+ \to J/\psi(\mu\mu)K^+$**
  - Many systematic uncertainties cancel in ratio
  - No need for absolute luminosity and b-quark cross section
  - Large B^+ yield and well known branching ratio to $J/\psi K^+$ (3% uncert.)
  - Ratio of fragmentation fractions, f_u/f_s, from PDG (13% uncert.)

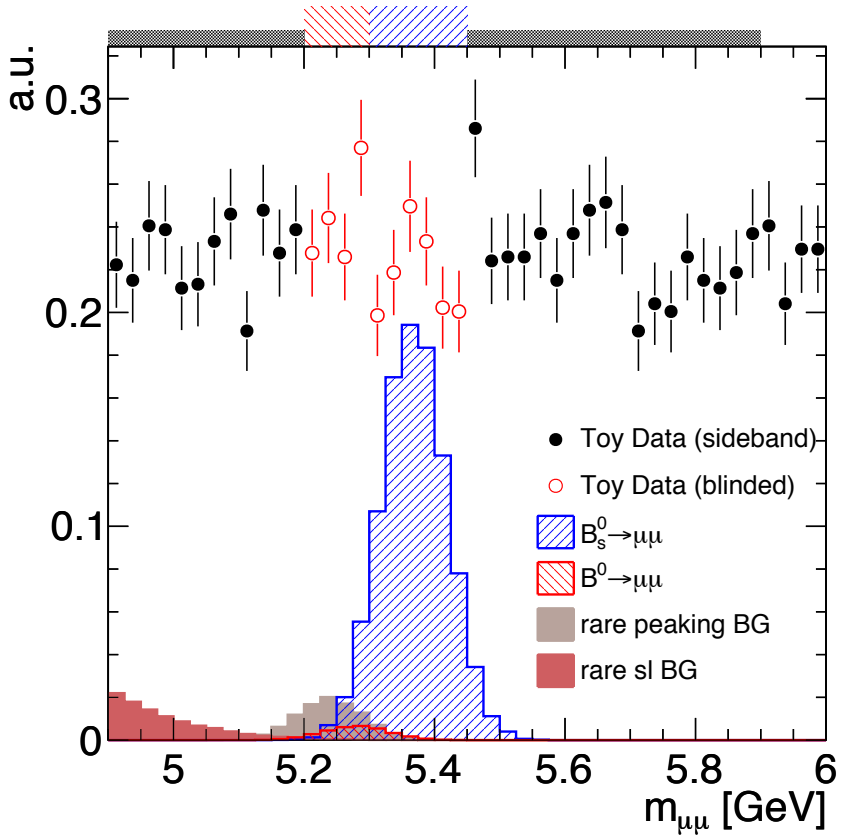
From PDG

$$\mathrm{Br}(\mathrm{B_s} \to \mu^+\mu^-) = \frac{\mathrm{N}(\mathrm{B_s} \to \mu^+\mu^-)}{\mathrm{N}(\mathrm{B^+} \to \mathrm{J}/\psi\mathrm{K^+})} \frac{\mathrm{f_u}}{\mathrm{f_s}} \frac{\epsilon_{\mathrm{tot}}^{\mathrm{B^+}}}{\epsilon_{\mathrm{tot}}^{\mathrm{B_s}}} \mathrm{Br}(\mathrm{B^+} \to \mathrm{J}/\psi\mathrm{K^+})$$



Background estimates

- **Combinatorial background:**
  - Measured in data from B mass sidebands
  - Interpolate to signal region under flat-shape assumption
- **Peaking backgrounds:**
  - B→hh backgrounds with two muons from misidentified hadrons
  - Muon mis-ID in data from $K_s \to \pi\pi$, $\phi \to KK$, $\Lambda \to p\pi$ decays
  - MC background samples with mis-ID probability from data
  - B^0 search more affected than B_s because of lower mass

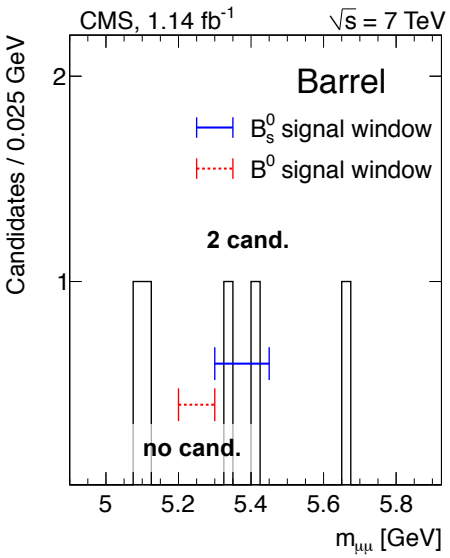


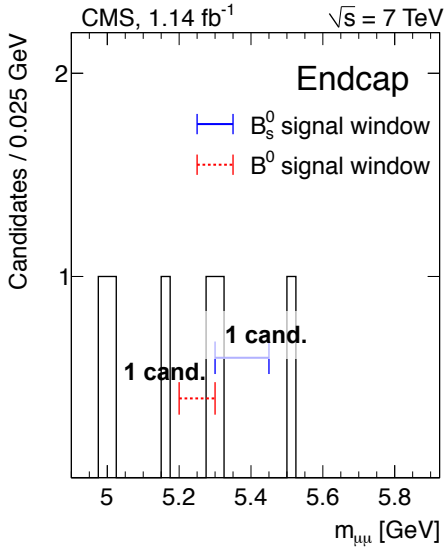
Toy MC

Systematic uncertainties

Fragmentation fractions from PDG	**13%**
Background estimation: *loosen cuts, invert isolation cut*	4%
Signal acceptance: *vary b-quark production processes*	4%
Signal selection efficiency: *cut-by-cut data/MC differences*	**8%**
Track momentum scale: *from J/ψ resonance*	3%
Normalization selection efficiency: *cut-by-cut data/MC differences*	5%
Hadron tracking efficiency: *from D* decays*	4%
Normalization yield: *vary fit functions*	5%
Muon identification efficiency ratio: *data/MC differences*	5%
Trigger efficiency ratio: *data/MC differences*	3%
Total	**19%**

Results with 1.1 fb^{-1}





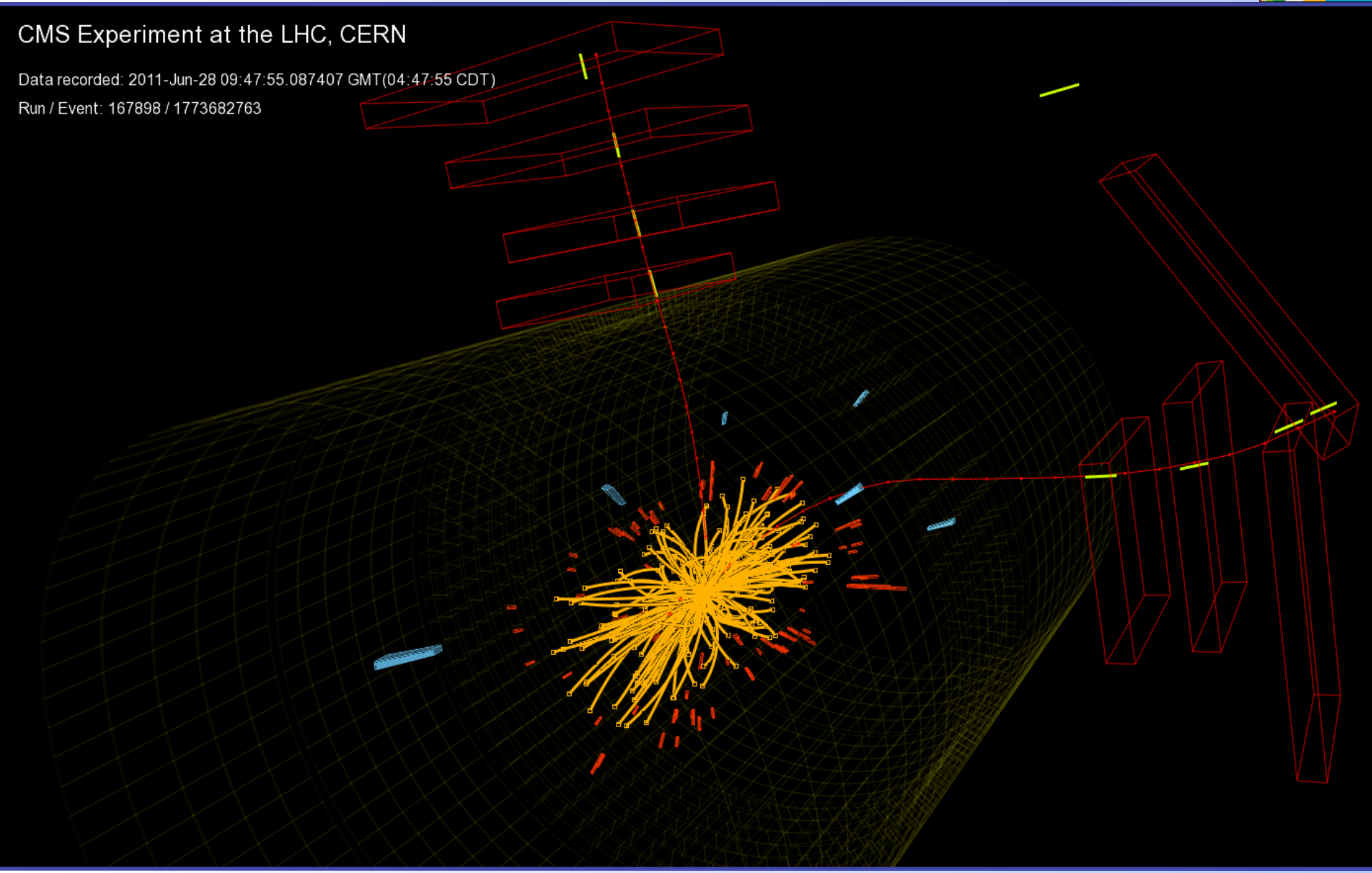
arXiv:1107.5834
Accepted by PRL

Consistent with expectation from background and SM signal in all four channels

	Barrel		Endcap	
	$B^0 \to \mu^+\mu^-$	$B_s^0 \to \mu^+\mu^-$	$B^0 \to \mu^+\mu^-$	$B_s^0 \to \mu^+\mu^-$
ε_{tot}	$(3.6 \pm 0.4) \times 10^{-3}$	$(3.6 \pm 0.4) \times 10^{-3}$	$(2.1 \pm 0.2) \times 10^{-3}$	$(2.1 \pm 0.2) \times 10^{-3}$
N_{signal}^{exp}	0.065 ± 0.011	0.80 ± 0.16	0.025 ± 0.004	0.36 ± 0.07
N_{comb}^{exp}	0.40 ± 0.23	0.60 ± 0.35	0.53 ± 0.27	0.80 ± 0.40
N_{peak}^{exp}	0.25 ± 0.06	0.07 ± 0.02	0.16 ± 0.04	0.04 ± 0.01
N_{obs}	0	2	1	1

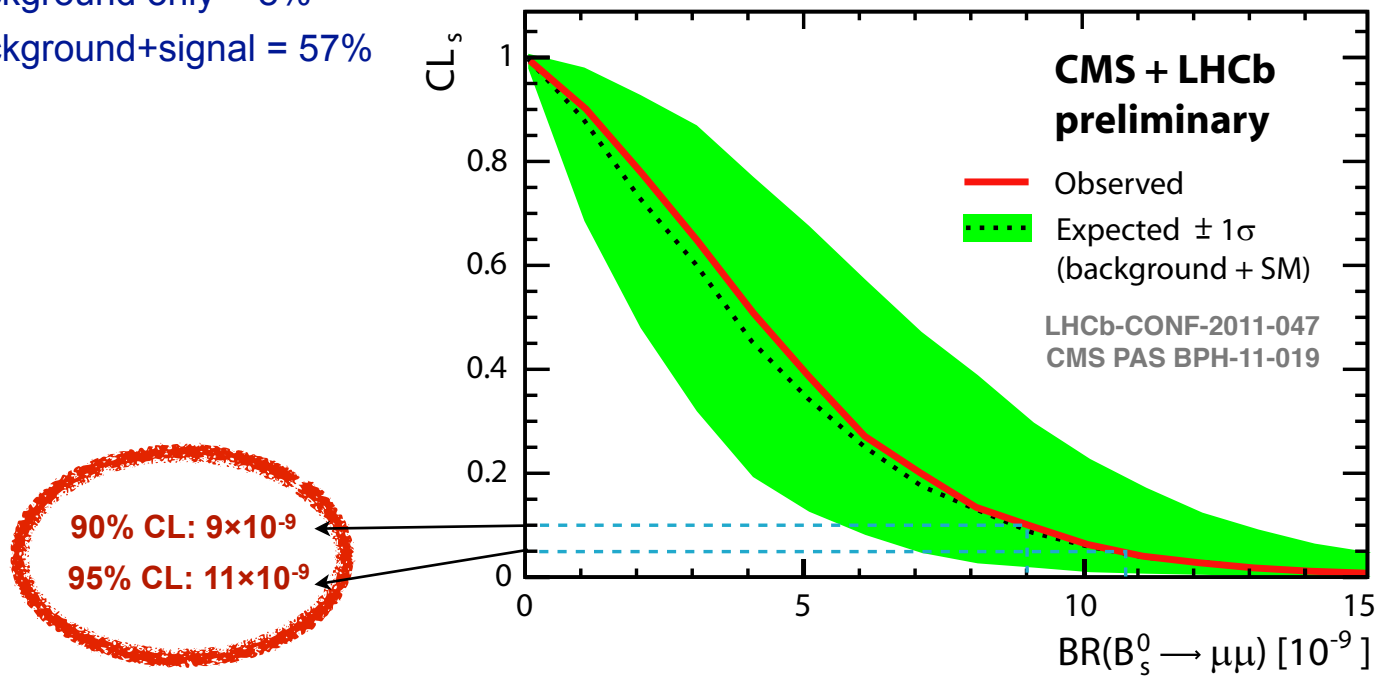
Decay	**Expected (95% CL)**	**Observed (95% CL)**	**Background-only p value**
$B_s \to \mu^+\mu^-$	1.8×10^{-8}	**1.9×10^{-8}**	11% (1.2σ)
$B^0 \to \mu^+\mu^-$	4.8×10^{-8}	**4.6×10^{-9}**	40% (0.3σ)

Candidate event



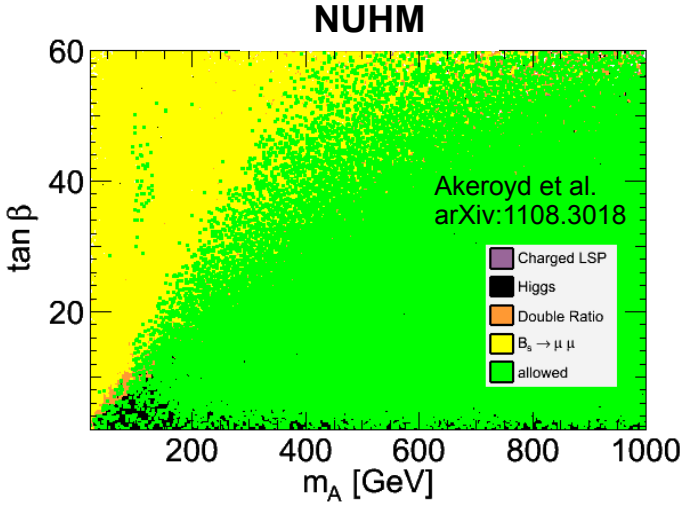
CMS+LHCb combination

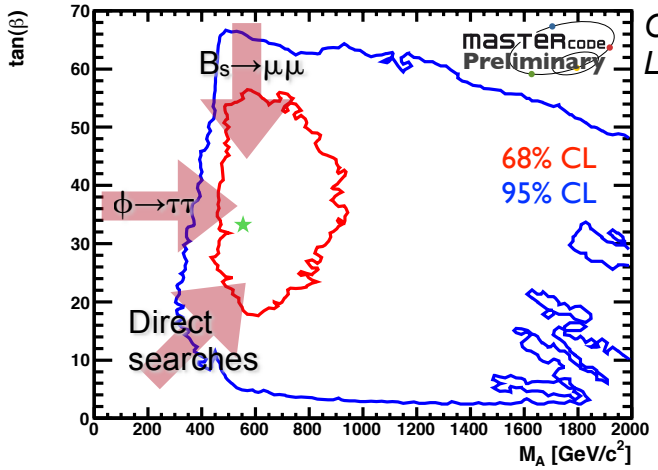
- **LHCb analysis released at EPS 2011, based on 370 pb^{-1}**
  - Upper limit = 1.6×10^{-9} at 95% CL (1.5×10^{-9} combining with 2010 result)
- **CMS and LHCb upper limits combined**
  - Using recent LHCb f_s/f_u value (8% uncert.)
    - Assumed 100% correlated between 48 LHCb bins and 2 CMS bins for signal expectation
  - p-value for background only = 8%
  - p-value for background+signal = 57%



