Measurements of BB Angular Correlations based on Secondary Vertex Reconstruction at $\sqrt{s}$ = 7 TeV in CMS

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Representing the CMS collaboration

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What we measure :

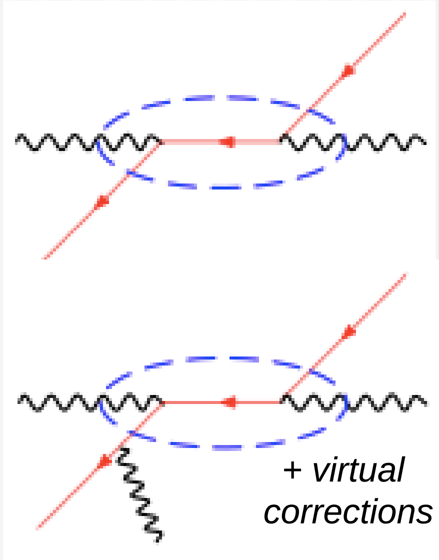
- **Goal :** study QCD dynamics in b-production via angular correlations between B and Bbar hadrons.

- **Measure** differential cross sections as function of opening angles between B and Bbar hadrons, down to very small angular separation, where higher order collinear emission processes are expected to substantially contribute.

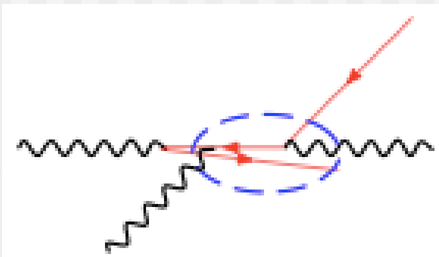
- **Method:**
  Determine B-hadron kinematics by reconstruction of secondary vertices, using an *inclusive secondary vertex* finder, independent of b-jet tagging

Production Processes in p-p Collisions

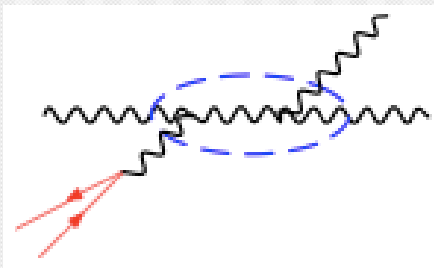
Flavour creation (FCR)



Flavour excitation (FEX)

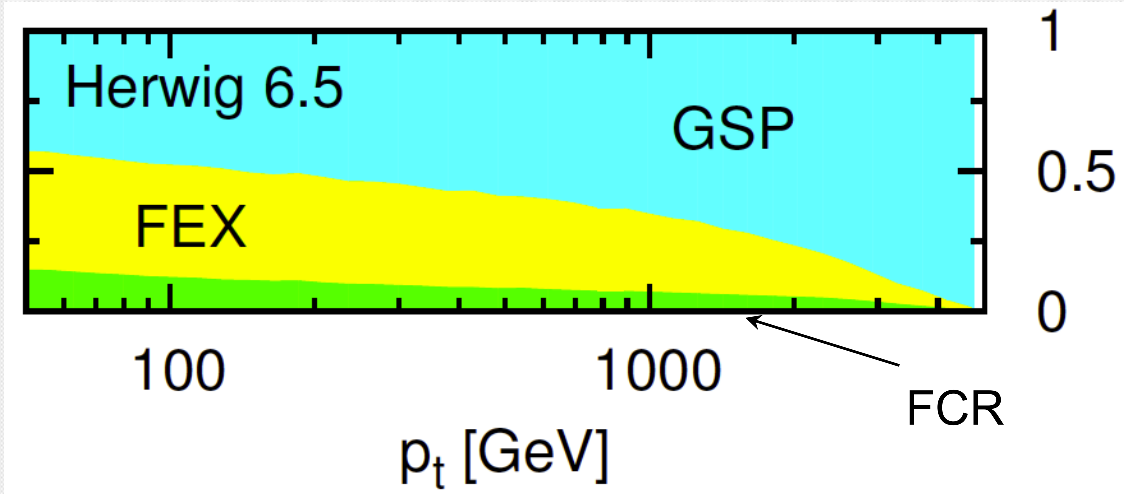


Gluon splitting (GSP)



- $2 \rightarrow 2$ processes:
  - <u>Flavour creation</u>: gluon fusion and qq annihilation
- $2 \rightarrow 3$ processes:
  - *<u>Flavour Excitation</u>*: bb from the proton sea, only one b participates in hard scatter,
  - *<u>Gluon splitting</u>*: g→ bb in initial or final state, b at low p_T and small opening angles
  - Real and virtual corrections to Flavour creation

arXiv:0705.1937 [hep-ph]

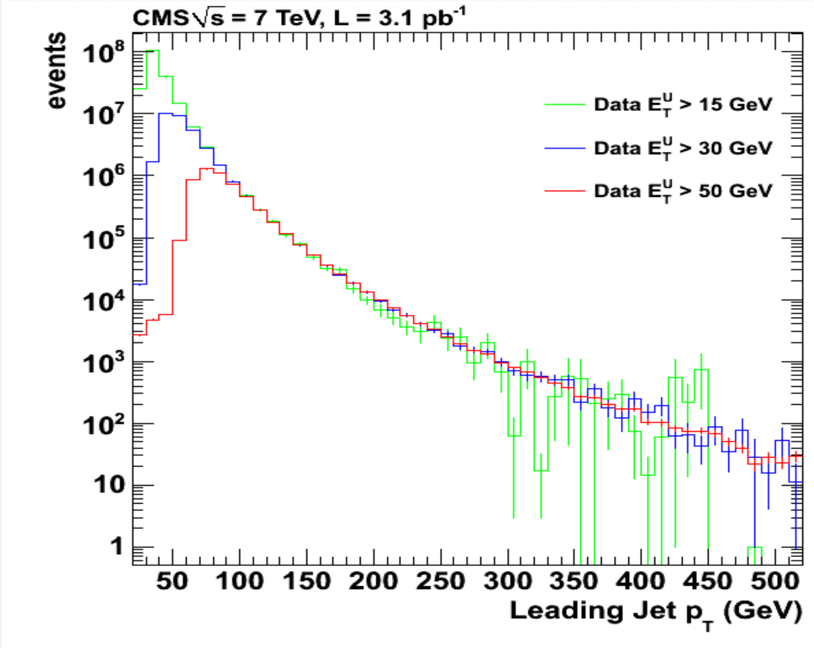


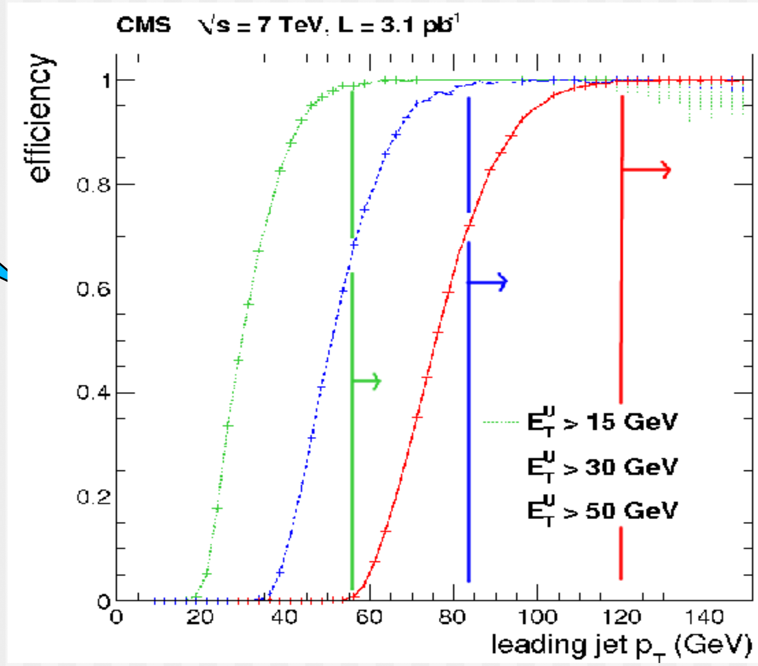
2 → 3 processes dominant at the LHC!
Expect gluon splitting to grow with E !