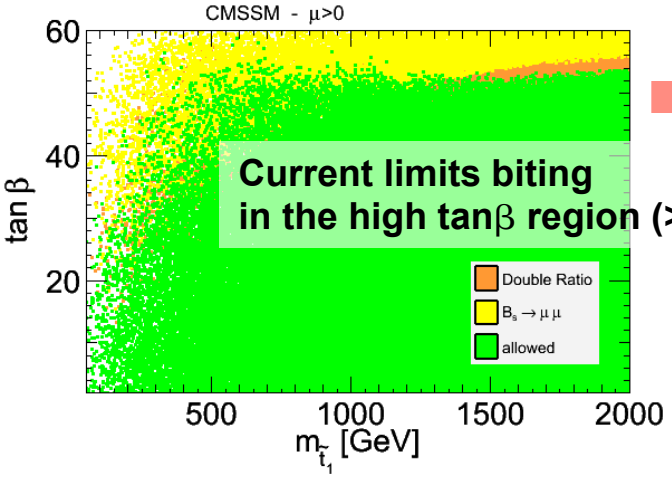
Implications on new physics

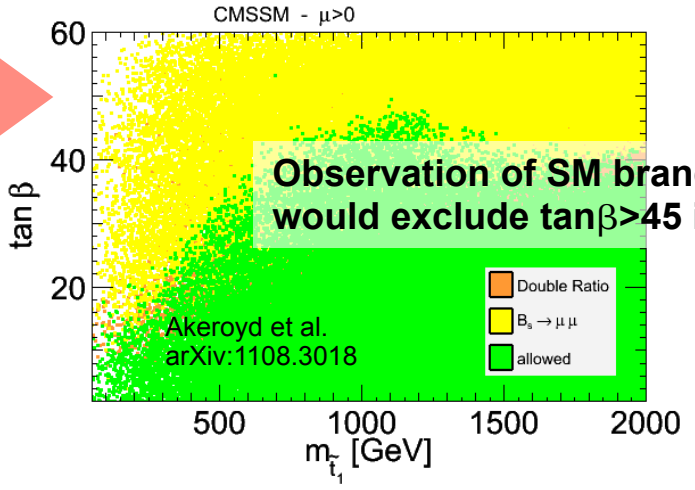
- **Relevant impact on various SUSY scenarios at large tanβ**
  - For large tanβ (50) can extend limits from direct searches in some SUSY models





O.Buchmueller et al.
LHC Implications workshop

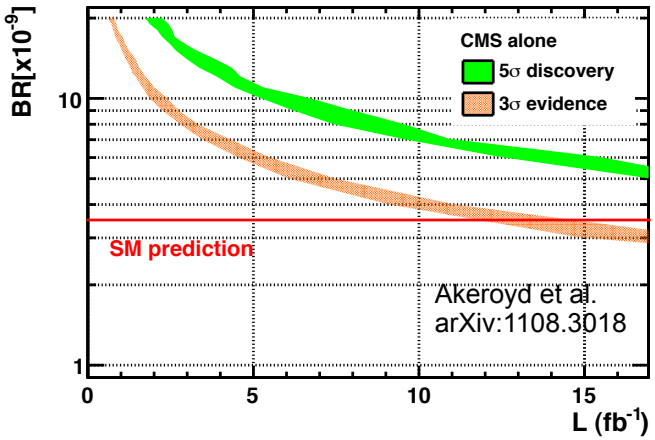




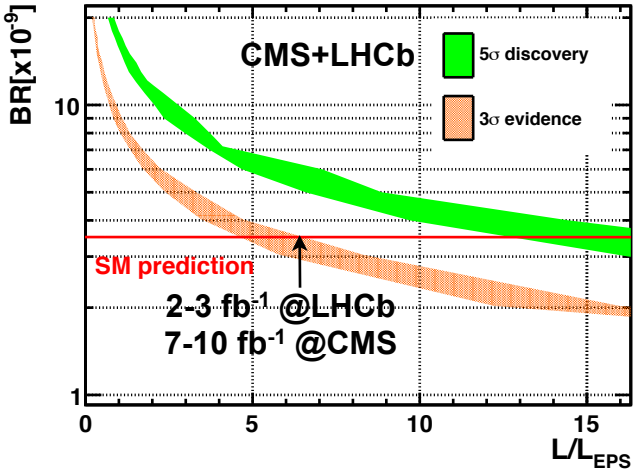
Many other global fitters available...

Closing fast?

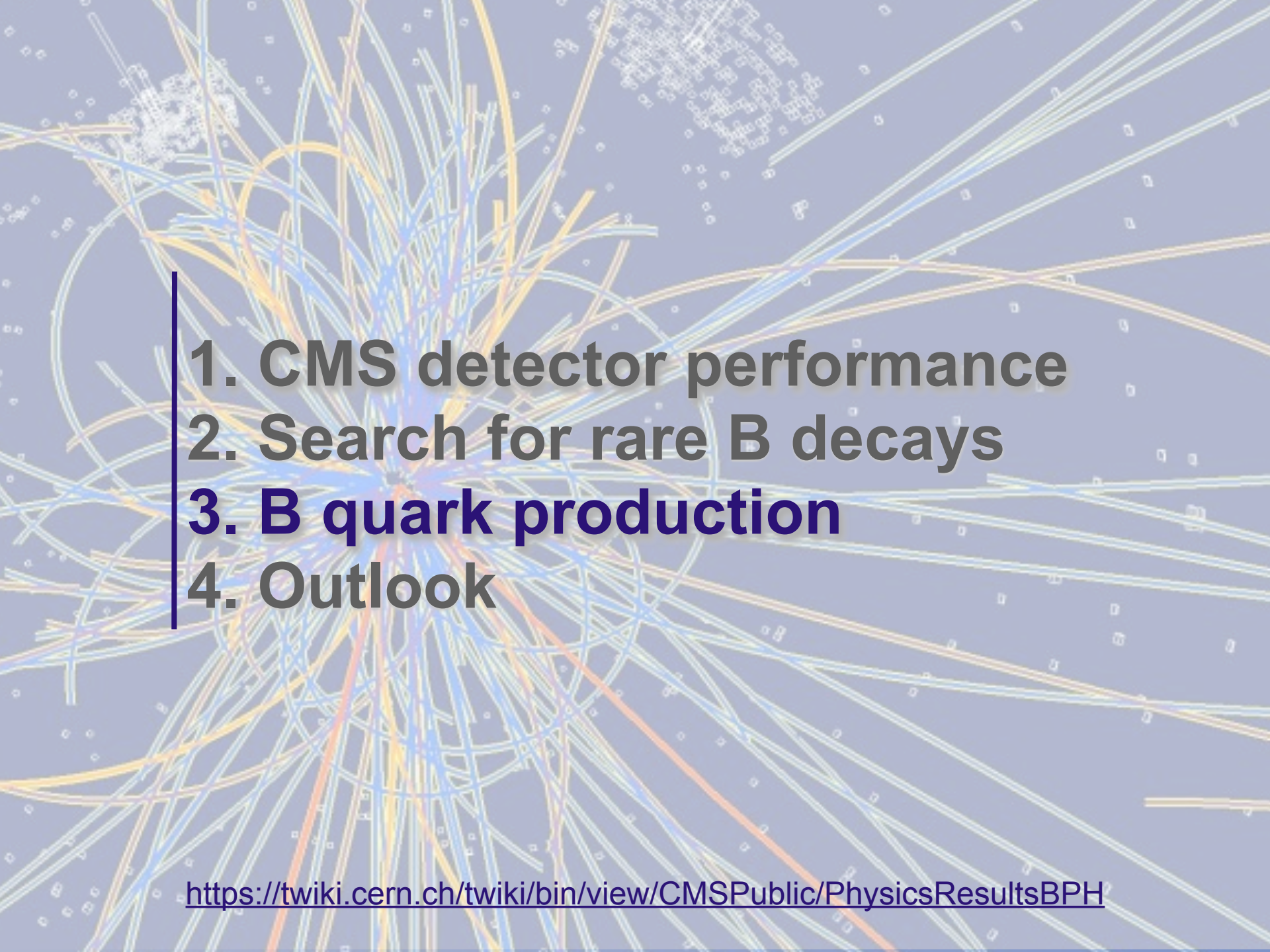
- **SM branching ratio within reach by early 2012**
  - Improved sensitivity may be expected by replacing cut&count with MV analysis



Simple scaling of current limits with no improvement in sensitivity!



5-7 times EPS11 luminosity needed for 3σ exclusion of SM prediction with CMS+LHCb combination (4.3 fb^{-1} already on tape!)



1. CMS detector performance
2. Search for rare B decays
3. **B quark production**
4. Outlook

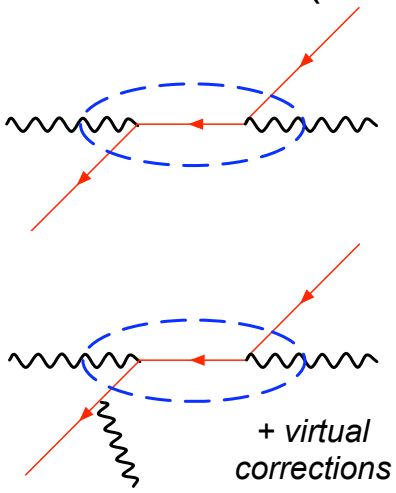
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH

B-quark production at LHC

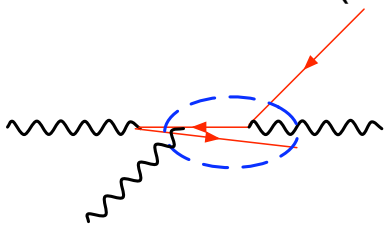
- **Excellent test bench for perturbative QCD and Monte Carlo models**
  - **Tensions between data and theory gradually resolved at hadron colliders with lower c.o.m. energy (Tevatron, HERA)**
  - **Measurements at LHC have smaller uncertainties than NLO QCD predictions**
- **B-quark jets are a frequent 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 tools for physics searches**
- **CMS detector is well suited for b-quark production measurements, thanks to its excellent tracking, vertexing and muon identification, combined with a flexible trigger system**

Production processes in p-p

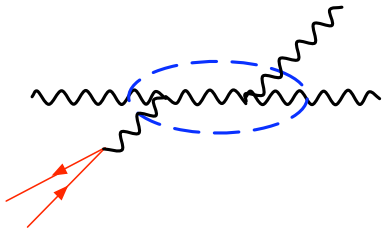
Flavour creation (FCR)



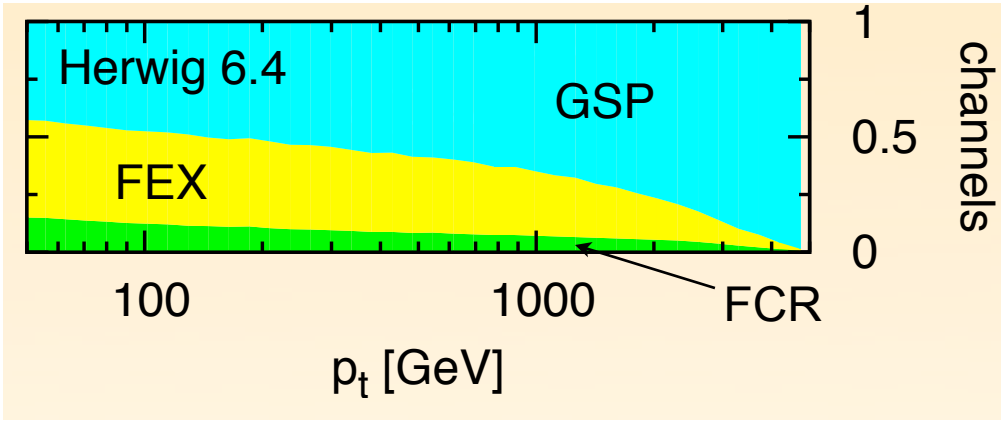
Flavour excitation (FEX)



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!

B-quark identification

- **Identification with semi-leptonic decay into muons**
  - Low momentum (3 GeV) single-muon trigger thresholds at CMS startup
  - Probe inclusive beauty production at low momentum
  - Both single and di-muon final states measured

JHEP 1103 (2011) 090
CMS-PAS-BPH-10-008
CMS-PAS-BPH-10-015

- **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
  - Angular correlation studies with inclusive secondary vertices

CMS-PAS-BPH-10-009
JHEP 1103 (2011) 136

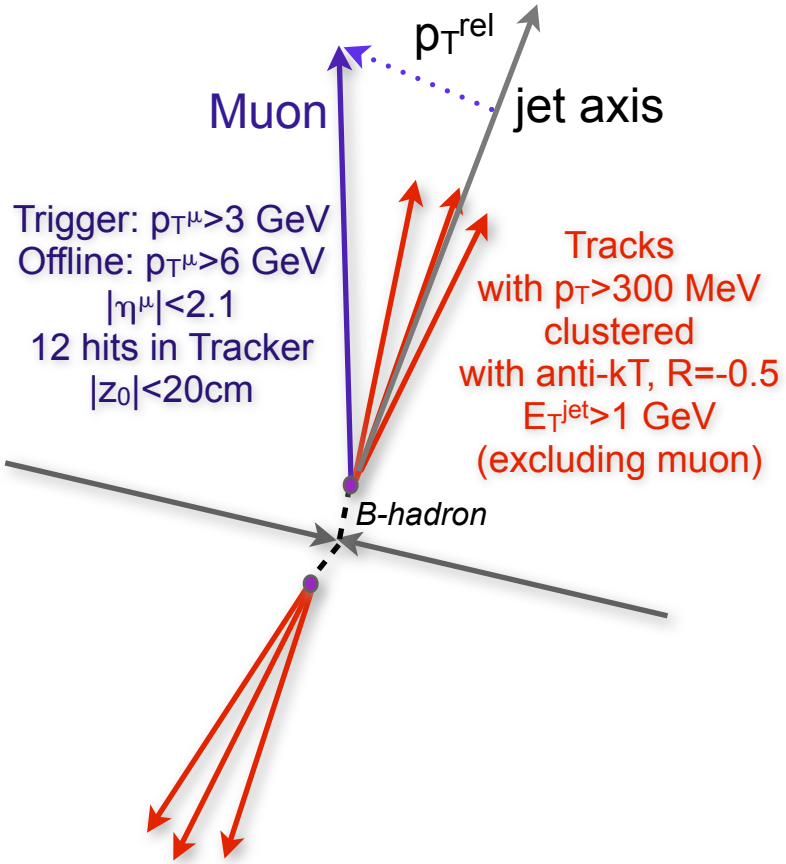
- **Fully reconstructed B-hadron decays**
  - Utilize J/ψ+X decay channels with J/ψ→$\mu^+\mu^-$
  - $B^+ \to J/\psi K^+$, $B^0 \to J/\psi K_s$, $B_s \to J/\psi \phi$ differential cross sections

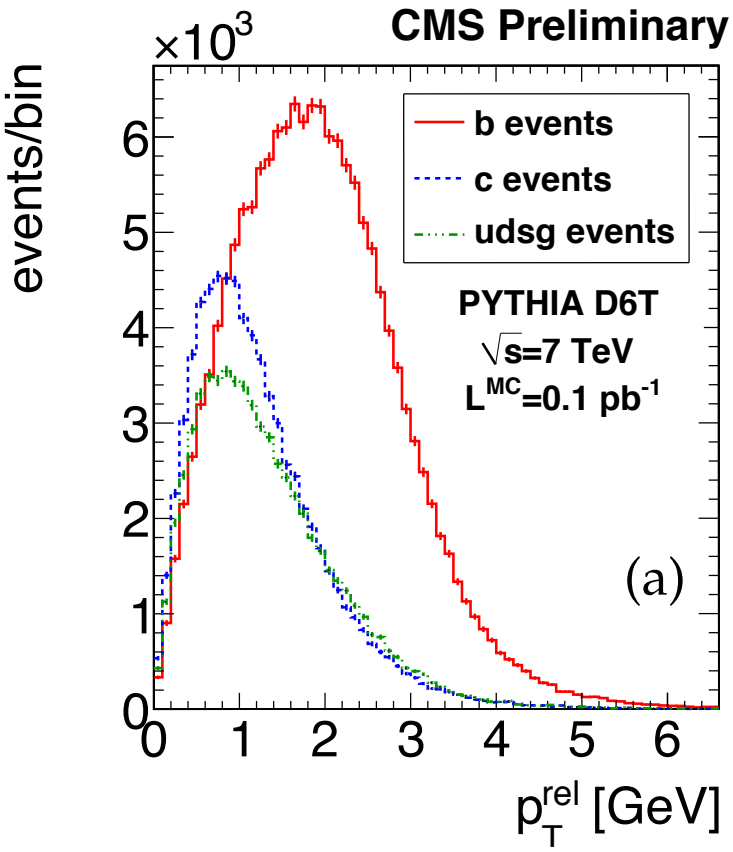
PRL 106, 112001 (2011)
PRL 106, 252001 (2011)
PRD 84, 052008 (2011)

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

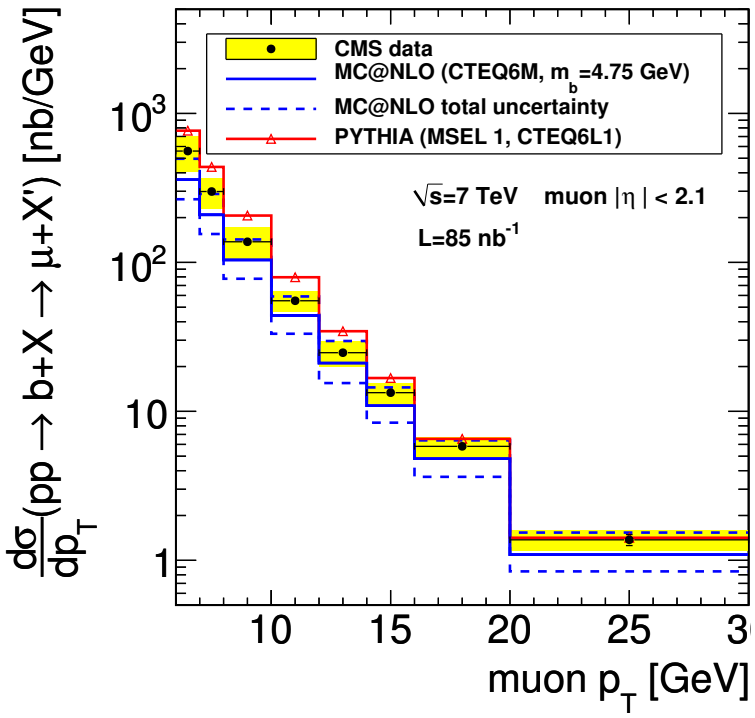
Semileptonic decays

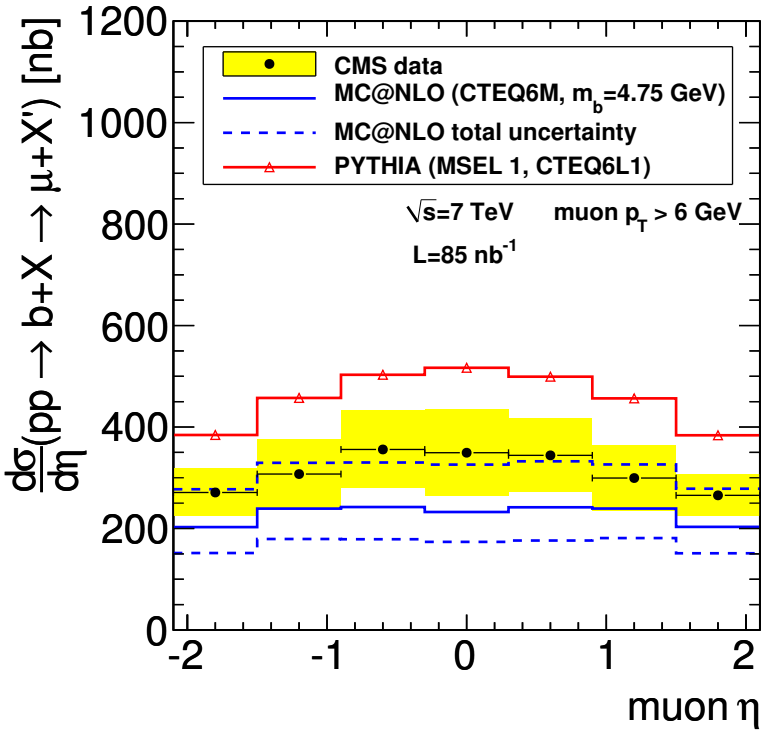
- Exploit kinematics of semi-leptonic decay due to heavy quark mass
  - Muon transverse momentum w.r.t. jet on average larger for b-quark
  - Fraction of events with b-decays extracted from a fit with simulated p_T^{rel} templates





Differential cross sections





$\sigma = 1.32 \pm 0.01(\text{stat}) \pm 0.30(\text{syst}) \pm 0.15(\text{lumi})\,\mu\text{b}$ **Measured visible cross section**

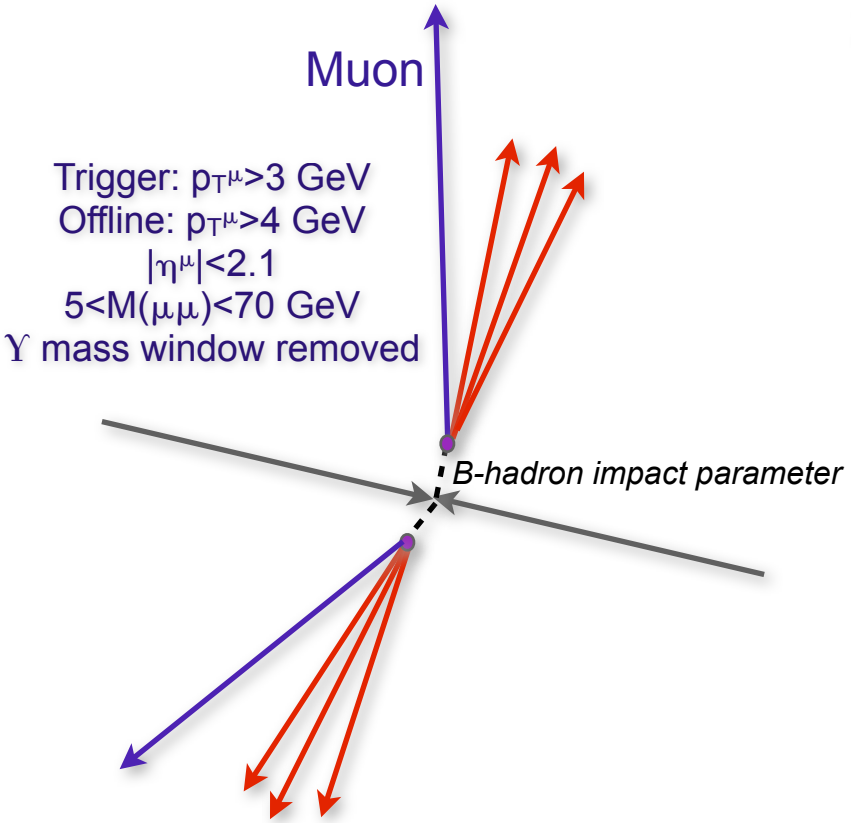
$\sigma_{\text{PYTHIA}} = 1.8\,\mu\text{b}$

$\sigma_{\text{MC@NLO}} = 0.95^{+0.41}_{-0.21}(\text{scale}) \pm 0.09(m_{\text{b}}) \pm 0.05(\text{pdf})\,\mu\text{b}$ ($\mu_F=\mu_R=p_T$)

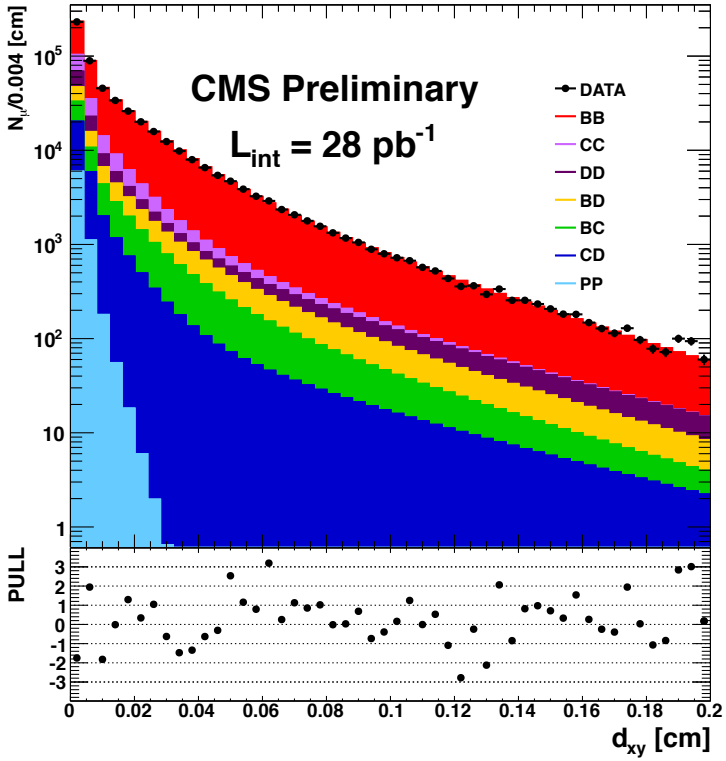
Experimental uncertainties (15-20%) dominated by modeling of fake muons and underlying event

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

Di-muon cross section



2D fit of di-muon impact parameter



B-fraction (65.1±0.3)%

$$\sigma(pp \to b\bar{b}X \to \mu\mu\Upsilon, p_T^{1,2} > 4\,\text{GeV}, |\eta^{1,2}| < 2.1)$$

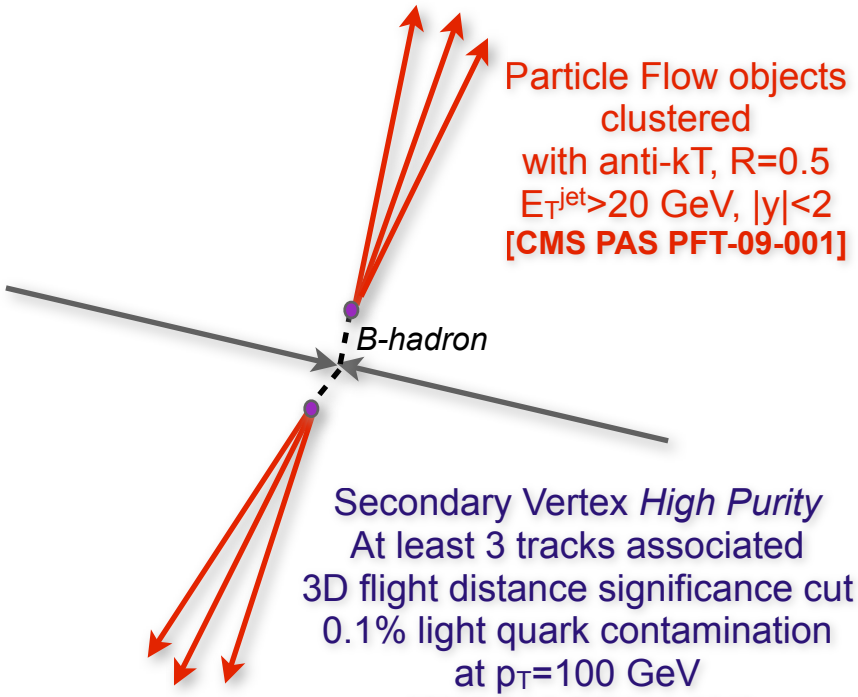
$$\sigma(pp \to b\bar{b}X \to \mu\mu\Upsilon) = 26.18 \pm 0.14\,(\text{stat.}) \pm 2.82\,(\text{syst.}) \pm 1.05\,(\text{lumi.})\ \text{nb}$$

$$\sigma_{MC@NLO}(pp \to b\bar{b}X \to \mu\mu\Upsilon) = 19.95 \pm 0.46\,(\text{stat.})\ ^{+4.68}_{-4.33}\,(\text{syst.})\ \text{nb}$$

Experimental uncertainties (11%) dominated by muon efficiency, MC templates shapes and fit

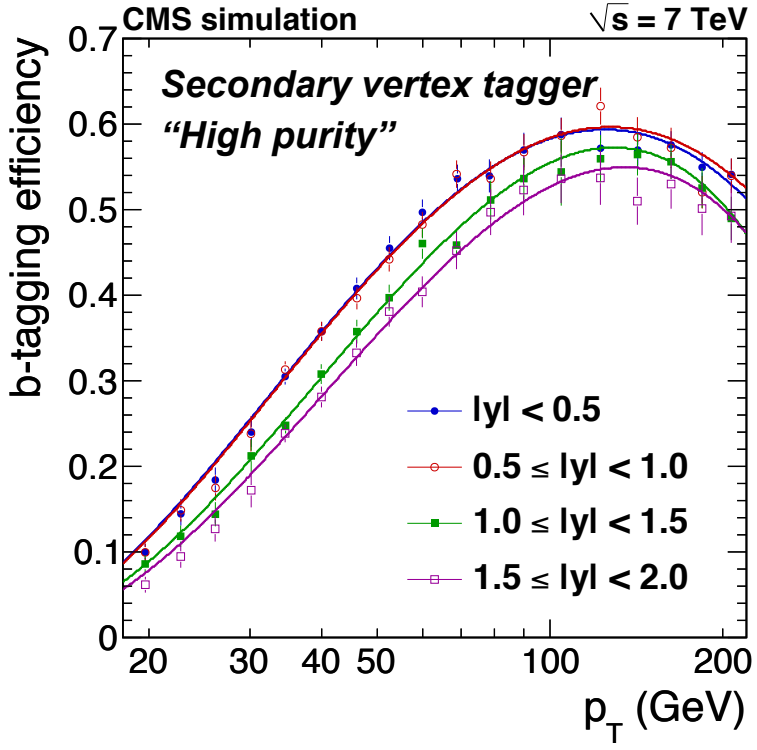
B jet with secondary vertices

- By tagging B jets the cross section measurement can be extended to large transverse momenta
  - Exploit secondary vertex (SV) 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

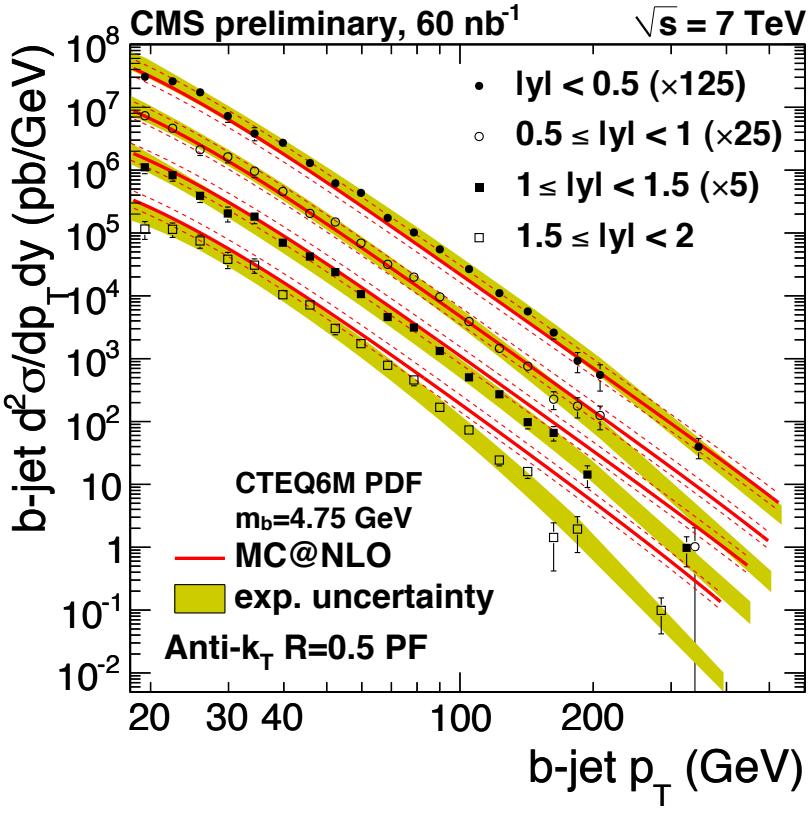


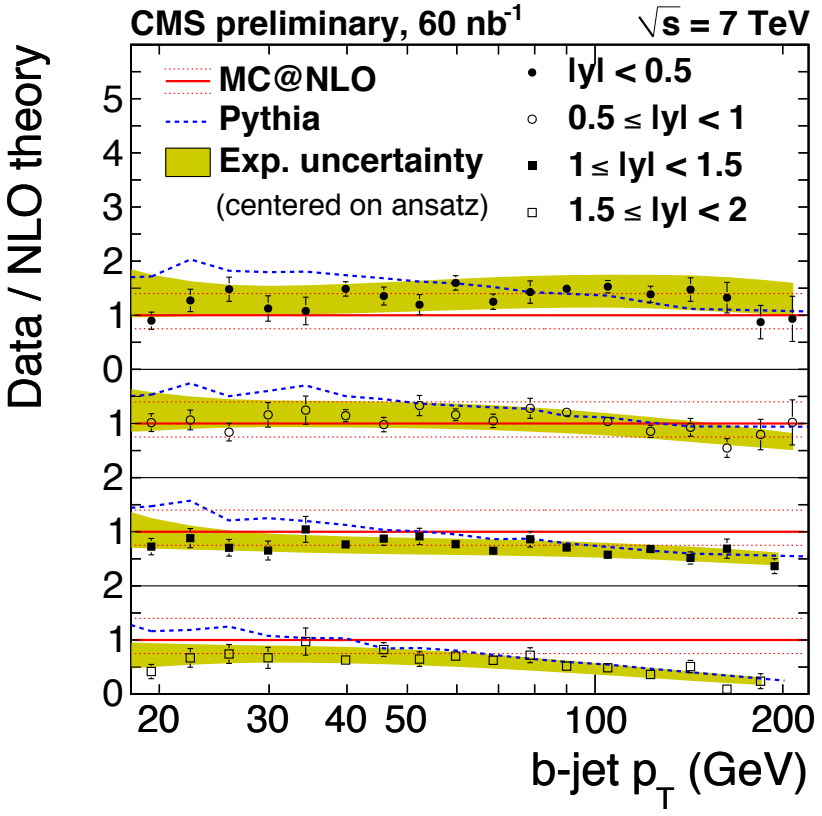
Particle Flow objects
clustered
with anti-kT, R=0.5
E_T^{jet}>20 GeV, |y|<2
[CMS PAS PFT-09-001]

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]



B jets: results

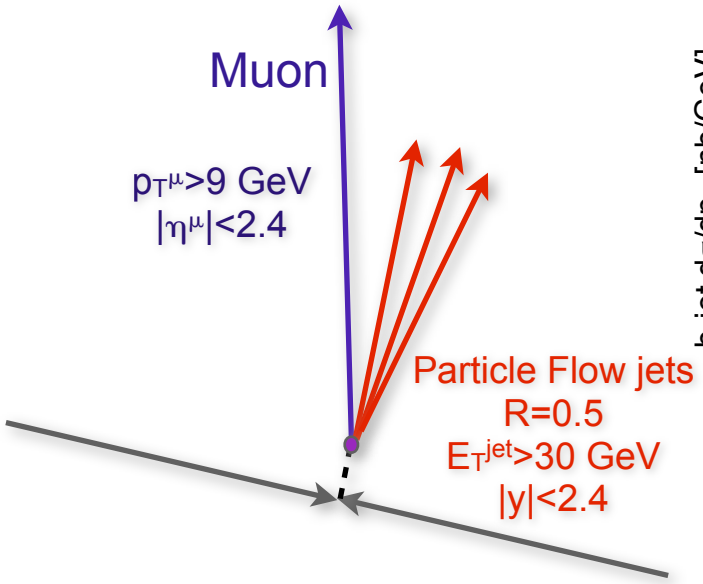


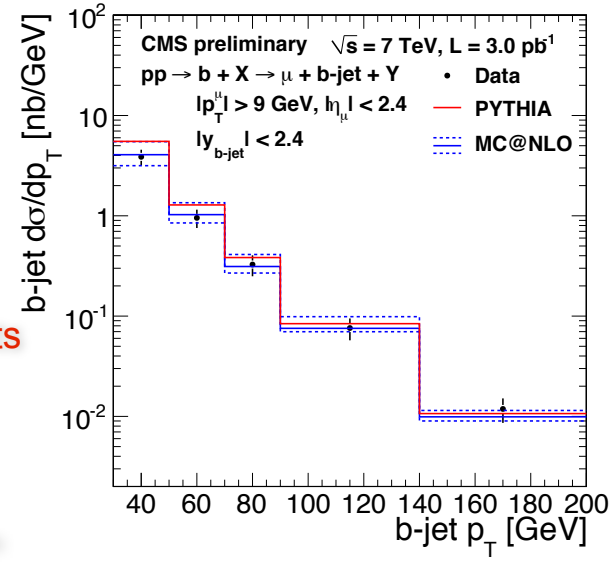


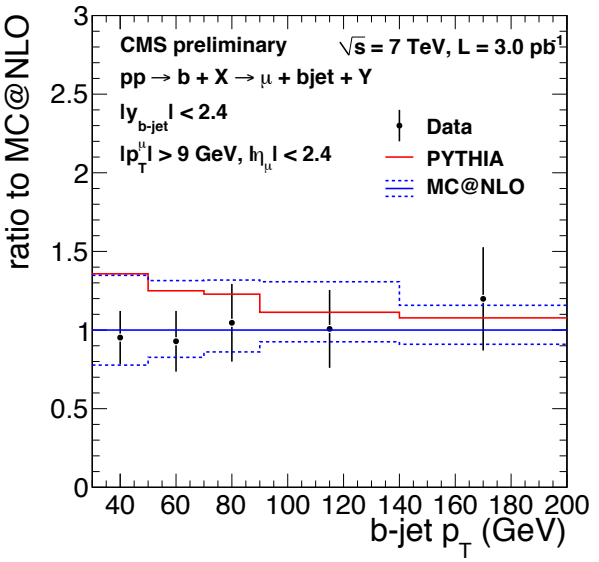
- Experimental uncertainties (~20%) dominated by b-tagging efficiency and jet energy scale
- MC@NLO uncertainties dominated by scale variations (+40%,-25%) and b-quark mass (+17%,-14%)