Trigger and Leading Jet Bins

- Chose single jet trigger for an unbiased trigger selections
- Use particle flow PF jets with anti-k_T jet algorithm (R=0.5)
- Define three bins in leading jet p_T such that the three single jet triggers are fully efficient (99%)
  - PF Jet p_T > 56 GeV
  - PF Jet p_T> 84 GeV
  - PF Jet p_T> 120 GeV
- They represent different event scales

➔ Correlations studied for each bin to see scale dependence

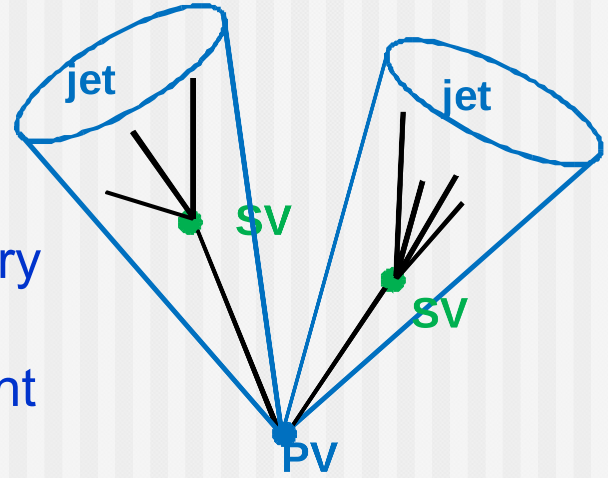




Angle and B-hadron Reconstruction

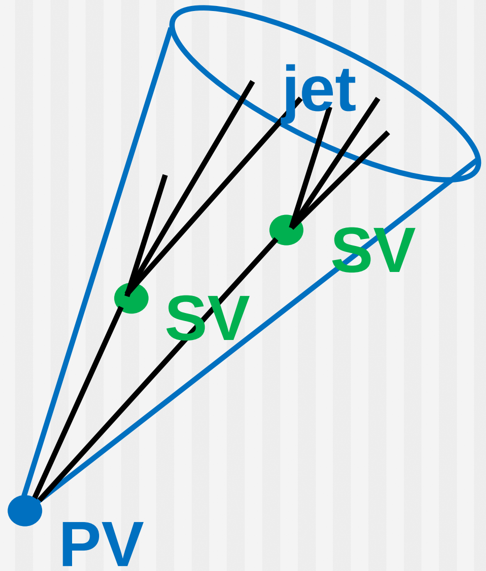
$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$

- Measure ΔR and Δϕ between two B-hadrons.
- Small angle region cannot be measured with jets.
- Flight direction of B is estimated by vector of Primary to Secondary Vertex PV-SV.
  B-candidates created for SV passing mass and flight distance significance cuts.



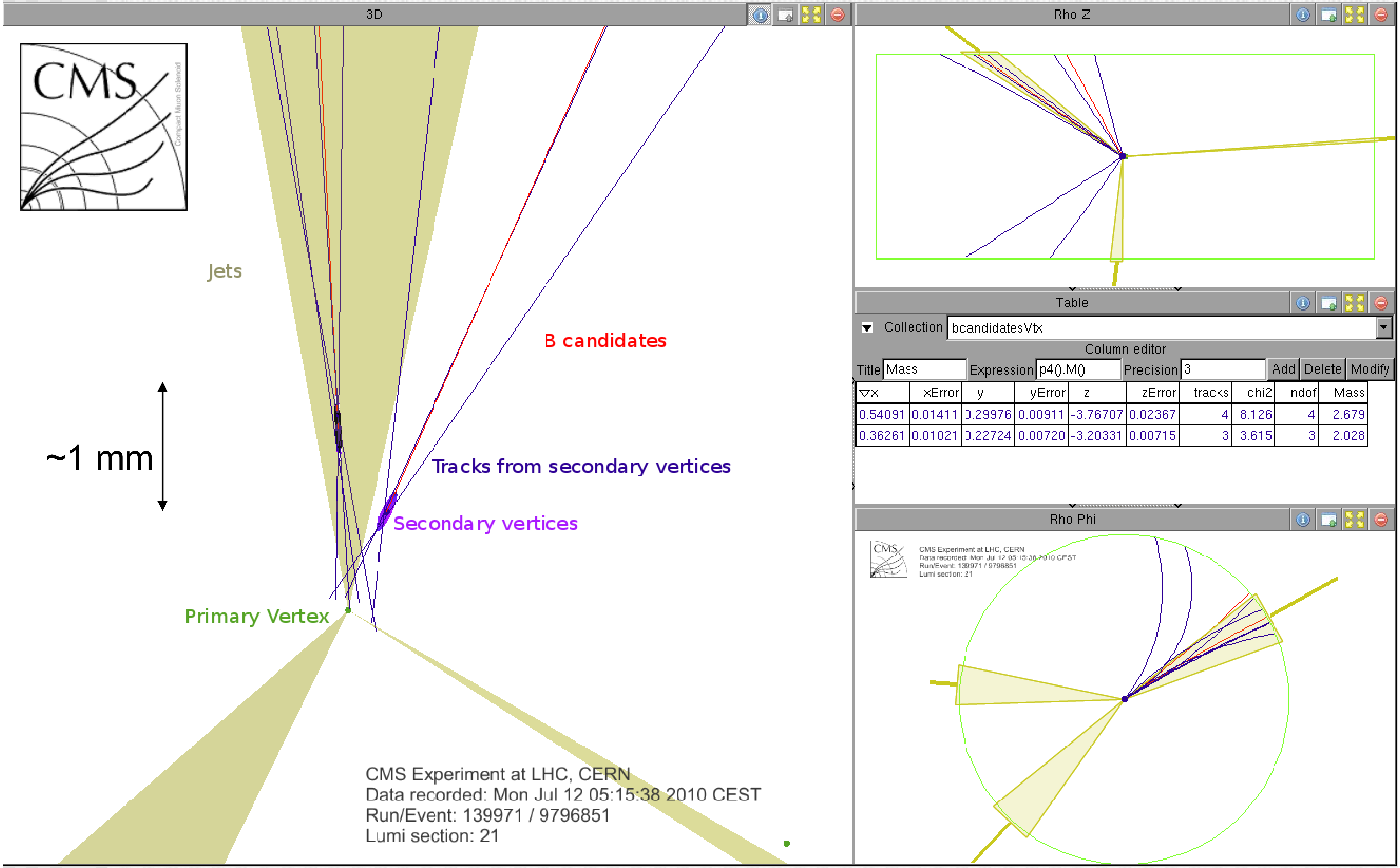
➔ **Advantage: Reconstruct SV also if 2 B in same jet.**
Method checked with jet based B-tag in large ΔR >1 region

→ **technique important for eg. H→ bb in a boosted regime !**



- **Use events with exactly two B-candidates to measure angular correlations (with sum of two B-candidate masses > 4.5 GeV)**
- Overall efficiency to reconstruct both B-hadrons is ~10 %
- Average B-Bbar purity is ~ 84%
  (incl. all BGNDs + migration)