- Generally good agreement with Pythia above 40 GeV
- Shape differences with MC@NLO at large p_T and forward region

B jets with muons







Independent method with muon trigger and SV tagged jets
B fraction=(86±5)%, from muon p_T^{rel} fit

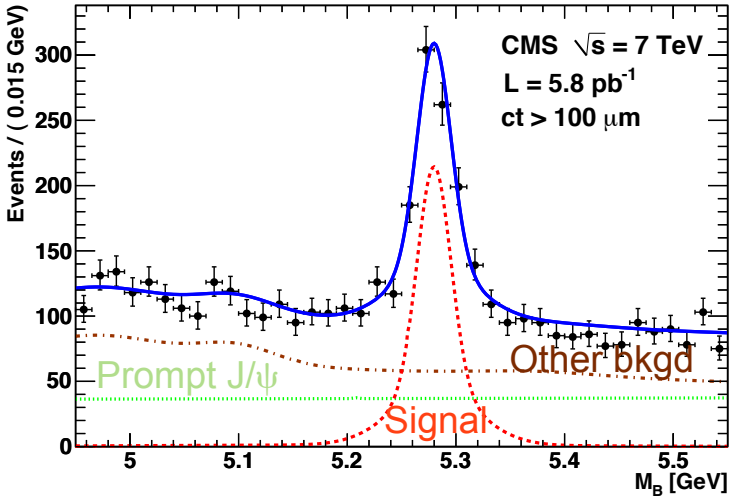
p_T^{jet}>30 GeV, $|y^{jet}|$<2.4 (muon extrapolated)

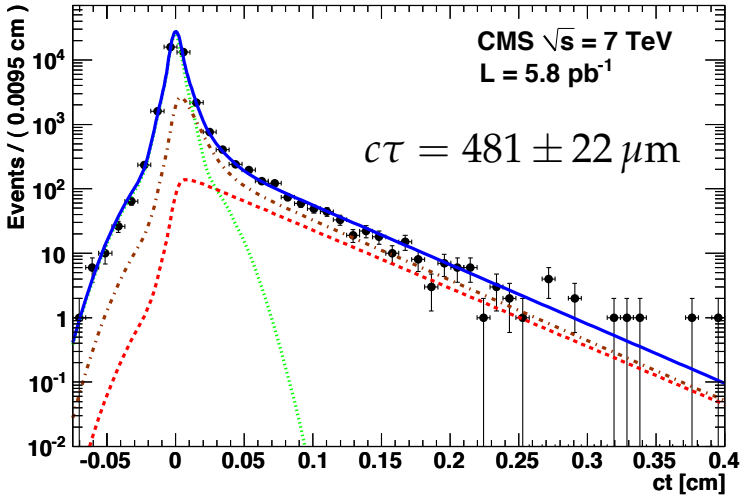
$$\sigma(\mathrm{pp} \to \mathrm{b} + X) = 2.14 \pm 0.01(\mathrm{stat}) \pm 0.41(\mathrm{syst}) \pm 0.09(\mathrm{lumi})\ \mu\mathrm{b},$$

$$\sigma_{\mathrm{MC@NLO}} = 1.83^{+0.64}_{-0.42}(\mathrm{scale}) \pm 0.05(m_{\mathrm{b}}) \pm 0.08(\mathrm{pdf})\ \mu\mathrm{b}$$

$B^+ \rightarrow J/\psi(\mu\mu)\ K^+$

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

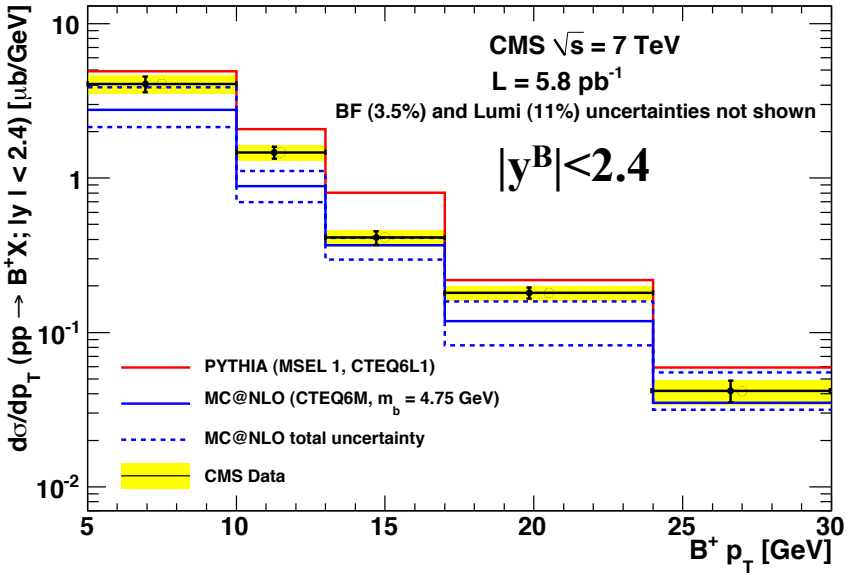


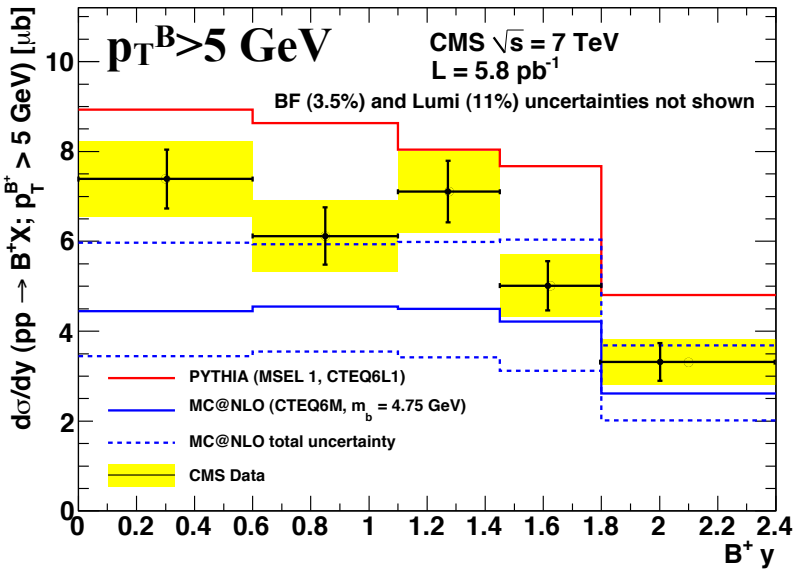


p_T^B>5 GeV
$|y^B|$<2.4

- **Event Selection:**
  - **Muons**: p_T>3.3 GeV for $|\eta| < 1.3$; p> 2.9 GeV for $1.3<|\eta|<2.2$, p_T> 0.8 GeV for $2.2<|\eta|<2.4$
  - 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 **900** signal candidates from mass and lifetime fit found in **5.8 pb-1**
  - **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**

$B^+ \rightarrow J/\psi(\mu\mu)\, K^+$





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

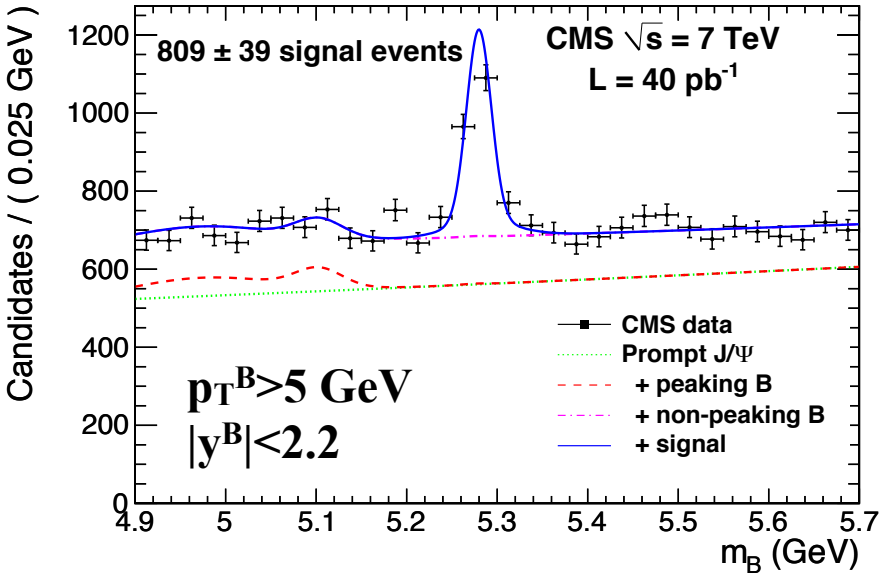
$28.1 \pm 2.4 \pm 2.0 \pm 3.1$ μb — **Measured visible cross section**

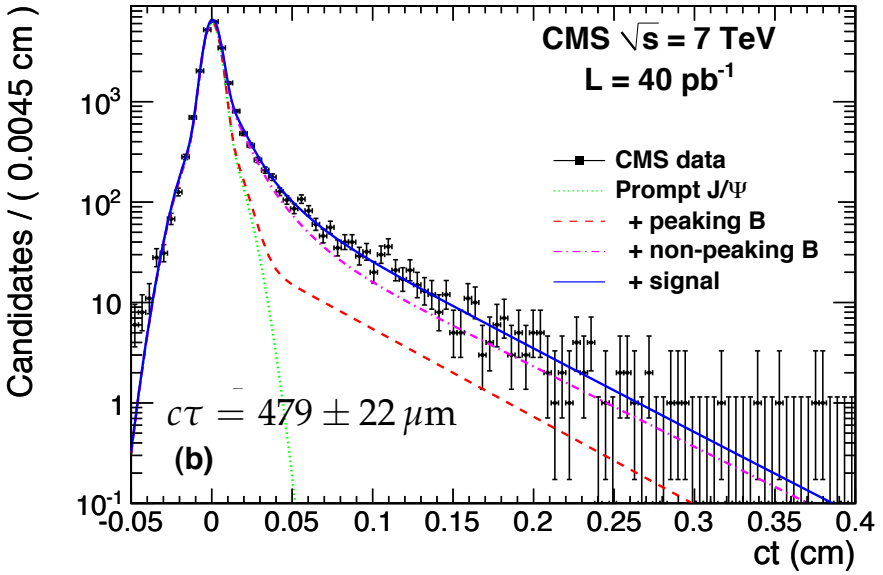
$19.1^{+6.5}_{-4.0}\,(\text{scale})^{+1.7}_{-1.4}\,(\text{mass}) \pm 0.6\,(\text{PDF})$ μb — **MC@NLO**

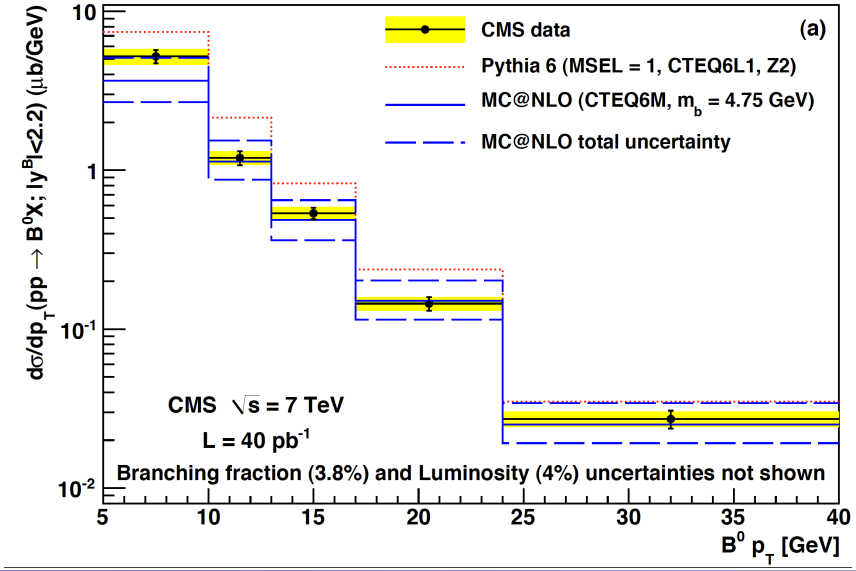
36.2 μb — **Pythia**

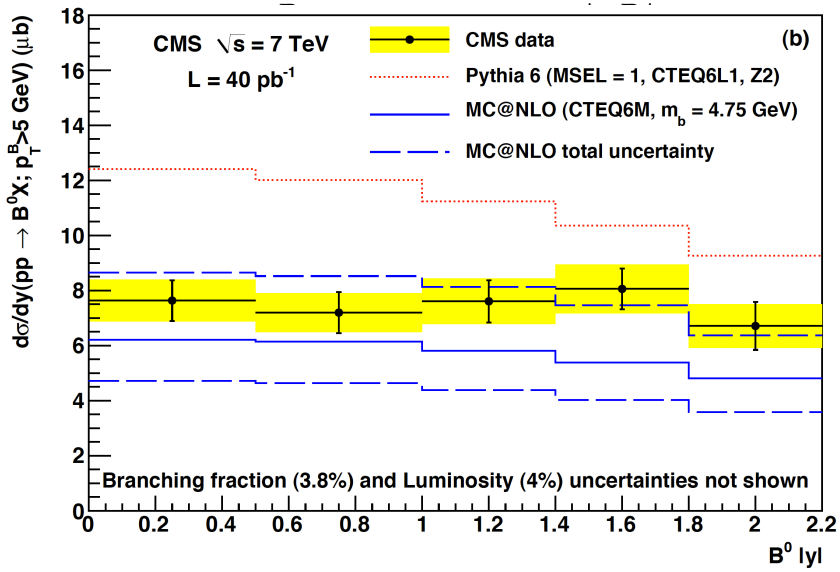
Experimental uncertainties (~7%) dominated by fit PDF shapes and tracking efficiency
BF (3.5%) and luminosity (11%) uncertainties not shown in figures

$B^0 \rightarrow J/\psi(\mu\mu)\, K_s(\pi\pi)$









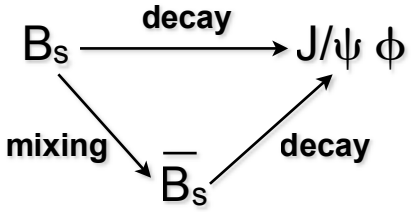
$B_s \rightarrow J/\psi(\mu\mu)\,\phi(KK)$

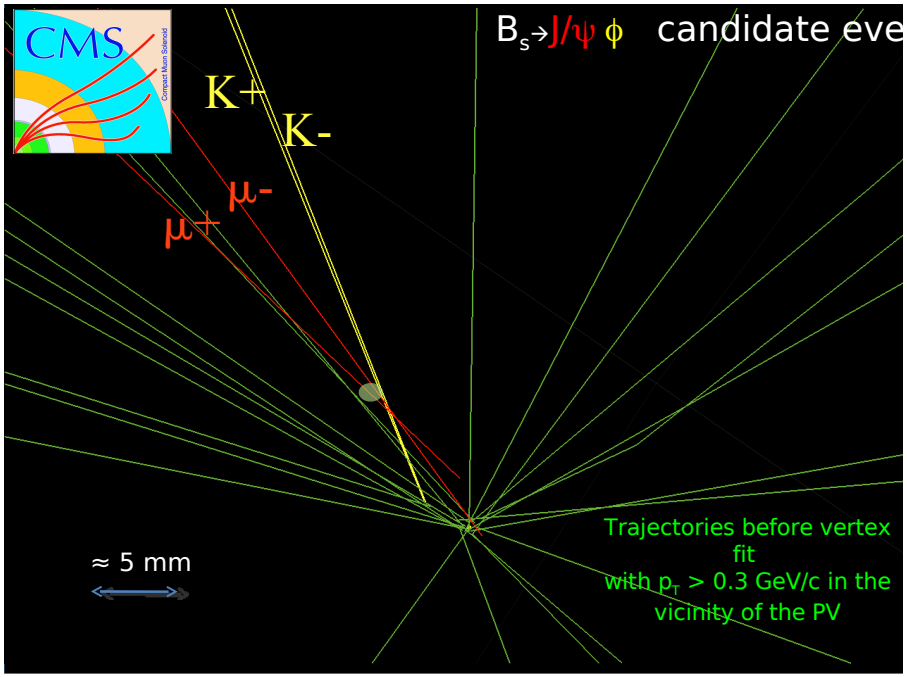
Small SM prediction, can be enhanced by BSM contributions