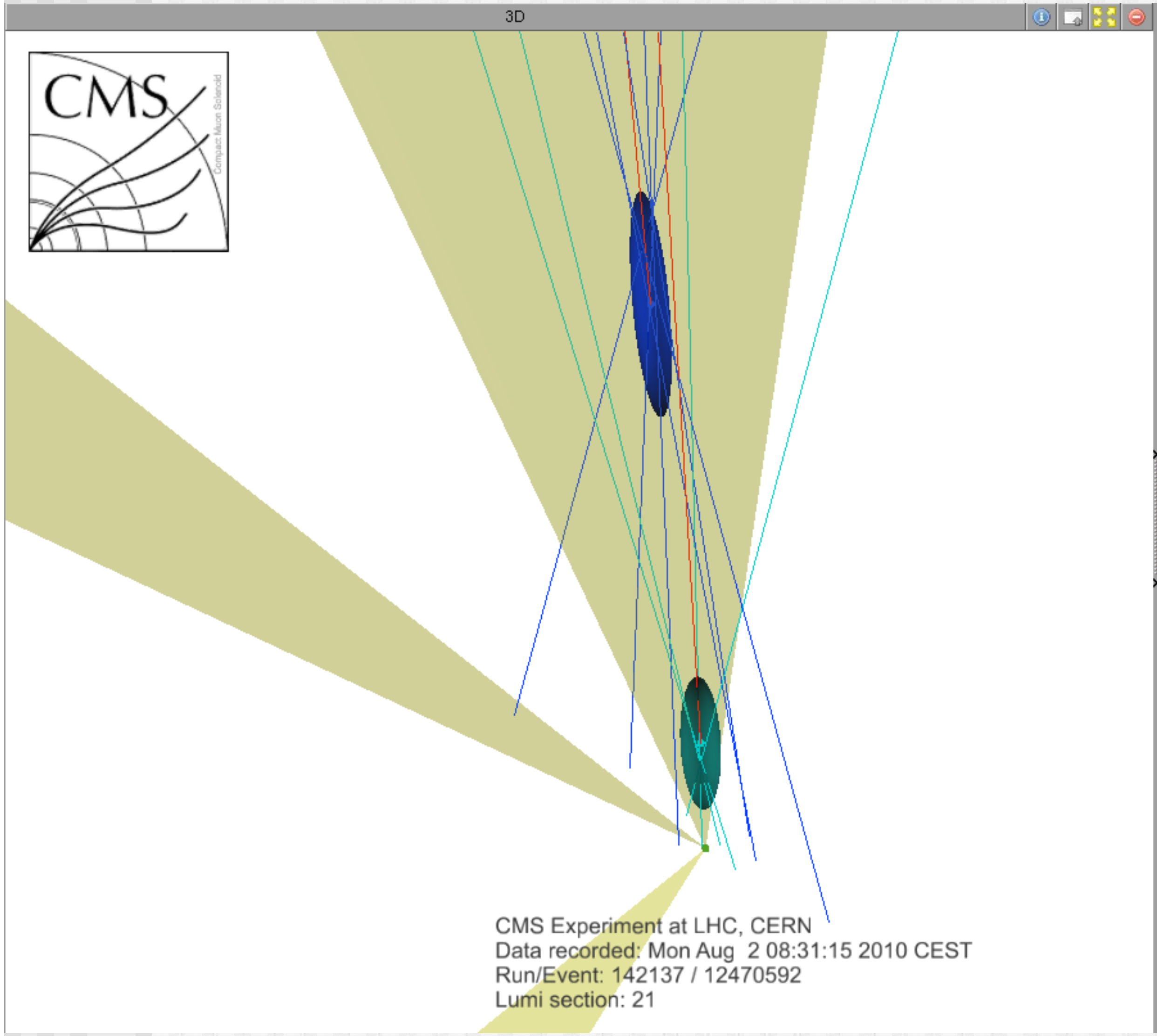
Example Event: small angle

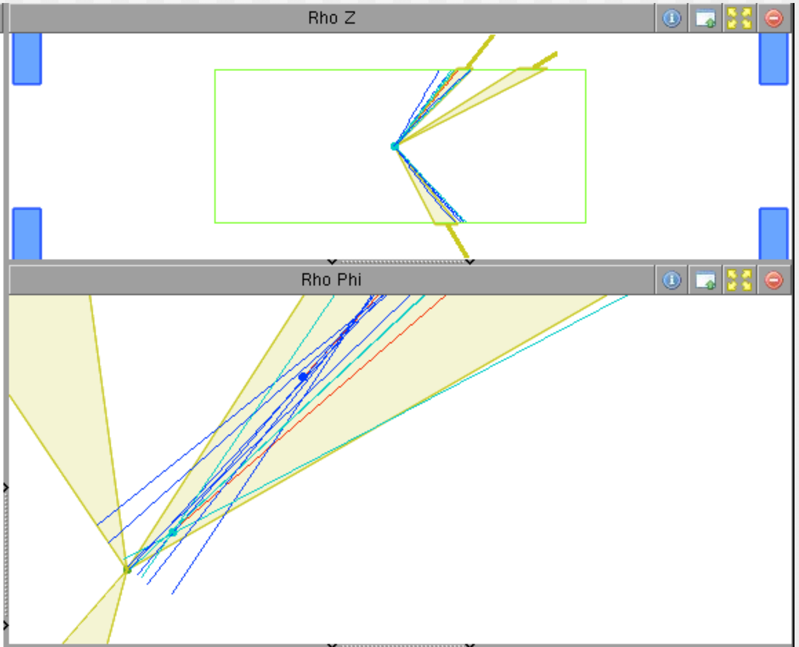


▽x	xError	y	yError	z	zError	tracks	chi2	ndof	Mass
0.54091	0.01411	0.29976	0.00911	-3.76707	0.02367	4	8.126	4	2.679
0.36261	0.01021	0.22724	0.00720	-3.20331	0.00715	3	3.615	3	2.028

Example Event : very small Angle

extremely small angle and both vertices have large masses





Table

Collection bcandidates

pt	phi	theta	eta	rapidity	y	vx	vy	vz	pdgId	sta
18.00968	0.71230	0.87865	0.75512	0.74514	0.74514	0.17103	0.07122	-8.93904	0	
24.61214	0.82441	0.89924	0.72859	0.72377	0.72377	0.39348	0.33639	-8.66985	0	

Table

Collection bcandidatesVtx

x	xError	y	yError	z	zError	tracks	chi2	ndof	Mass
0.17103	0.00794	0.07122	0.00679	-8.93904	0.00863	6	6.896	6	3.217
0.39348	0.01036	0.33639	0.01141	-8.66985	0.01210	7	5.528	9	3.080

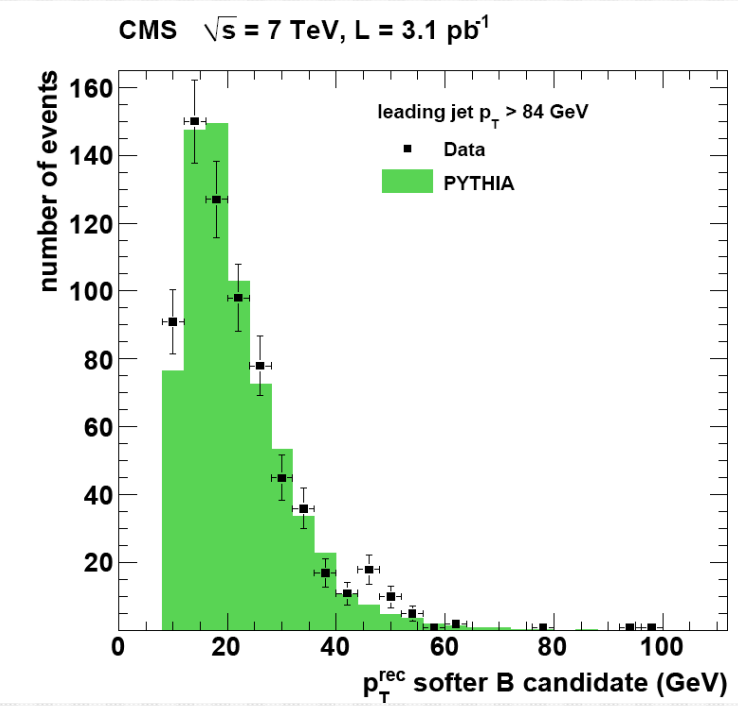
Efficiency for B Reconstruction

- **B-candidate reconstruction efficiency taken** from Monte Carlo: Efficiency is determined by two effects; data driven checks done:

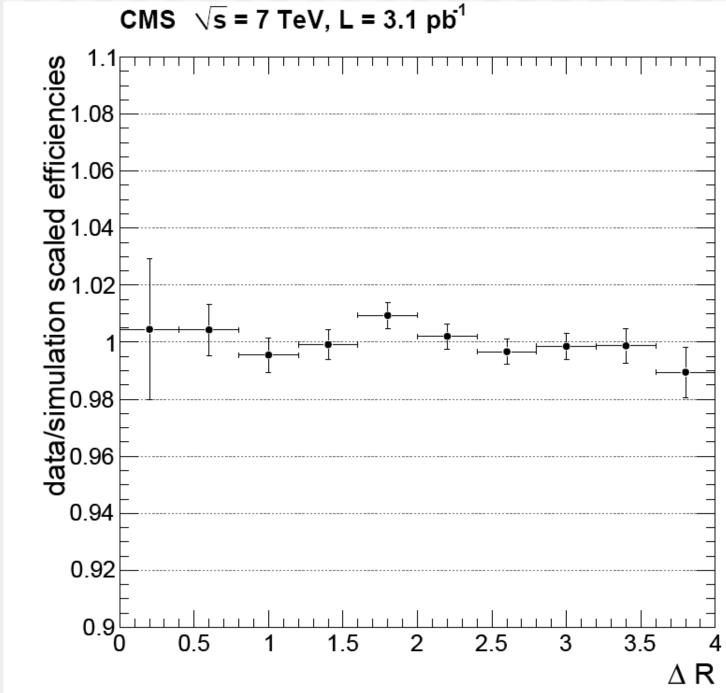
B-hadron kinematics:
→ quality of B description checked in MC

Algorithmic efficiency :
ΔR dependence description is verified with data mixing technique (on data and MC)

p_T^{rec} of softer B candidate



Ratio of efficiency in data / MC



Description is well controlled my MC

ΔR –dependence of ε well described in MC

➔ ***Overall efficiency to reconstruct both B-hadrons is ~10 %***

Results

- quoted in terms of differential cross sections

$$\frac{d\sigma_{visible}(pp \to B\bar{B}\,X)}{\Delta R} = \frac{N_b^{data} \cdot f_{purity}}{\varepsilon \cdot L \cdot \Delta R}$$

- are quoted for luminosity of 3.1 pb-1,
  for the visible phase space region with both
  B-hadrons satisfying:

  $|\eta(B)|<2.0$; $p_T(B) > 15$ GeV

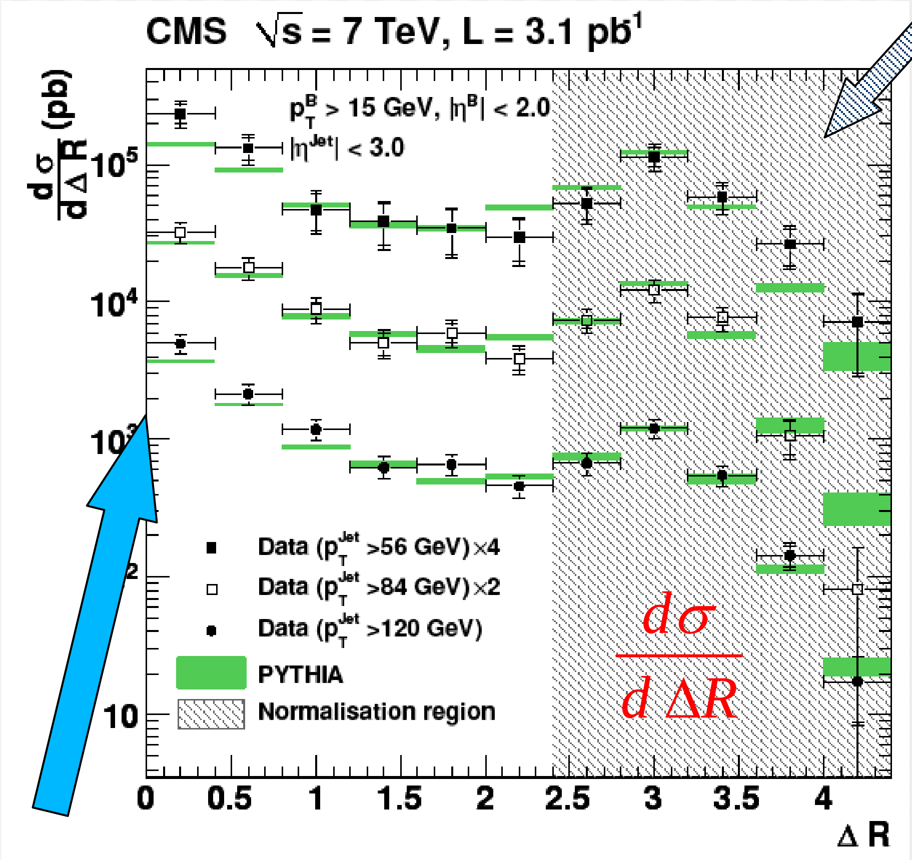
- Results given for three leading jet p_T^{jet} bins (~ energy scales) of > 56, 84, 120 GeV

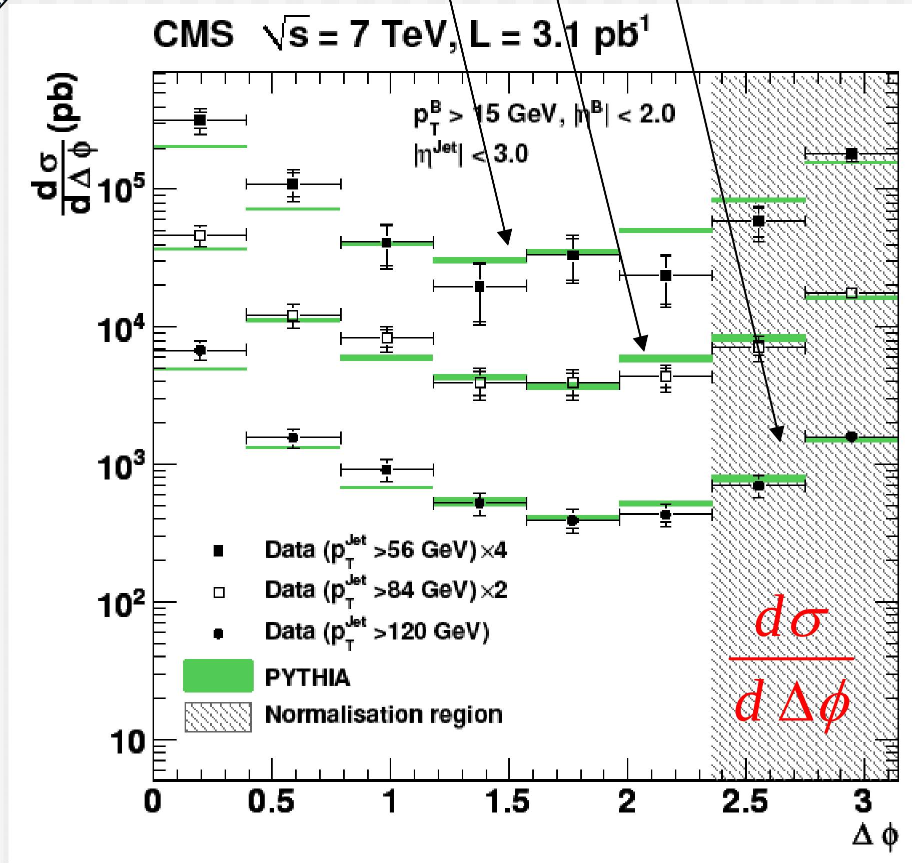
- Simulations are normalized to the **"back-to-back" region** (ΔR, $\Delta\phi > 2.4$),
  - independent of efficiency and luminosity
  - Normalize to a well defined region, where LO diagrams dominate (MC believed to be more reliable)

Cross Sections Results in ΔR, ΔΦ

for leading jet p_T^{jet} > 56, 84, 120 GeV

- Data values are absolute
- Simulations are normalized to **"back-to-back" region**

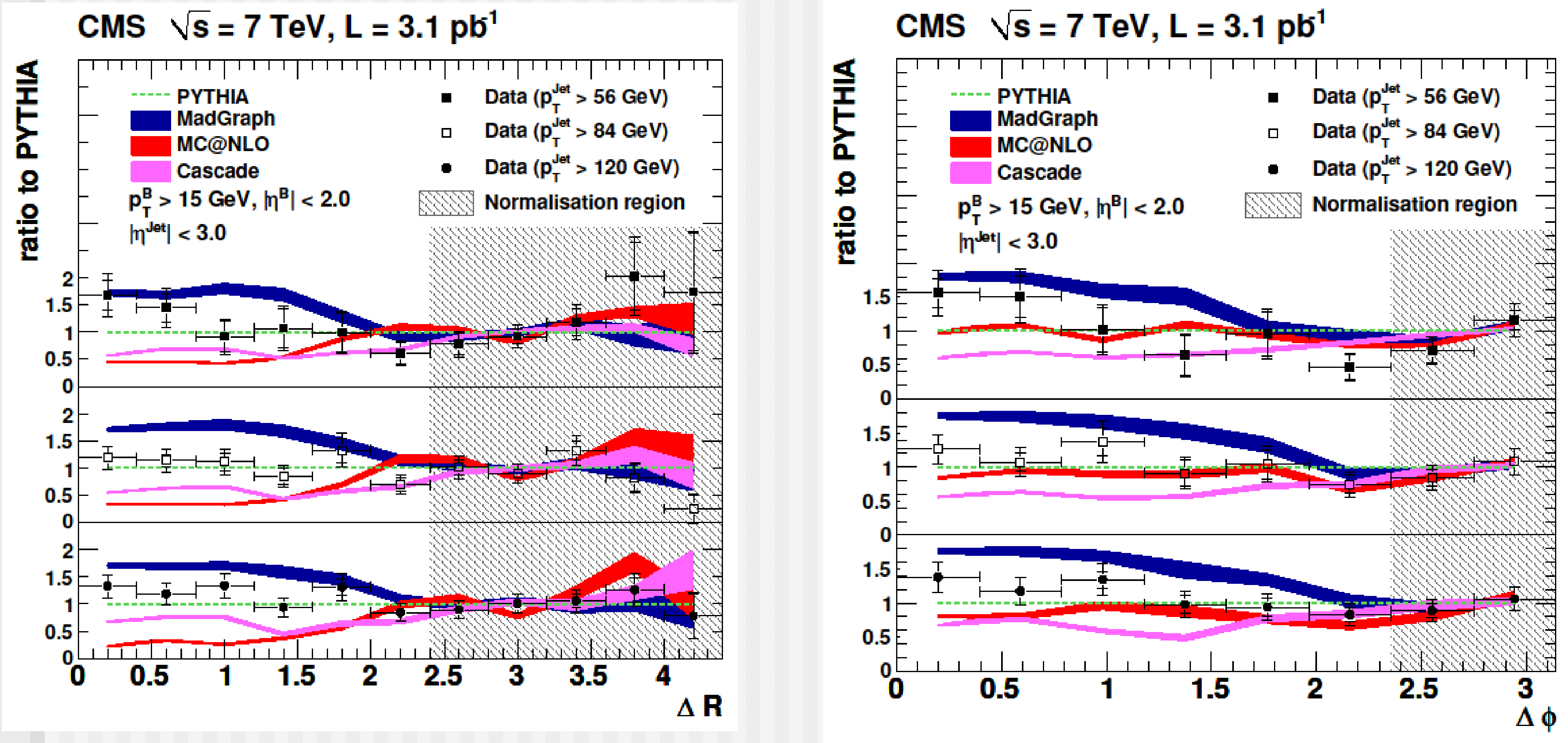




Small angular separation region dominant!