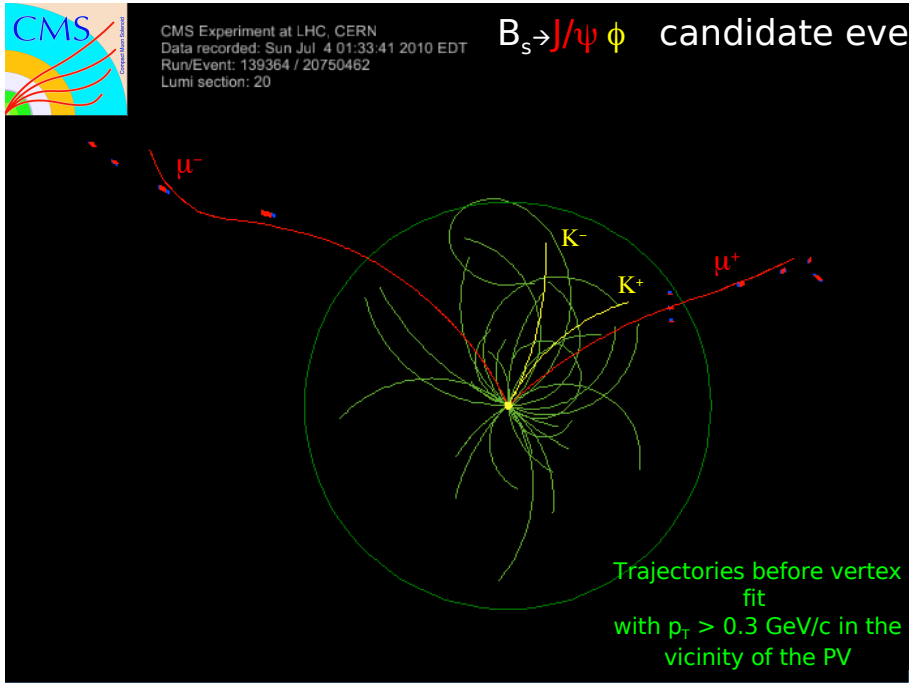
***CMS roadmap**: cross section → lifetime difference $\Delta\Gamma$ → CP violating phase ϕ_s*

$\beta_s = \arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*)$

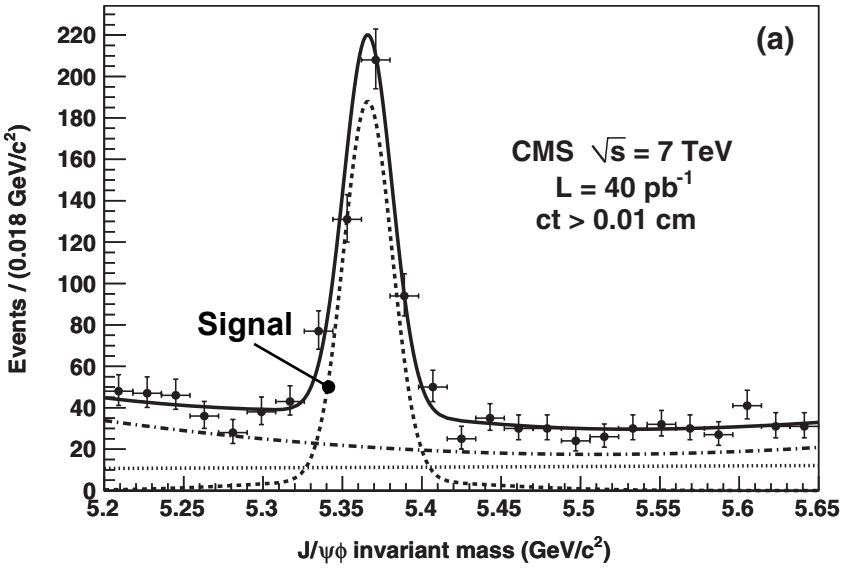
$\phi_{s[SM]} = -2\beta_s = (-36 \pm 2)$ mrad

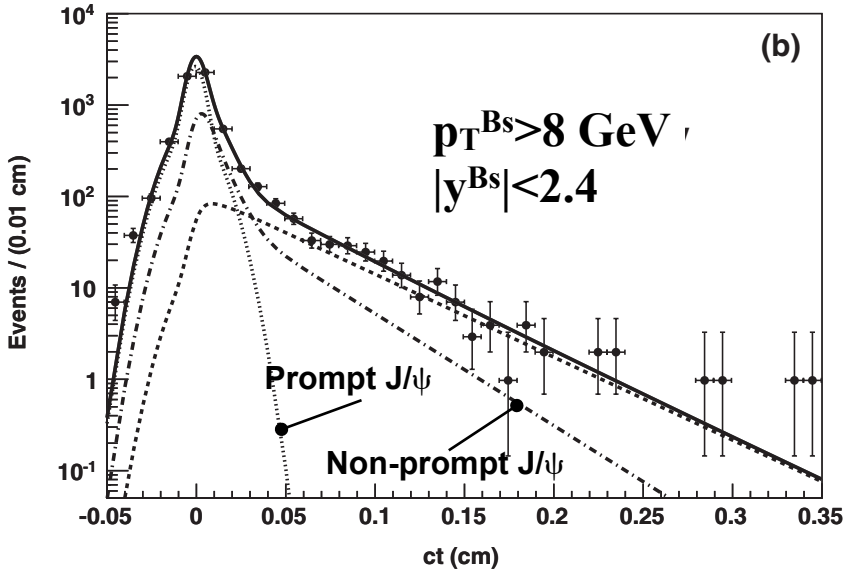






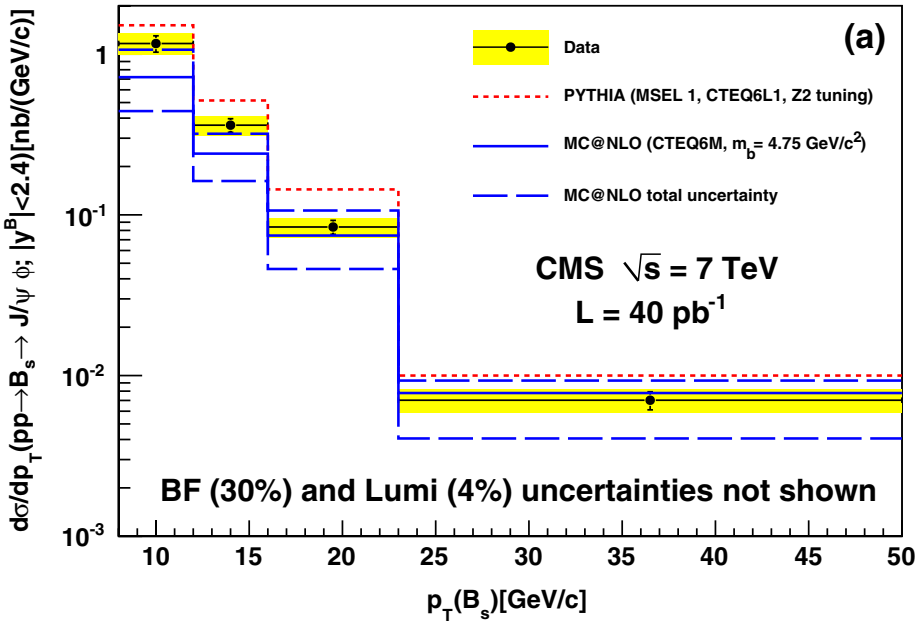
$B_s \rightarrow J/\psi(\mu\mu)\,\phi(KK)$

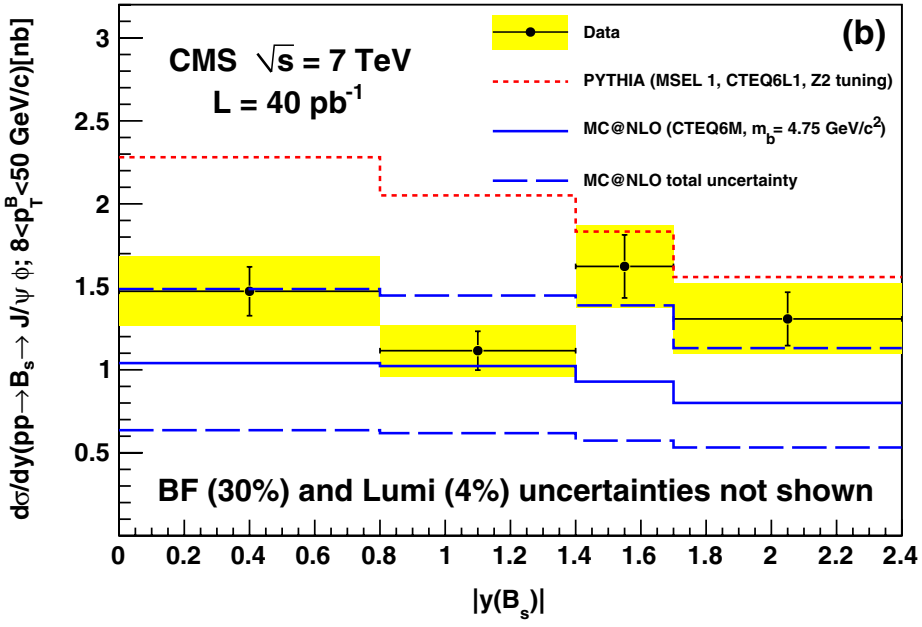




- **Event selection:**
  - **Muons:** Same J/ψ cuts as B^+ and B^0 analyses
  - **Kaons:** φ candidates from oppositely charged tracks with p_T>0.7 GeV, requiring 5 tracker hits and M(KK)=M(φ)±10 MeV
  - About **550** signal candidates in 40 pb^{-1} from combined mass and lifetime fit

$B_s \to J/\psi(\mu\mu)\,\phi(KK)$



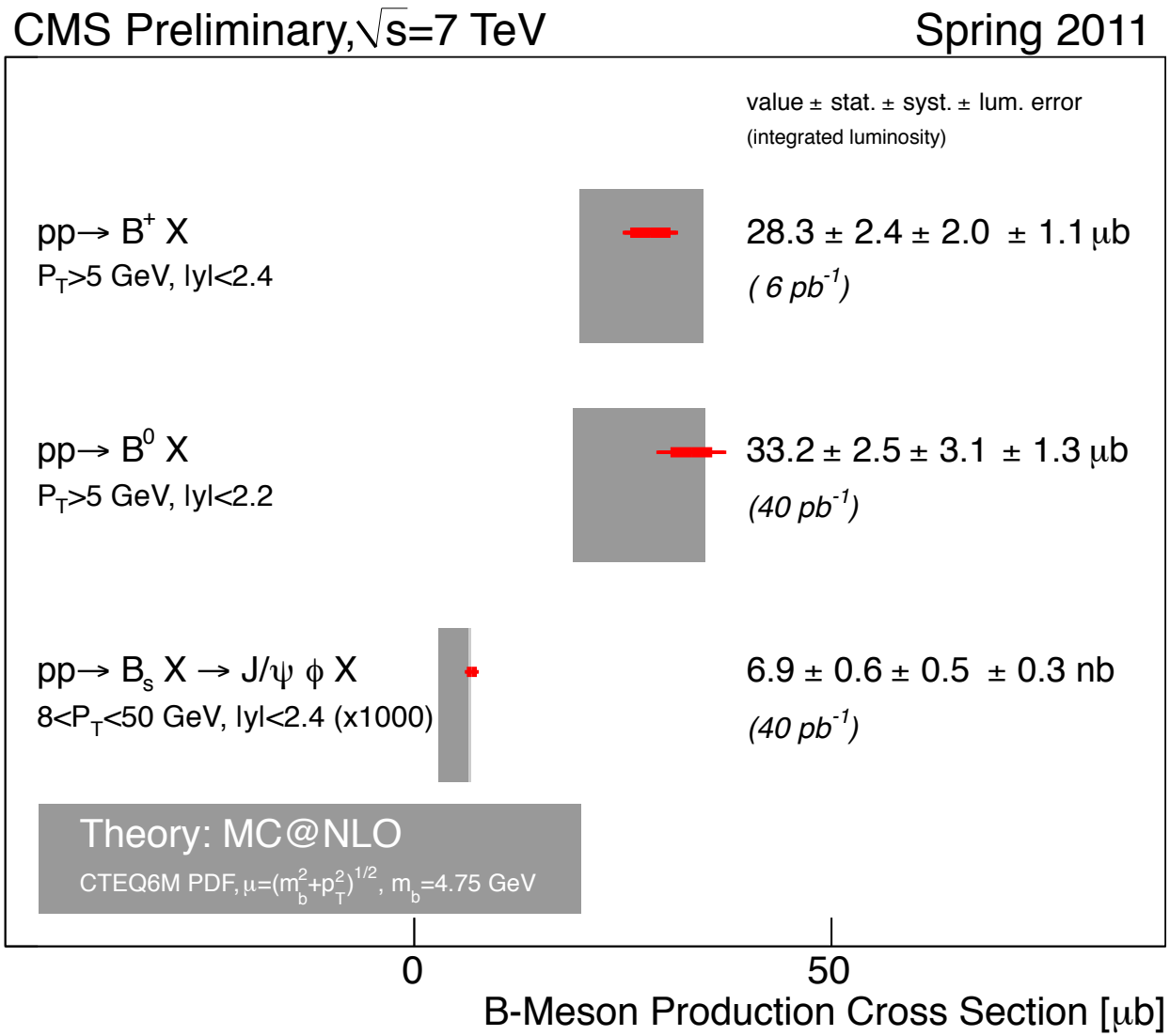


$pp \to B_s X \to J/\psi\phi X$, $p_T^B > 8$ GeV, $|y^B| < 2.4$

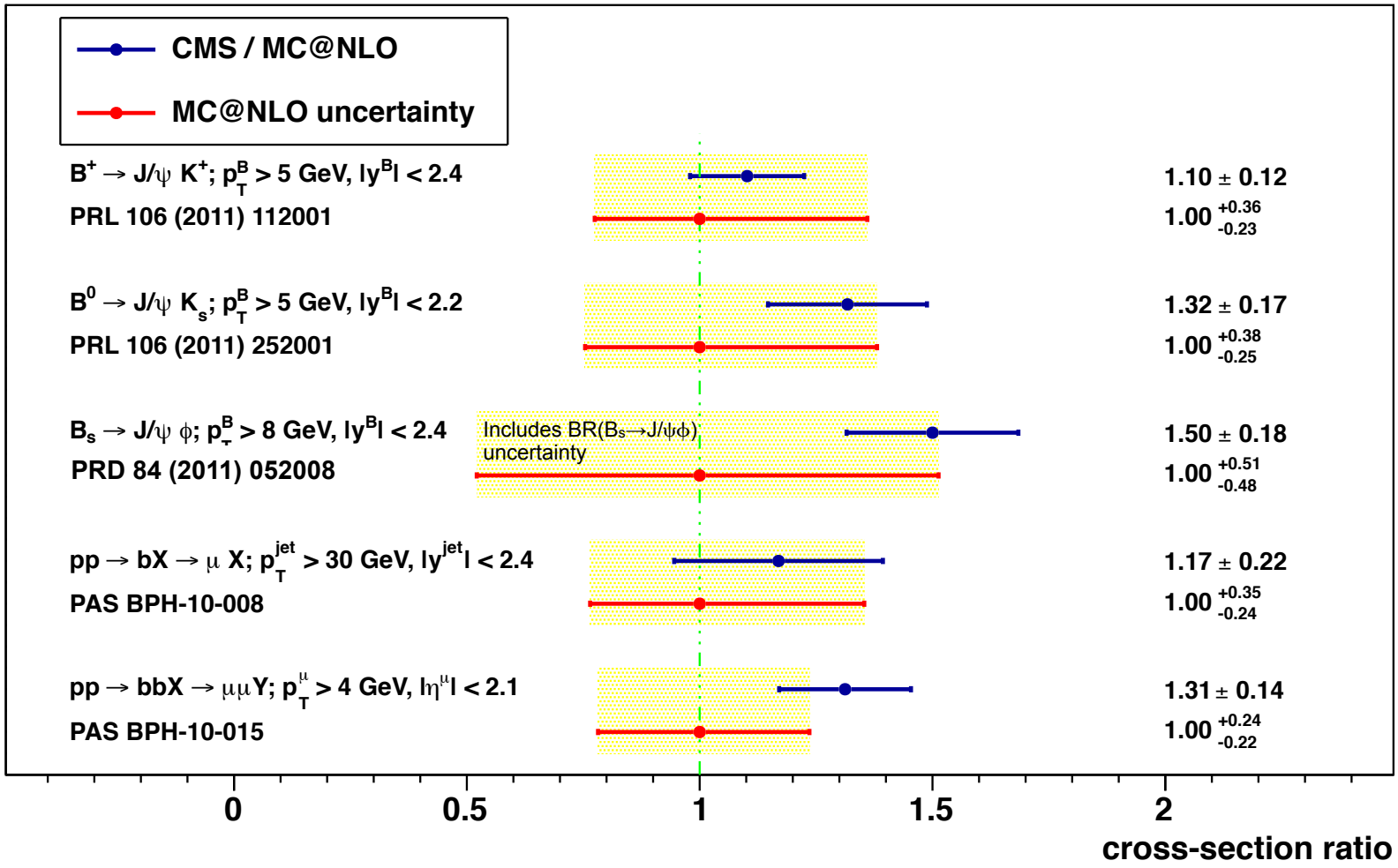
$6.9 \pm 0.6(\text{stat}) \pm 0.5(\text{syst}) \pm 0.3(\text{lumi})$ nb	**Measured visible cross section**
$4.57^{+1.93}_{-1.71}(\text{scale}) \pm 1.37(\text{B.F.})$ nb	**MC@NLO**
$9.39 \pm 2.82(\text{B.F.})$ nb	**Pythia**

Experimental uncertainties (~11%) dominated by tracking efficiency (9%) and luminosity (4%)