Comparison with Theoretical Predictions

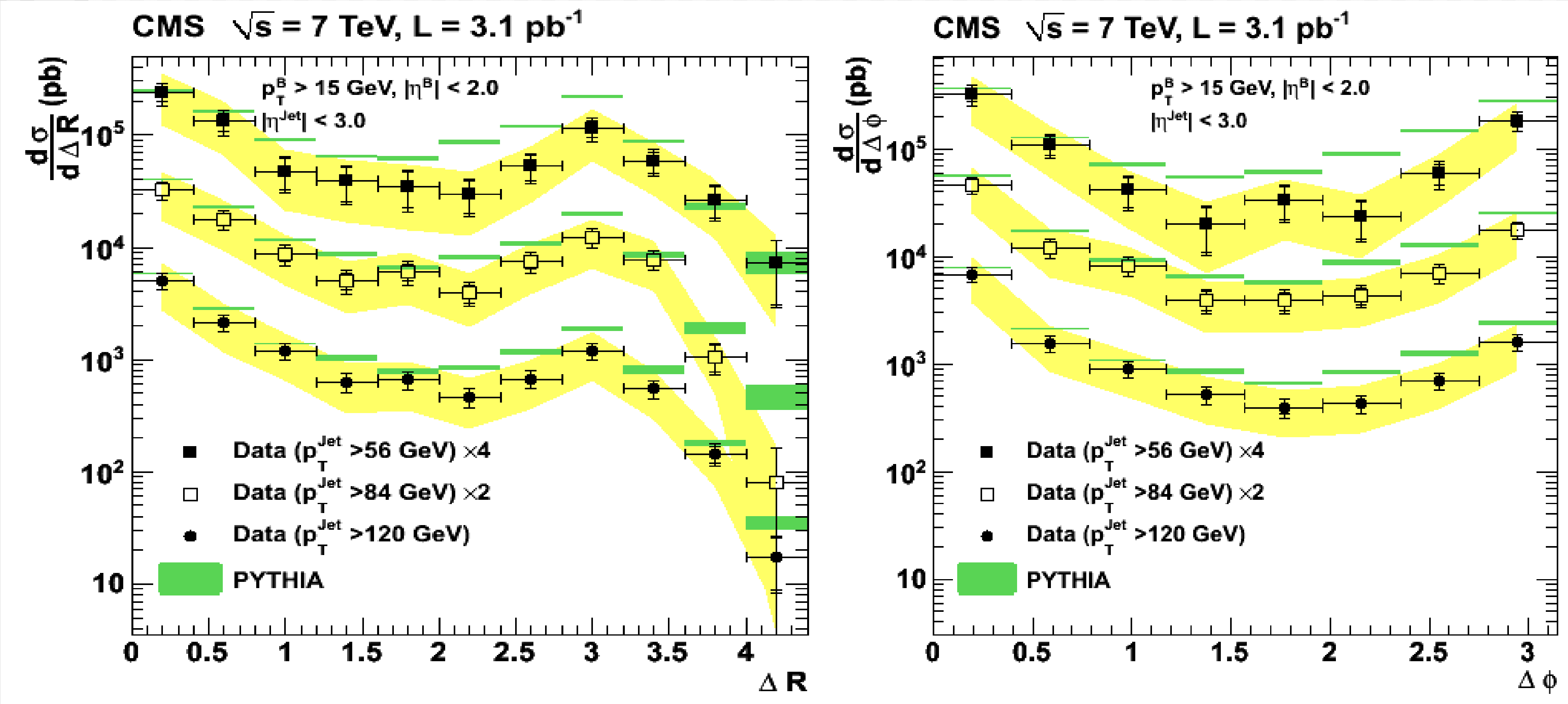
Ratio of Cross sections shown relative to Pythia → sensitive to shapes



- None of the predictions describe shape of data accurately.
- Apart from Madgraph, all predictions underestimate small angle production (low ΔR).
- Δϕ slightly better described.

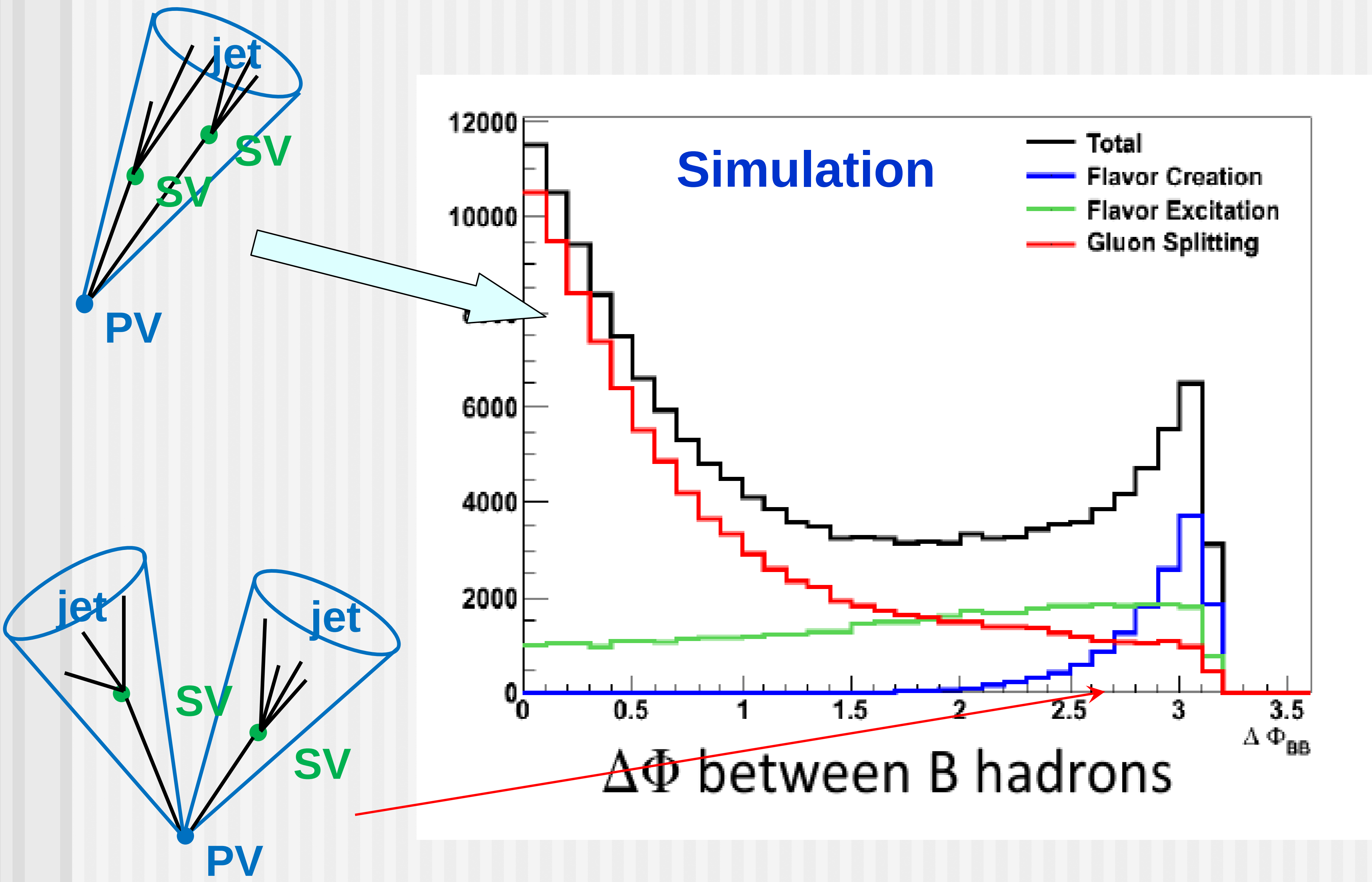
Absolute Cross Sections

- Absolute normalization uncertainty is dominated by B-candidate reconstruction efficiency (uncertainty ~20%), requiring two B and adding luminosity uncertainty, the total is about 45% (yellow bands):



Pythia clearly overestimates date.