Summary of exclusive decays



CMS b cross sections

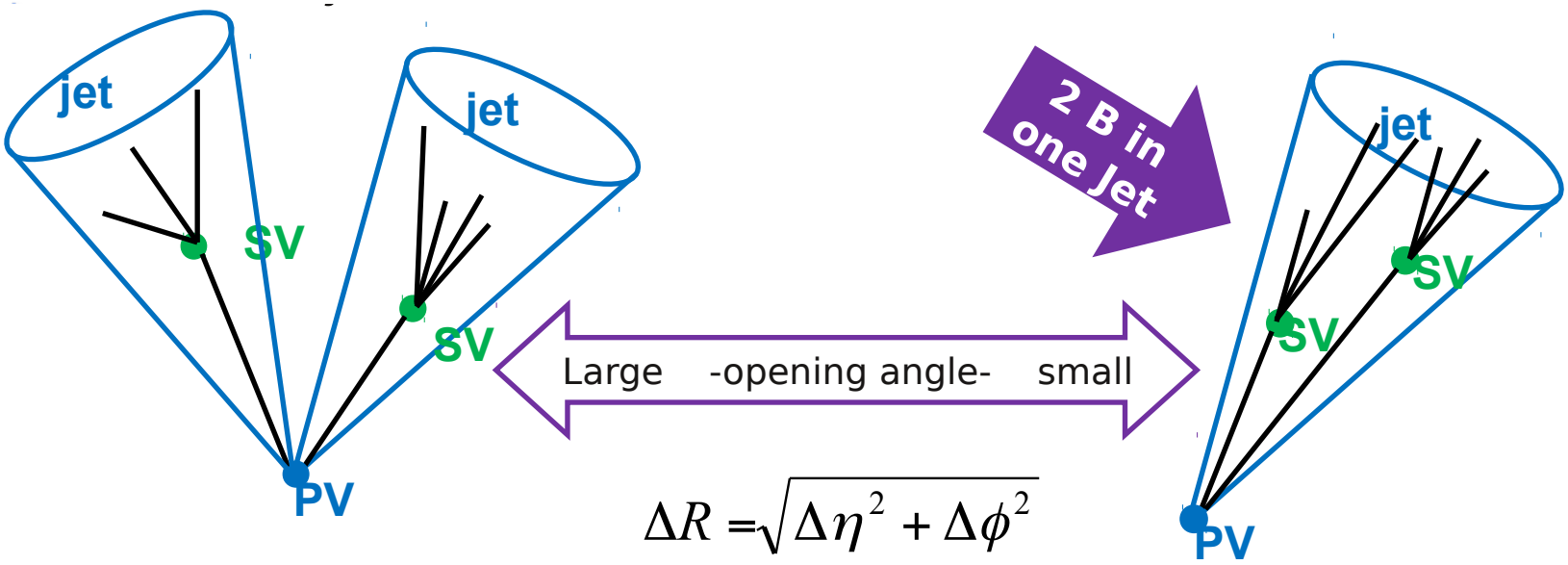


All measurements above NLO

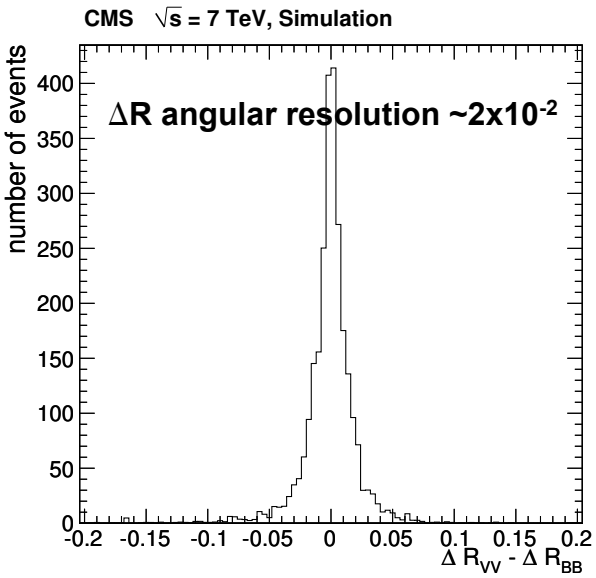
but in agreement within uncertainties

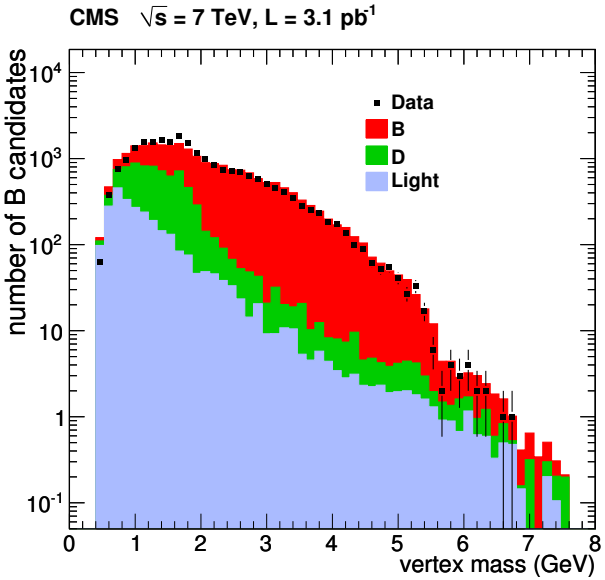
B-hadron angular correlations

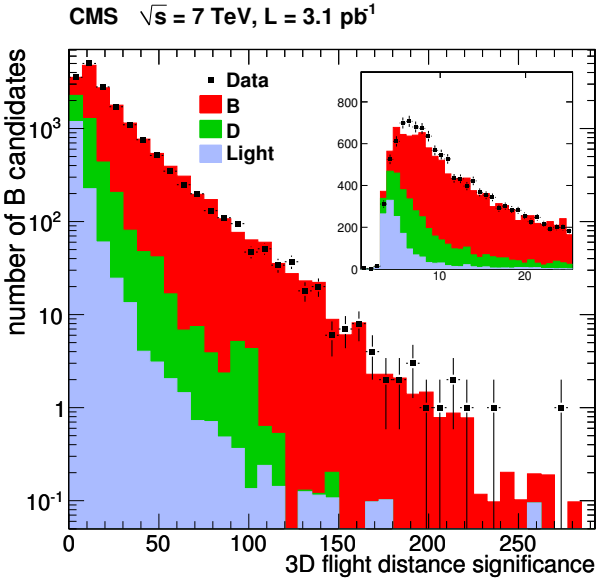
- **Questions**:
  - What fraction of the b-quark cross section is given by collinear b pair production?
  - How does this fraction evolve with the hardness of the scattering process?
- **Experimental problem:**
  - Measurements based on tagged jets have finite resolution due to jet clustering sizes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



B-hadron angular correlations

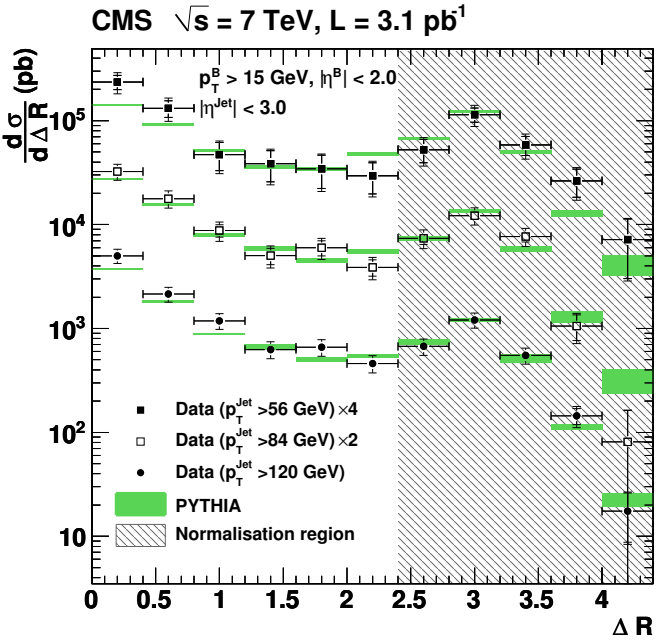


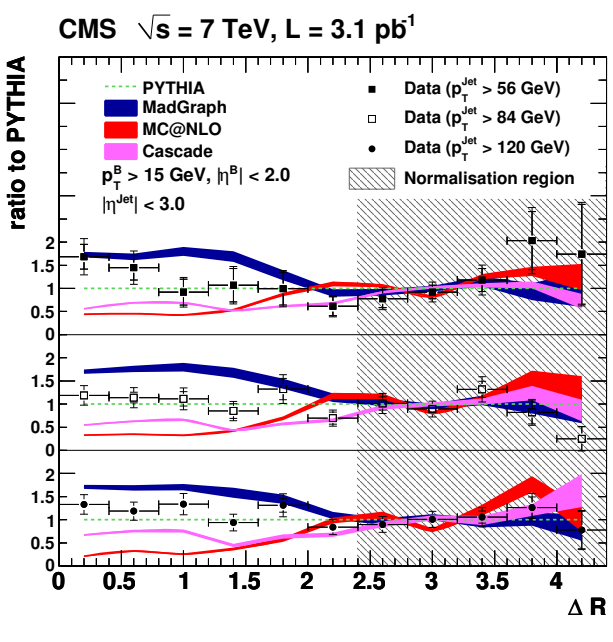


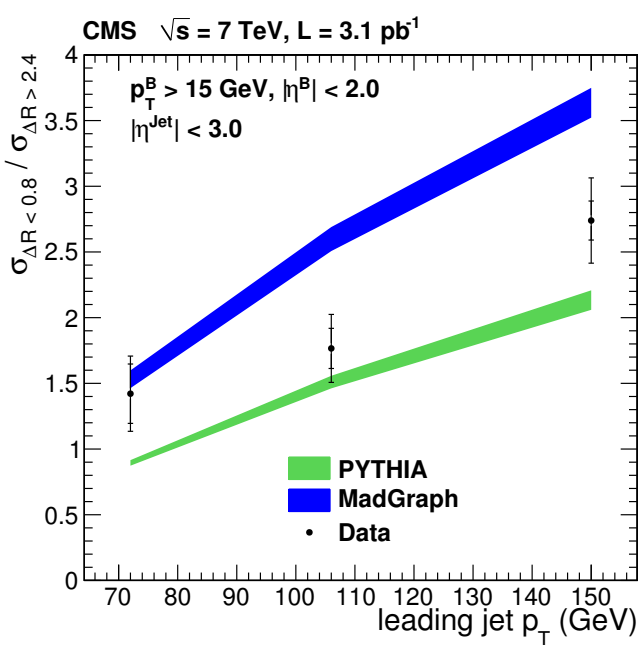


- Angular separation measured ten times more precisely than bin size allowed by available statistics
- Pythia MC describes very well vertex kinematic variables
  - Used for efficiency and purity correction
  - ΔR and $\Delta\phi$ dependence of secondary vertex finding efficiency cross checked with data-driven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

Angular correlations: results





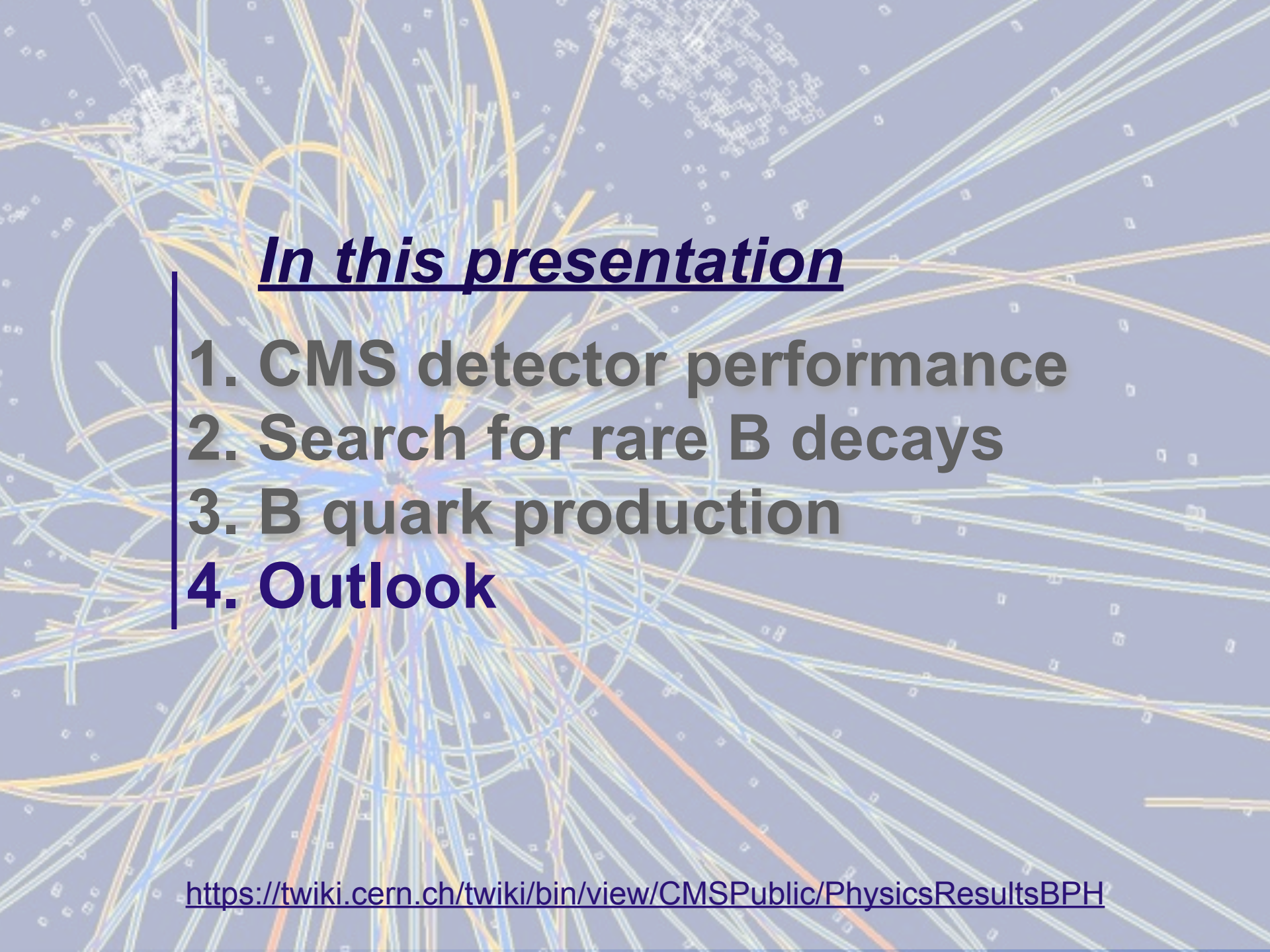


$p_T(B)>15$ GeV, $|\eta(B)|<2$, $|\eta(\text{lead.jet})|<3$

MC normalized to shaded 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 the data



In this presentation

1. CMS detector performance
2. Search for rare B decays
3. B quark production
4. **Outlook**

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

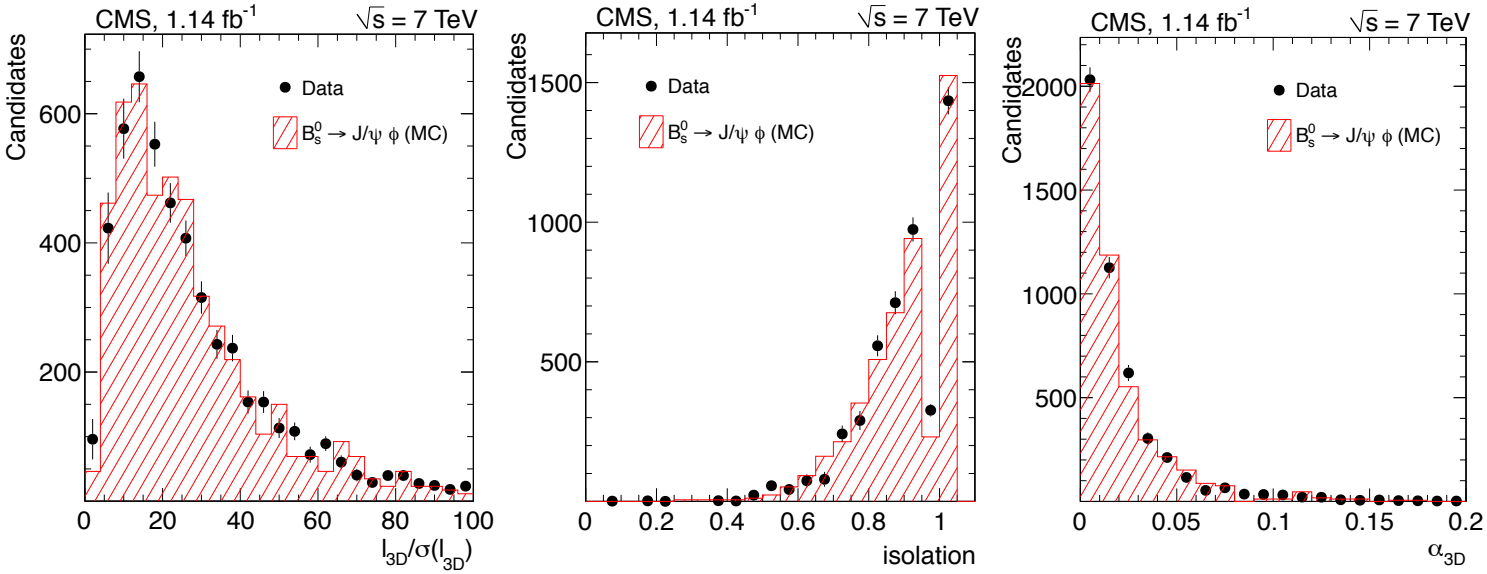
Outlook

- **Many published and preliminary results on heavy flavor physics from CMS**
  - Competitive (best) upper limit on B_s (B_d) branching ratio to dimuons
  - Several measurements of B quark production in inclusive and exclusive channels
  - Angular correlation measurements help disentangle underlying production processes
  - Not shown today: Quarkonium production, searches for exotic states
- **Large data samples from 2011/12 data taking will disclose new opportunities**
  - Rare decays (e.g. $B_{s,d} \to \mu\mu$, $B \to K^* \mu\mu$) and CP violation (e.g. $B_s \to J/\psi\phi$)
  - Quarkonium polarization measurements
  - Heavy baryon production and polarization (e.g. Λ_b, Σ_b)
  - Exotic states in the bottomonium sector
- **Challenges ahead:**
  - Trigger bandwidth optimization at high instantaneous luminosities

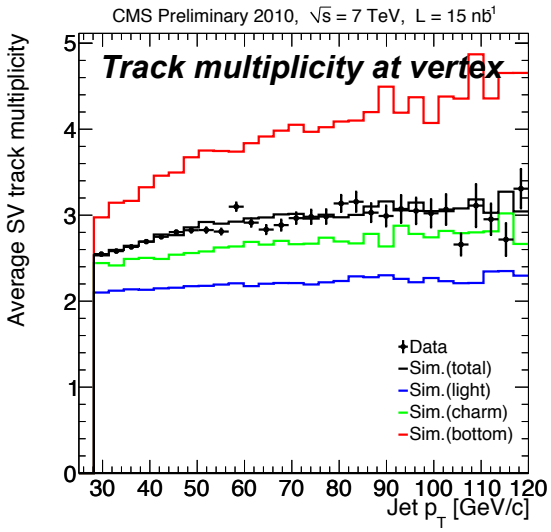
BACKUP

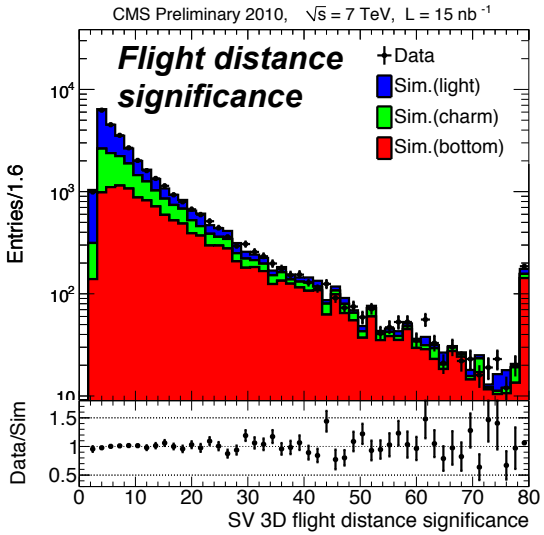
$B_s \to \mu\mu$: Selection efficiency

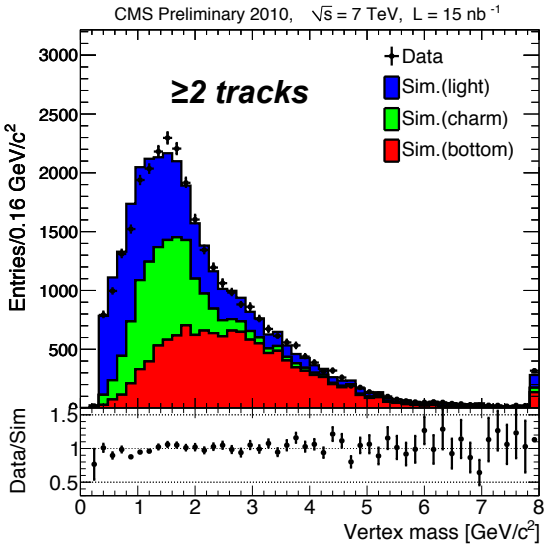
- Validation of MC simulation performed with **two exclusive decays**
  - $B_s \to J/\psi(\mu^+\mu^-)\phi(KK)$
  - $B^+ \to J/\psi(\mu\mu)K^+$
- Signal and normalization efficiencies from simulation
  - **Signal efficiency:** 0.4% (0.2%) in barrel (endcap)
  - **Normalization efficiency:** 0.08% (0.03%) in barrel (endcap)
- Good agreement with simulation after sideband subtraction
  - Residual differences adopted as systematics

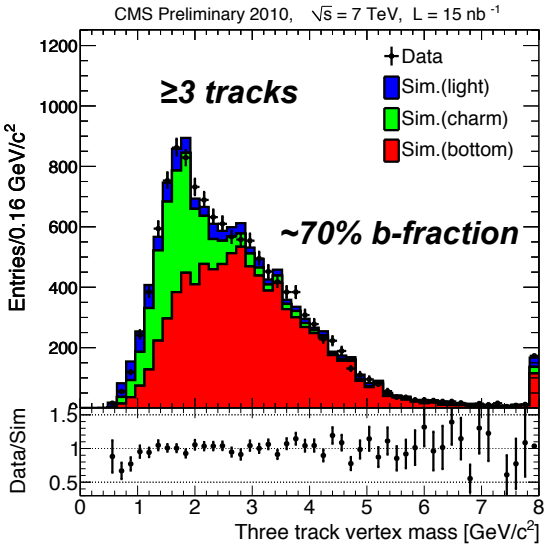


Secondary vertices





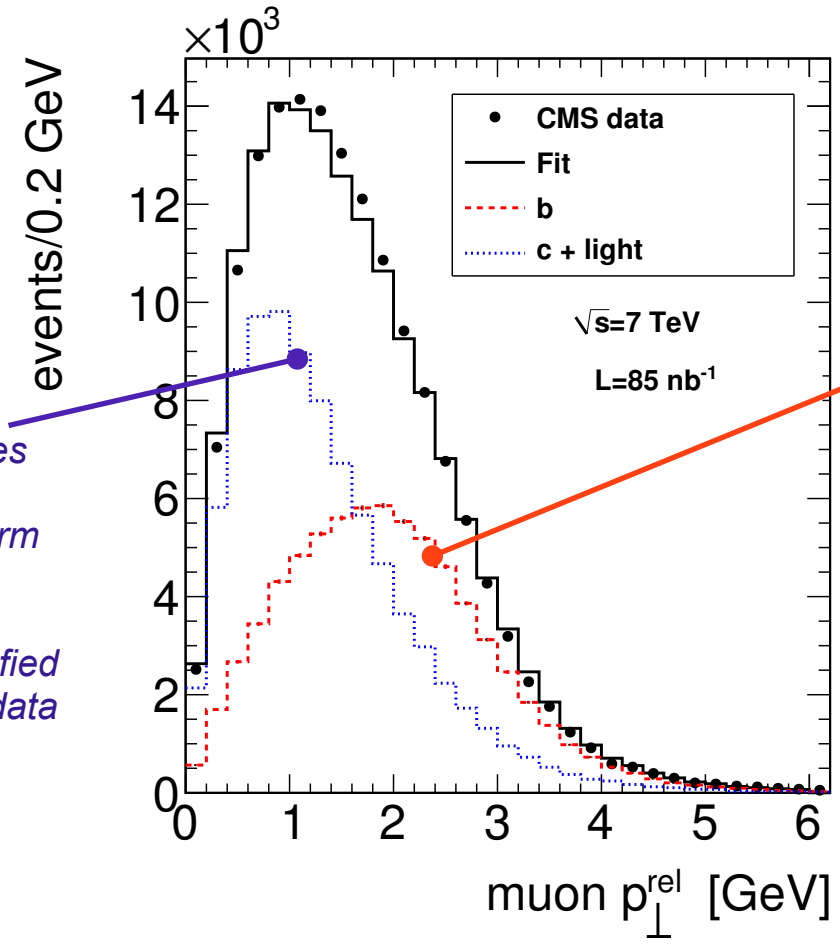




- Based on primary vertex finder tool applied to tracks in a jet
- Commissioning of secondary vertex reconstruction shows very good understanding of discrimination variables
  - **Track multiplicity**
  - **Flight distance significance**
- Invariant mass of tracks associated to the vertex is a useful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

CMS-PAS-BTV-10-001

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

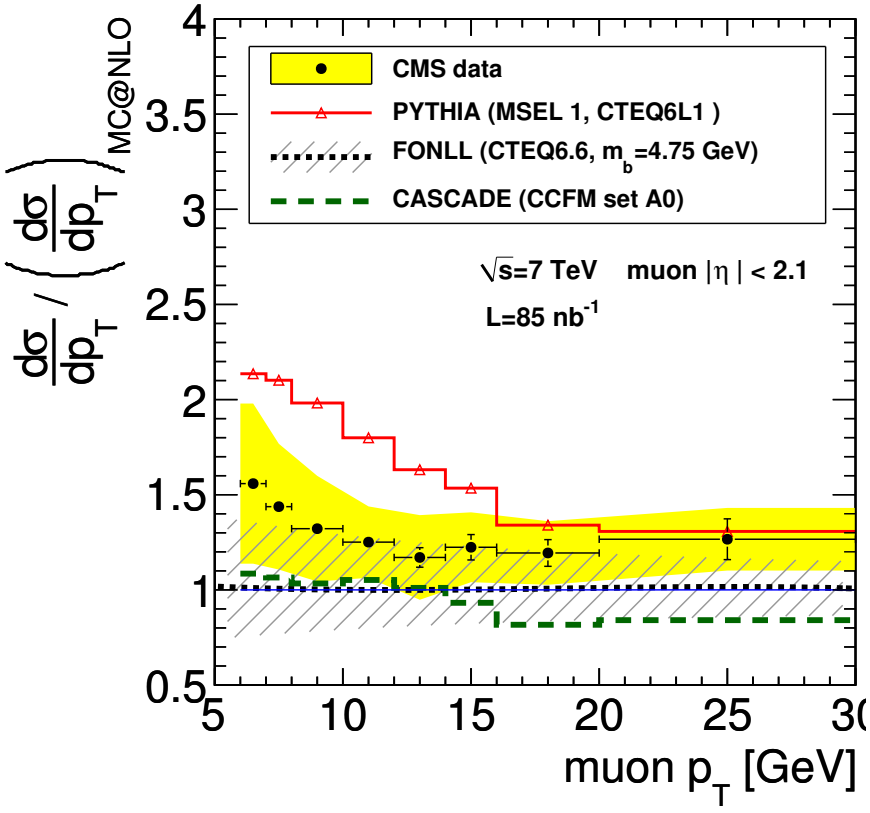
f_b from fit (46±1)%

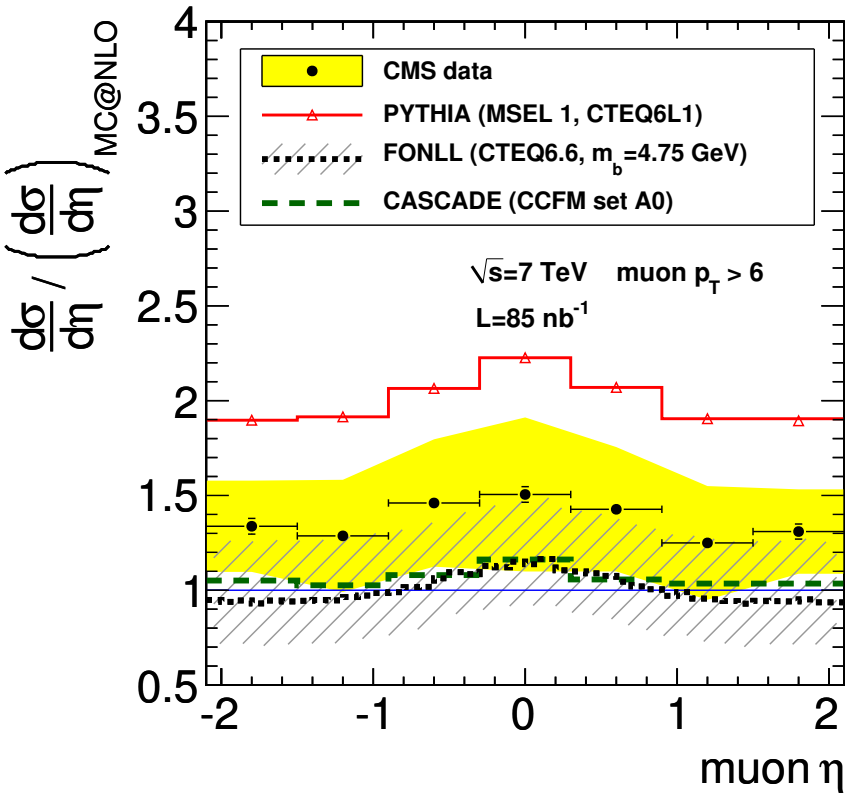
Efficiencies (ϵ):
Muon trigger ~82% (Data)
Muon reconstruction ~97% (MC)
Muon-jet association ~77% (MC)

Luminosity ($\mathcal{L}$): 85 nb^{-1}

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

Comparison with QCD



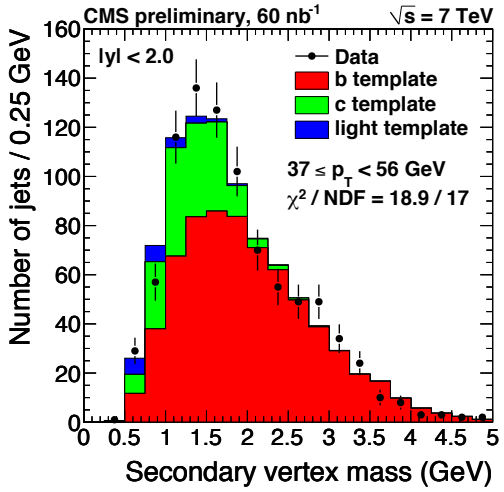


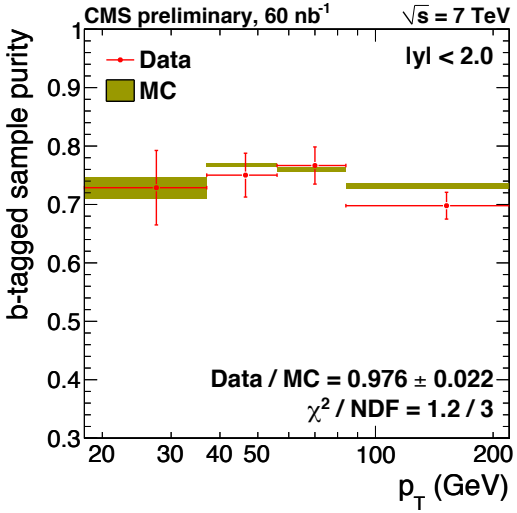
Muon cross section: systematics

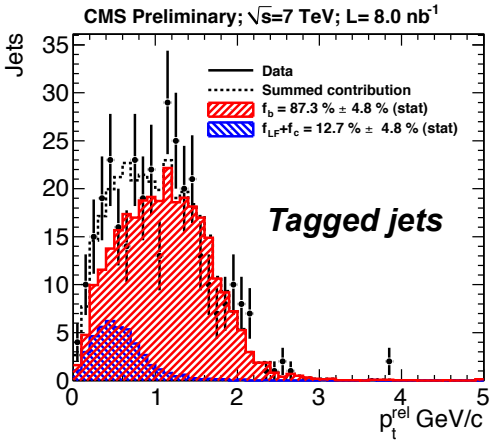
source	uncertainty
Trigger	3–5 %
Muon reconstruction	3 %
Tracking efficiency	2 %
Background template shape uncertainty	1–10 %
Background composition	3–6 %
Production mechanism	2–5 %
Fragmentation	1–4 %
Decay	3 %
MC statistics	1–4 %
Underlying Event	10 %
Luminosity	11 %
total	16–20 %

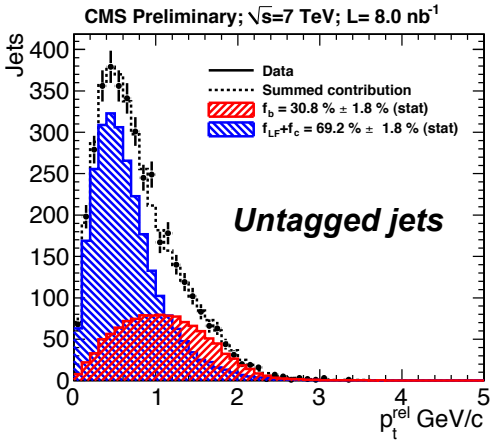
Cross section calculation

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

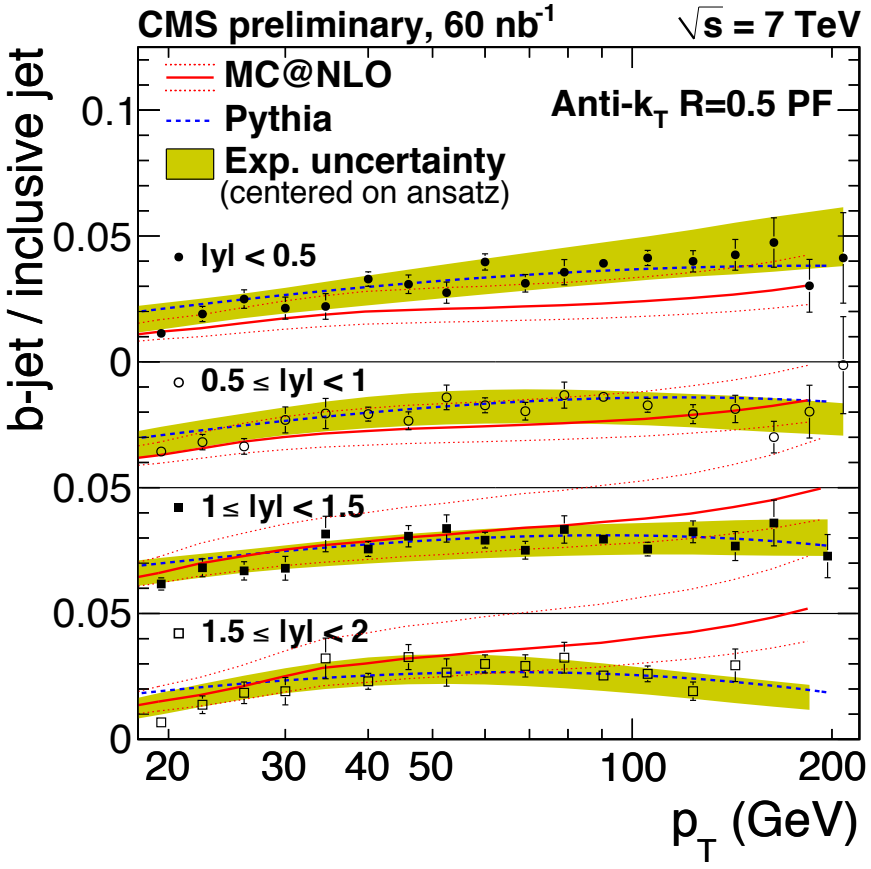
$\epsilon_{data}/\epsilon_{MC}$=0.98±0.08(stat)±0.18(syst)