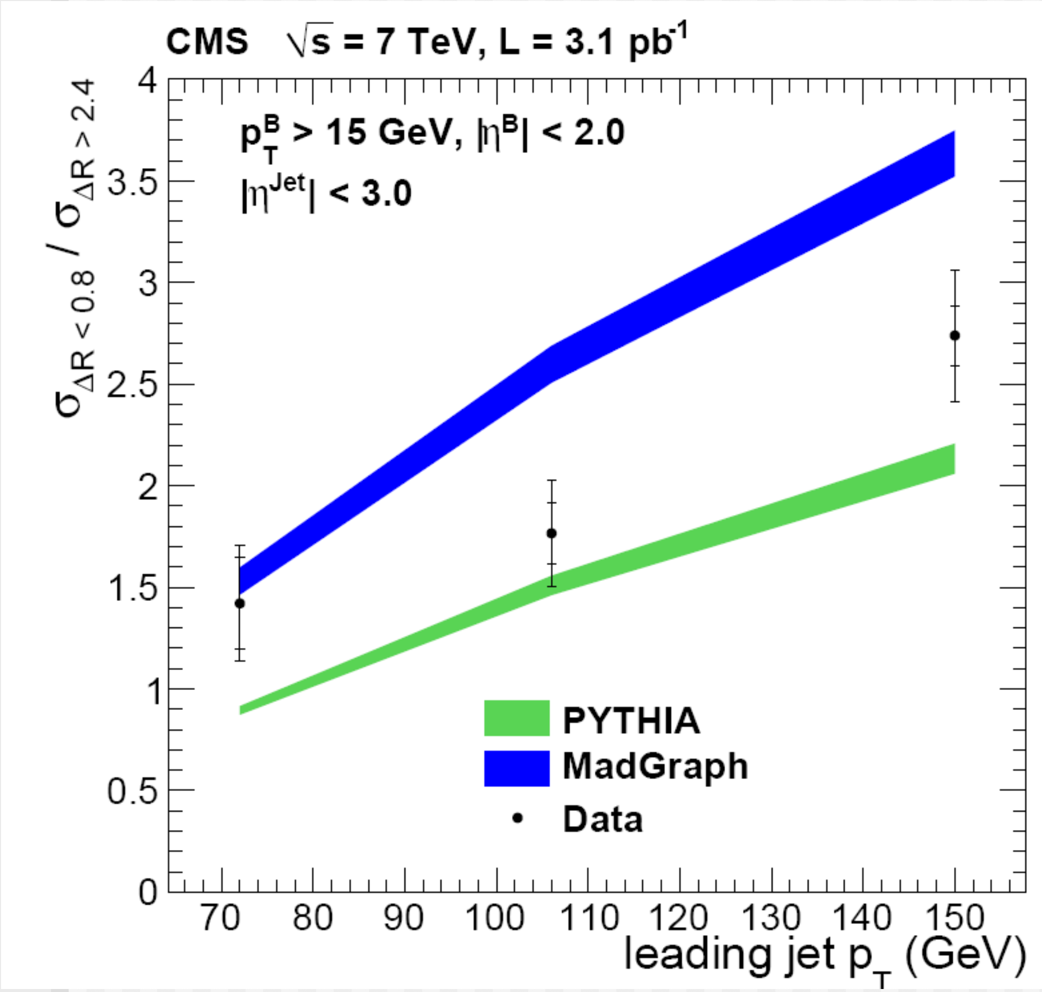
Interpretation of Angular Separation …



Asymmetry Scaling "FCR vs GSP"

Ratio of cross section contributions as function of leading jet p_T (~"scale") ;
small vs large ΔR region → "GSP vs FCR"

$$\rho_{\Delta R} = \frac{\sigma(\Delta R < 0.8)}{\sigma(\Delta R > 2.4)}$$



- **$\rho_{\Delta R}$ increases with larger p_T^{jet} values → more collinear emission processes (HO contributions), e.g. gluon radiation**
- **Trend of leading jet p_T dependence reproduced correctly by both MC.**
- **But normalization is off:**
- **Pythia underestimates $\rho_{\Delta R}$, Madgraph overestimates it.**

Two Types of Systematic uncertainties

- Uncertainties affecting total cross sections
  - Not relevant for the angular distribution, large uncertainties from average efficiency correction. this uncertainty is found ~45% total.
- Uncertainties affecting the shape of angular distributions:
  - Quantify this in terms of variation in ratio between GSP and FCR regions ($\Delta R < 0.8$ and $\Delta R > 2.4$) ➔ **~ 8-10%**
- Additional bin-by-bin uncertainty from limited MC statistics ~13%

Source of uncertainty in shape	Change in $\rho_{\Delta R} = \sigma_{\Delta R<0.8}/\sigma_{\Delta R>2.4}$ (%)		
	Leading jet p_T bin (GeV)		
	> 56	> 84	> 120
Algorithmic effects (data mixing)	2.0	2.0	2.0
B hadron kinematics (p_T of softer B)	8.0	7.0	4.0
Jet energy scale	6.0	6.0	6.0
Phase space correction	2.8	2.8	2.8
Bin migration from resolution	0.6	1.3	2.1
Subtotal shape uncertainty	10.6	9.9	8.3
MC statistical uncertainty	13.0	13.0	13.0
Total shape uncertainty	16.8	16.4	15.4

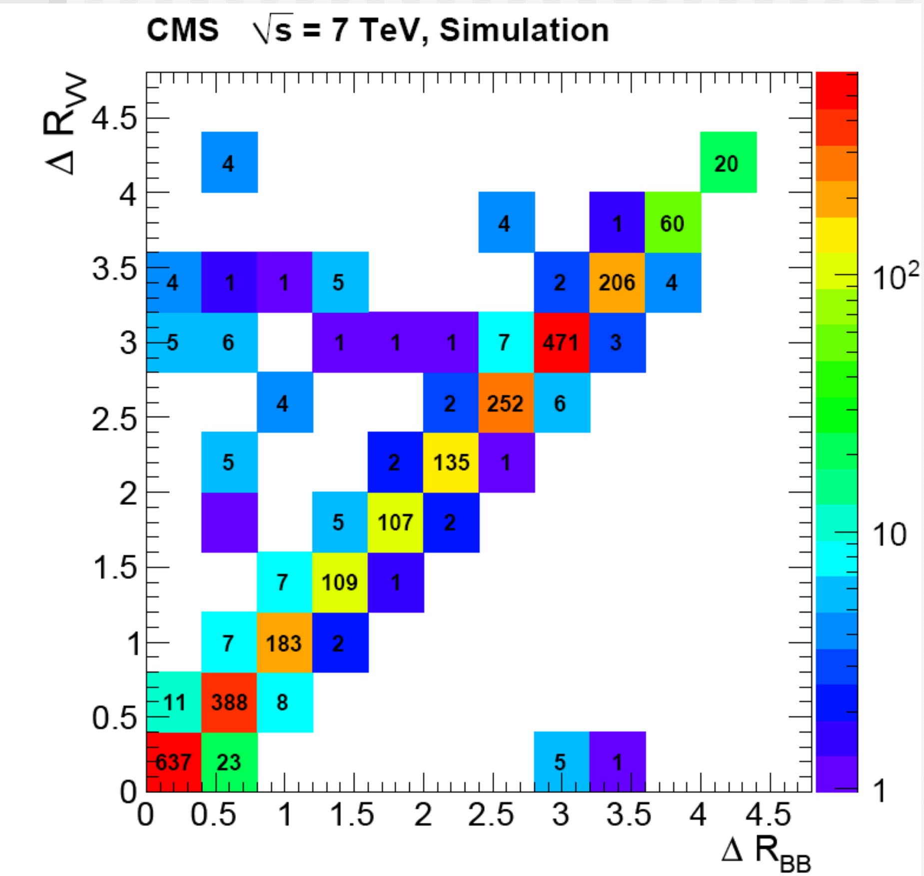
Conclusions

- The first LHC measurement of **BB angular correlations** using secondary vertices and probing the very small angle region performed
  - Substantial enhancement of cross section is observed at small opening angles between B and Bbar hadrons.
  - The production in the collinear regime is dominant at high energy scales
- The measurements are compared with QCD predictions:
  - Existing Monte Carlo such as Pythia and MadGraph are found to reproduce measured shape within 30-50% (ratio of two angular regions), but not the normalization.
  - Predictions are quite different for the different generators.
  - Also constitutes first steps in the understanding of one of the main background for searches with bb final states.

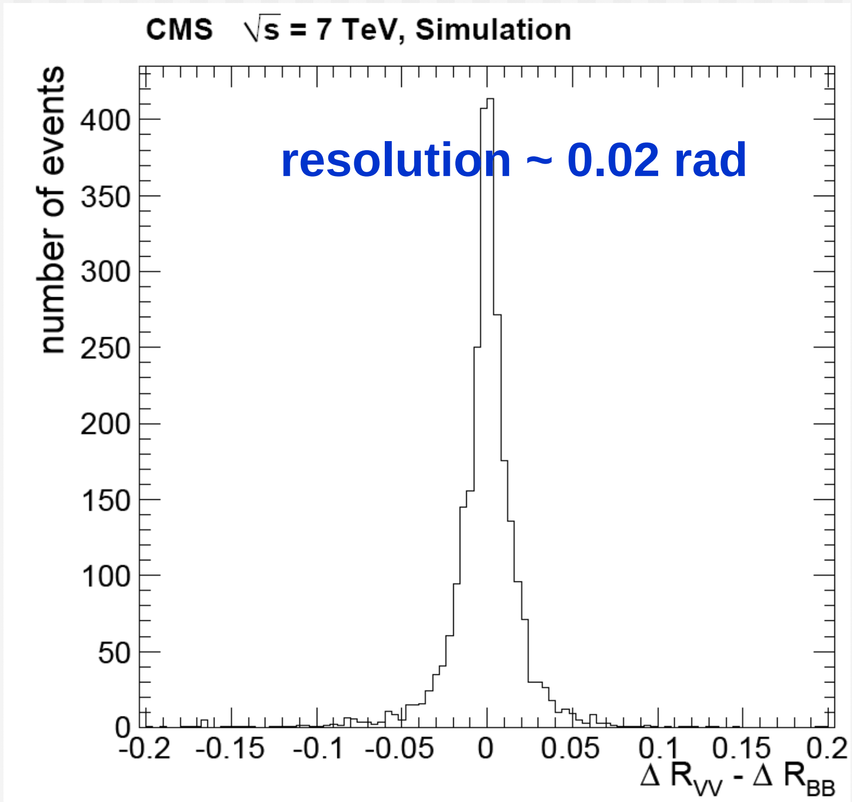
Backup slides
B-Bbar Angular Correlations

Resolution and Purity (opt)

- Angular resolution from MC: relate ΔR(vertices) with ΔR(true generated B-hadrons)
- Find a **resolution of order 0.02 rad ➔ chose angular binning of 0.4**
- Overall purity from migration and including background is 84% on average.
- Off-diagonal contributions about 3% (mostly one correct, one fake vertex) → corrected

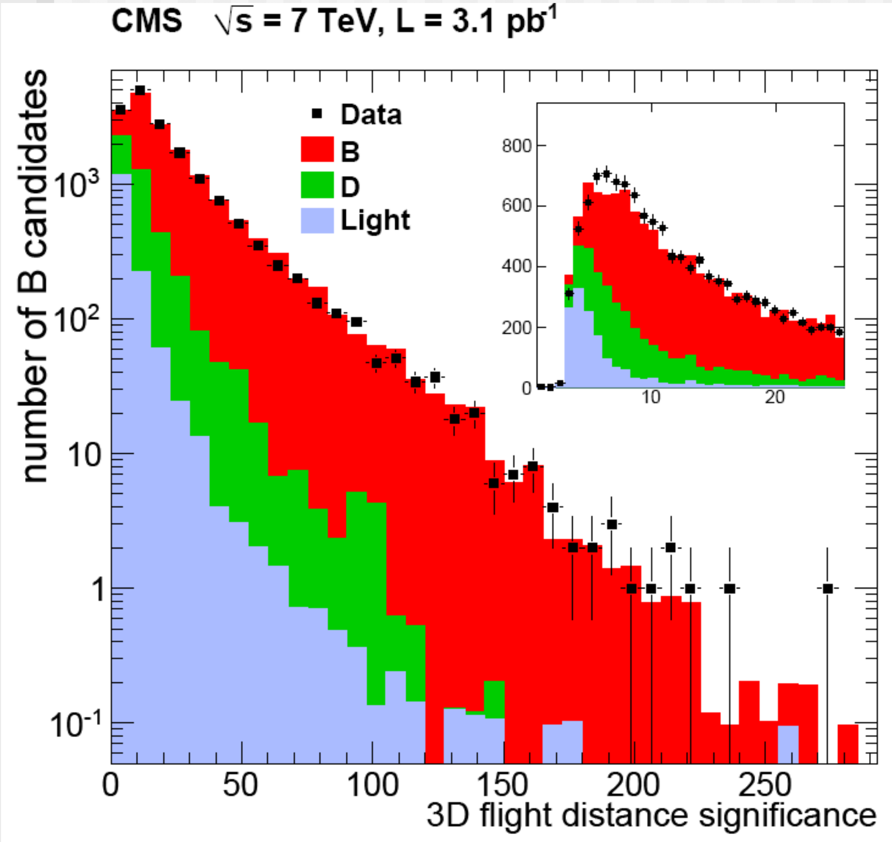


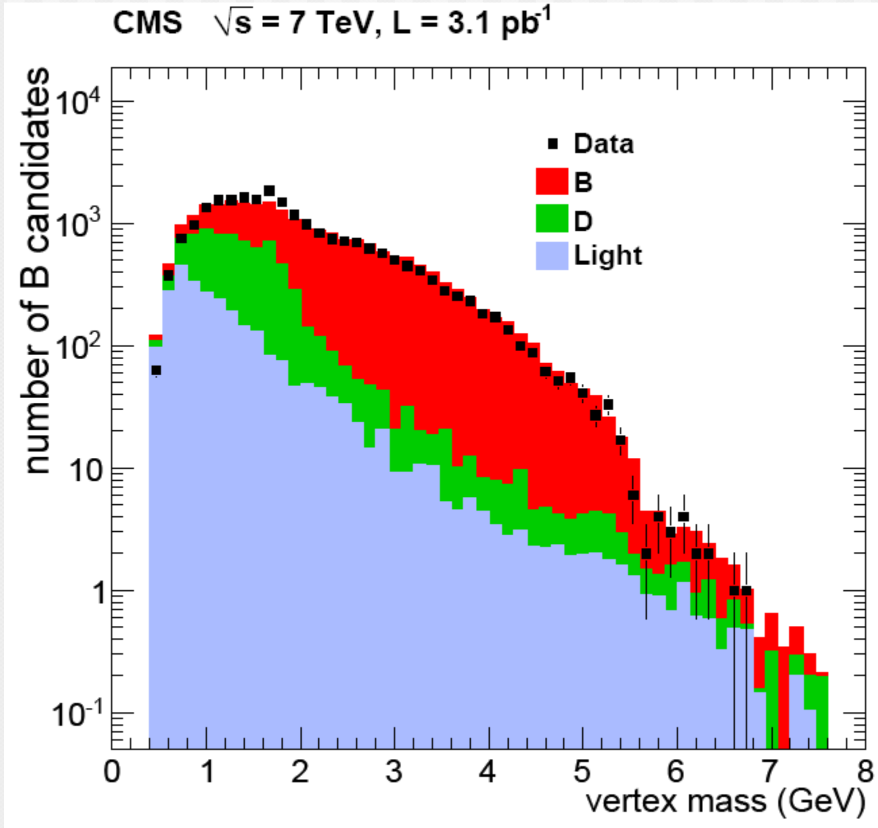
ΔR(2 vertices) - ΔR(true BB)



B-candidate Properties

[CMS PAS BPH-10-010]