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

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

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

Ratio to inclusive jets

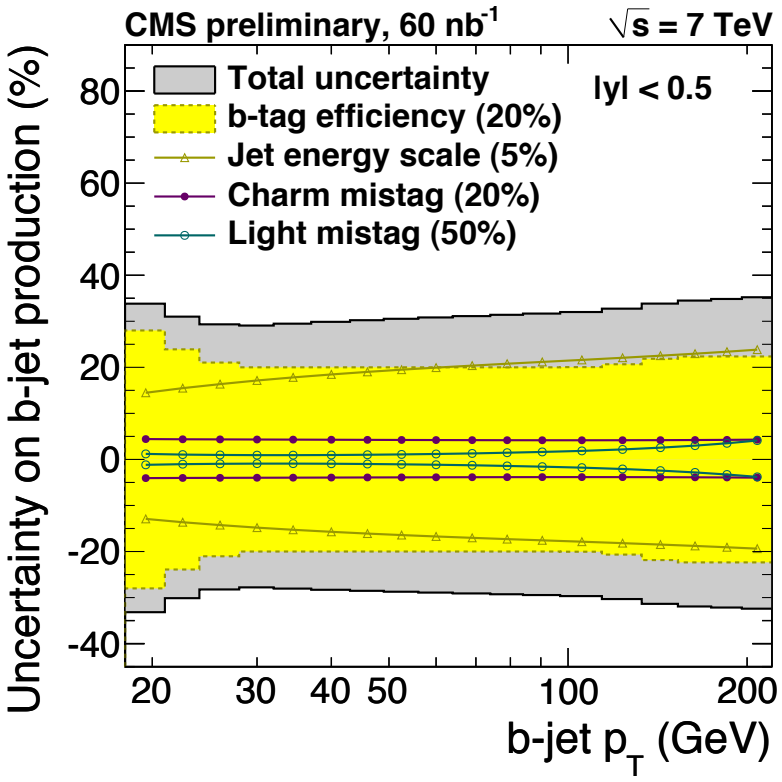


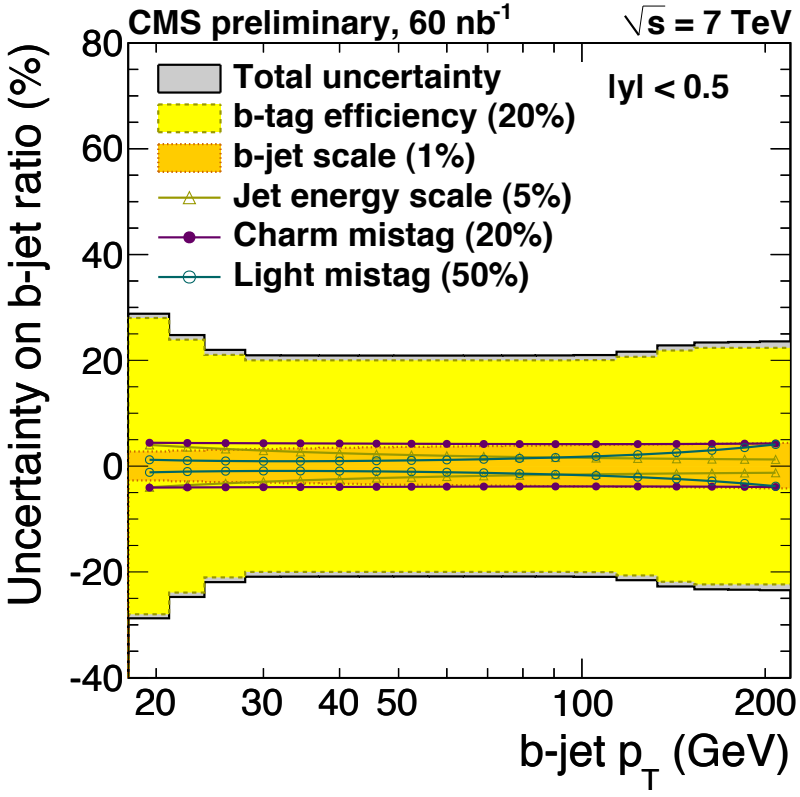
$$R = \frac{\text{B-jets cross section}}{\text{All jets cross section}} \sim 2\text{-}3\%$$

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

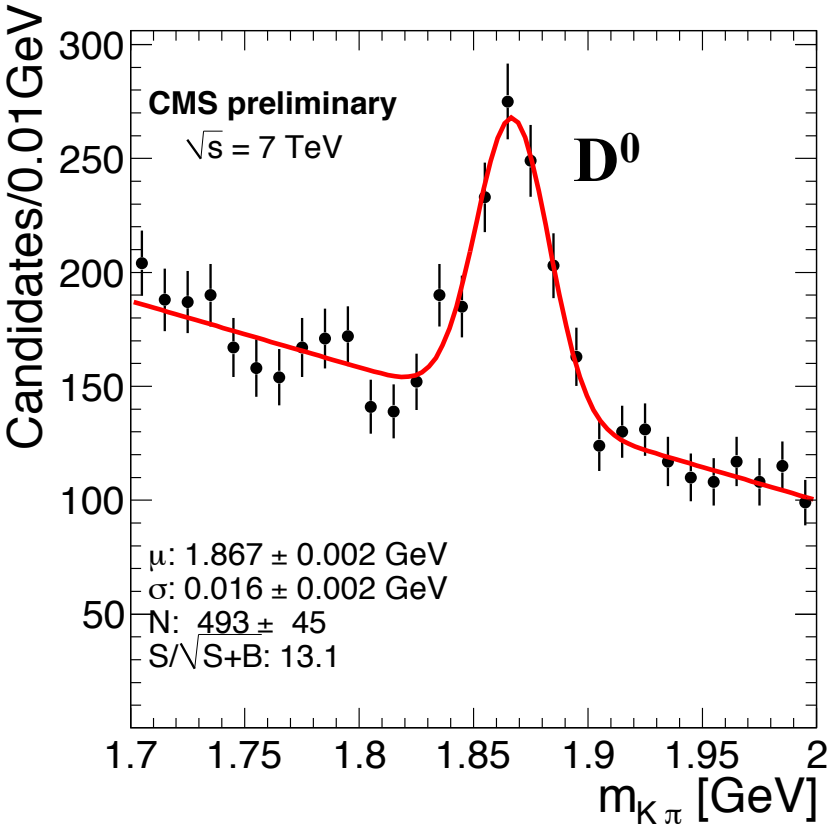
Inclusive jet measurement:
CMS PAS QCD-10-011

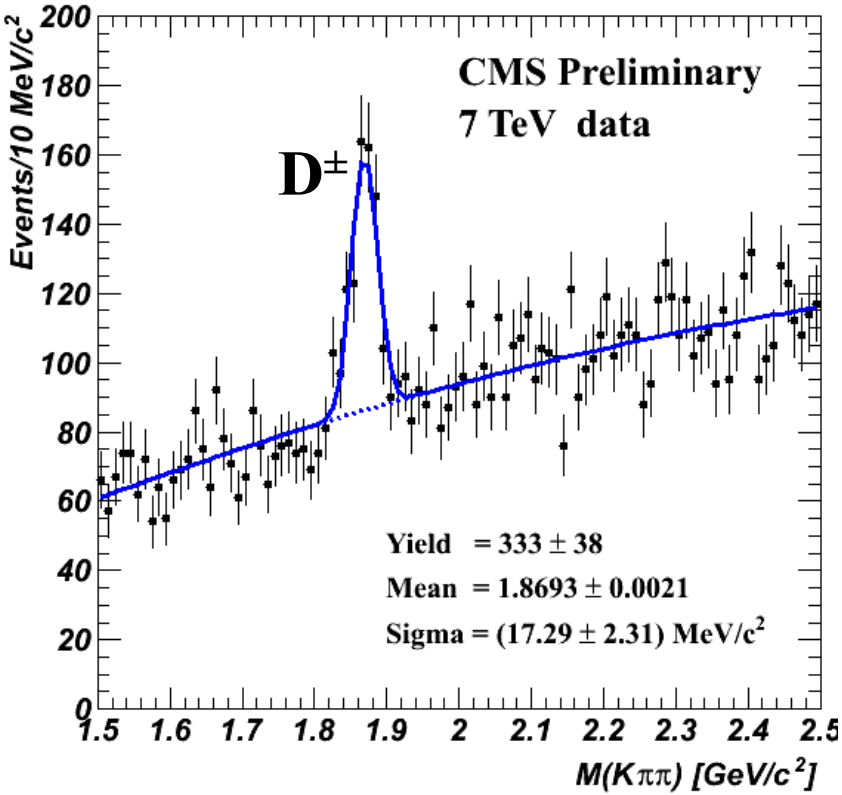
B jets: systematic uncertainties





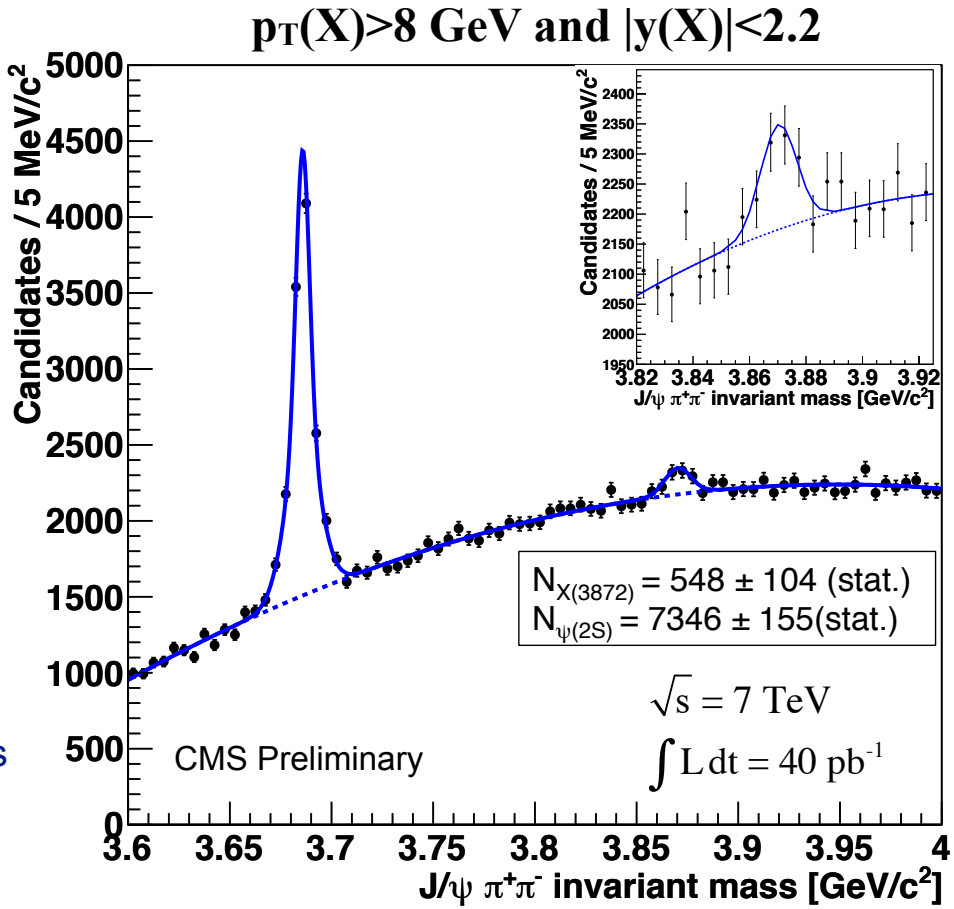
Charmed mesons





X(3872)→J/ψ π^- π^+

- State discovered by Belle in 2003 and later confirmed by BaBar, CDF and D0
- Quantum numbers not well established and production mechanism unknown
  - From CDF angular analysis: $J^{PC}=1^{++}$ or 2^{-+}.
  - J=2 disfavored by radiative decays
  - Molecular D-D state?
- State clearly observed in CMS data
  - We measured the yield ratio w.r.t. ψ(2S)
  - J/ψ candidates combined with two oppositely charged tracks with p_T>0.7 GeV
  - Next steps: differential cross section and determination of prompt/non-prompt fractions

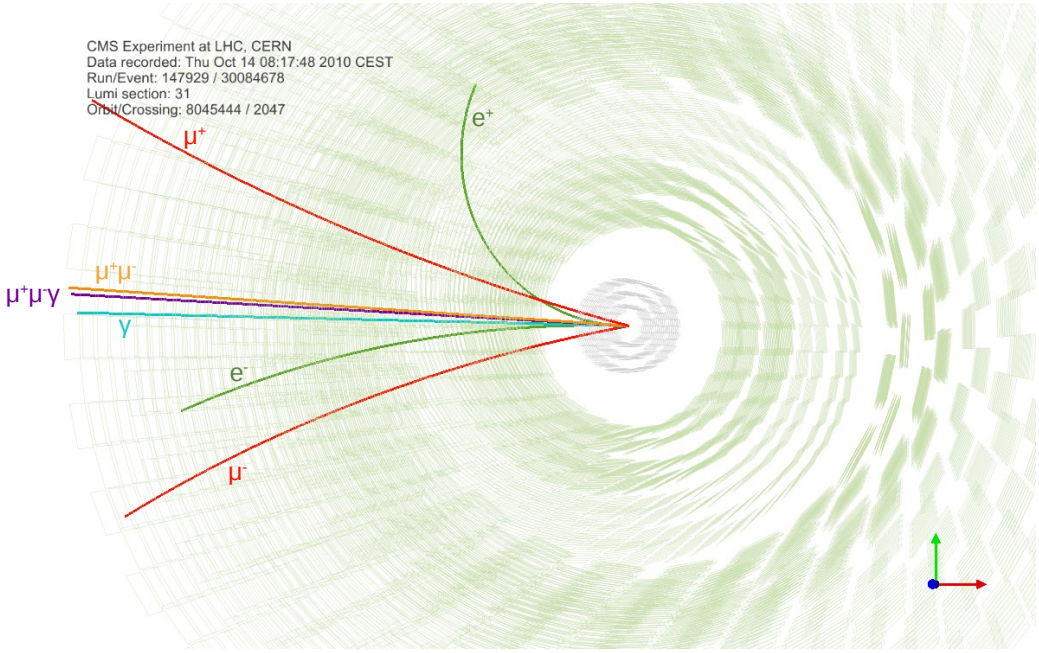


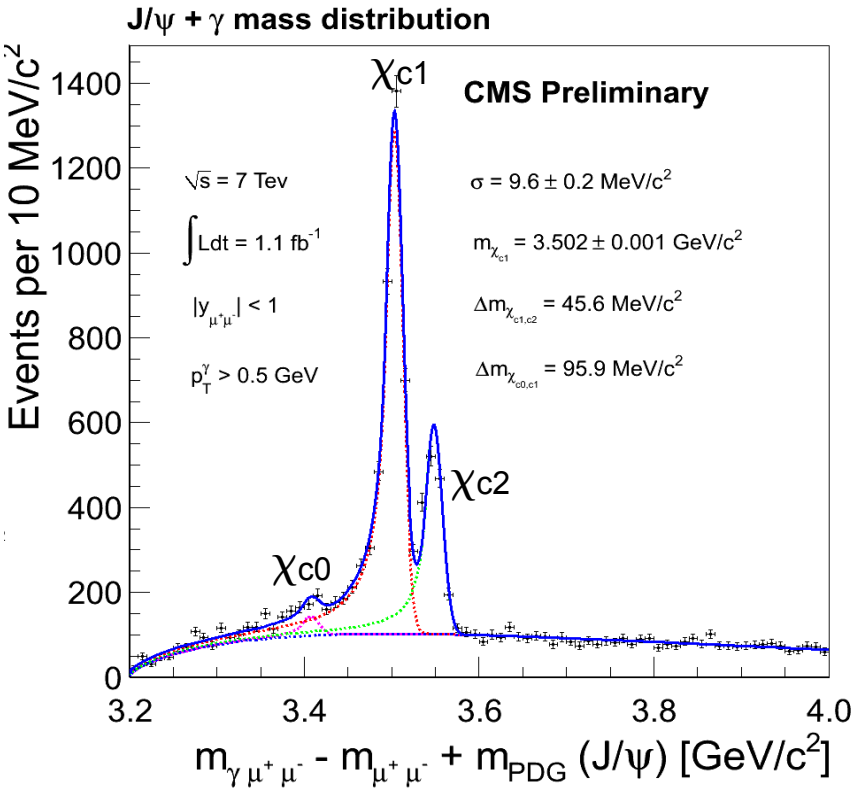
$$R = \frac{\sigma(pp \to X(3872) + \text{anything}) \times BR(X(3872) \to J/\psi\pi^+\pi^-)}{\sigma(pp \to \psi(2S) + \text{anything}) \times BR(\psi(2S) \to J/\psi\pi^+\pi^-)}$$

$$R = 0.087 \pm 0.017(stat.) \pm 0.009(syst.)$$

CMS-PAS-BPH-10-018

χ_c observation in radiative decays





- Observation of χ_c states in radiative decays to J/ψ γ
  - Low momentum photons reconstructed with conversion in the silicon tracker
  - Excellent mass resolution. Can resolve 45 MeV mass separation.
  - Next steps: χ_{c2}/χ_{c1} cross section ratio vs. p_T

CERN-CMS-DP-2011-011