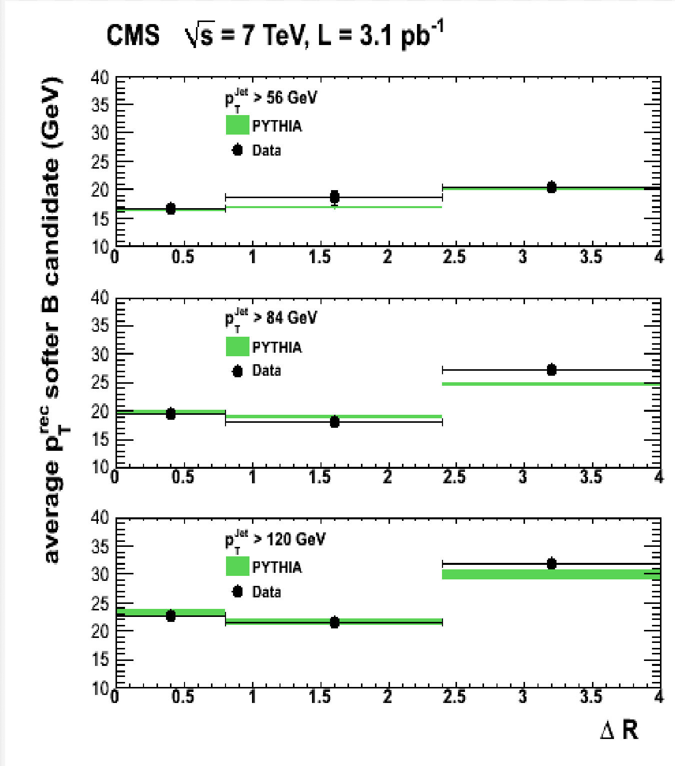




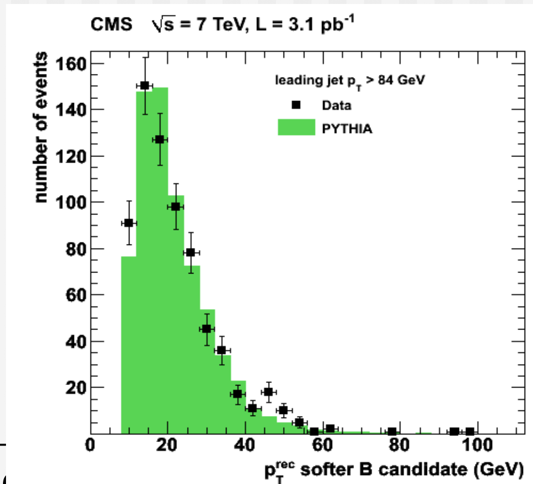
- B-properties distributions for events with at least <u>one</u> B-Candidate
- Data and MC normalized to same number of entries
- Events selected with Leading PF Jet p_T > 84 GeV
- **Good agreement between MC and data**

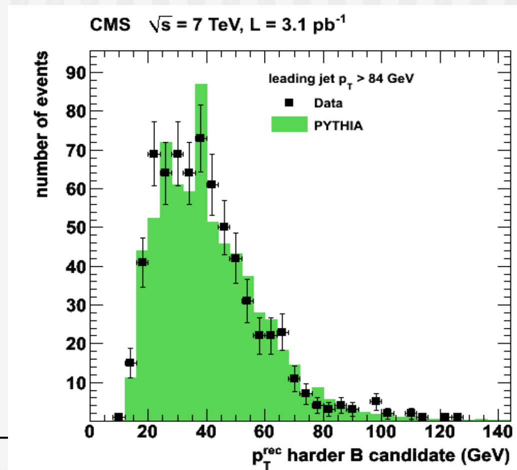
B-hadrons kinematics

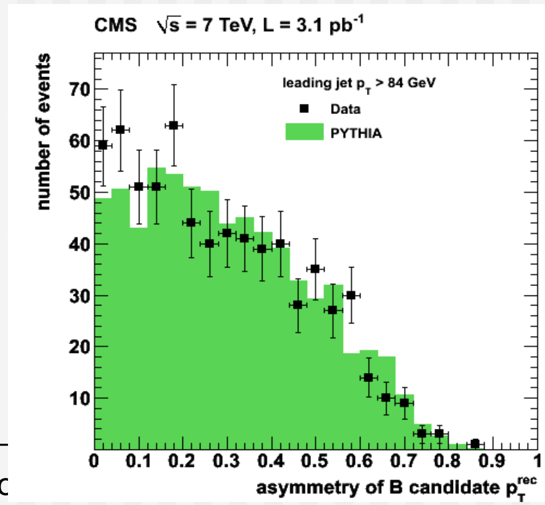
- The MC derived efficiency correction can be wrong if the spectrum of B-hadrons, for a given ΔR is not well simulated
  - The efficiency has a quite large pt dependency at low momentum
- Cross checks on the momenta of the reconstructed B-candidates have been performed:
  - Distribution of the momentum asymmetry between the two B
  - Distribution of the pT of softer and harder B
  - Trend of the mean pT for the softer B as function of ΔR
- The discrepancy is convoluted with an estimate of the efficiency vs pT dependency to compute the systematics



- Estimate MC efficiency uncertainty from the observed discrepancy estimated to be 8% to 3%.

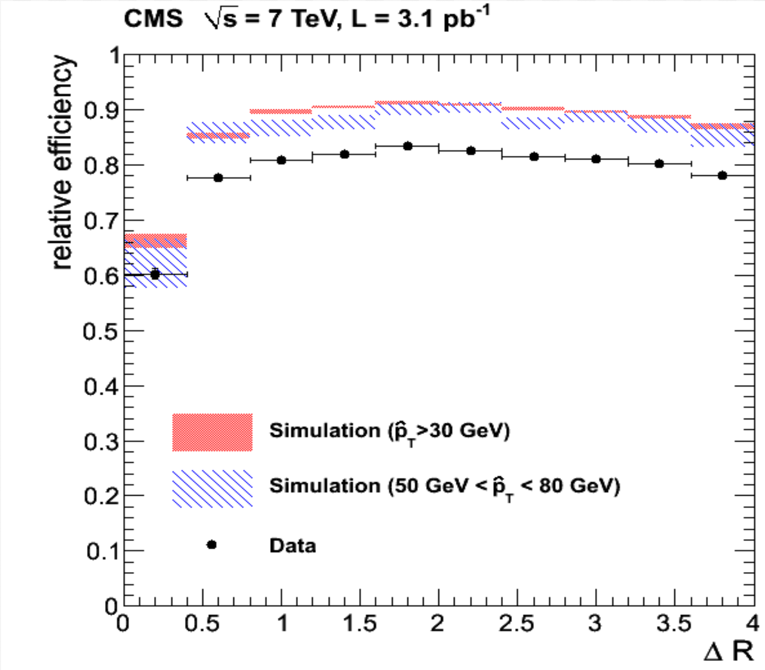


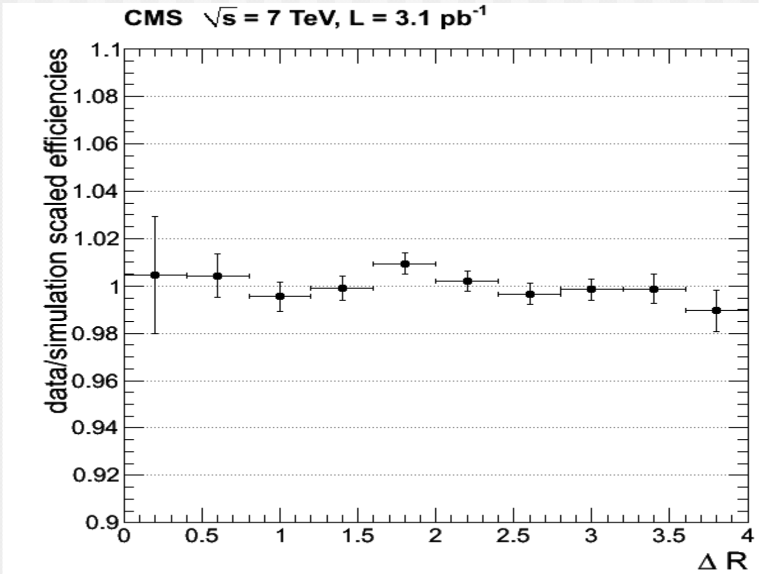




Algorithmic efficiency loss at small ΔR :Event mixing

- In order to verify that the small ΔR efficiency loss is well modeled in MC we used both on data and MC an event mixing technique
- Events are pre-selected if they contain at least one B-candidate
- Pairs of events are *mixed* at the level of the electronics readings if their Primary Vertices are within the typical PV resolution (20um)
- The mixed event is re-reconstructed, re-running tracking and secondary vertex reconstruction
- A *relative efficiency* is defined by counting the fraction of mixed events where the two B candidates from the two original events are re-reconstructed
- The shape of the MC and Data *relative efficiencies* is compared and used to set a systematic uncertainty (2%)





Systematic Uncertainties on scale

BPH-10-010:

Source of systematic uncertainty	Relative uncertainty
Luminsosity	11%
Jet Energy Scale	10%
Full phase space corr. (no jet matching)	5%
Average efficiency (no jet matching)	40%
Average efficiency (jet matching)	20%
Jet phase space corr (jet matching)	20%
Jet matching region uncertainty (jet matching)	5%
Total w/o jet matching	43%
Total w/ jet matching	32%

BB-Correlations – Systematics

[CMS PAS BPH-10-010]

- **Algorithmic effects:**
  - use of event mixing ; find differences between data and MC over DR are < 2%
    → use 2% for systematics
- **kinematic properties of the B hadron pair**:
  - use MC, cross-check with data the kinematical variables pt(soft) etc…
    The differences between the data and the simulation, (convolved with the pT-dependent efficiency), are found to have an effect of 4-8%
- **Uncertainty on the Jet Energy Scale (JES).**
  - Variation of JES of 3% gives one uncertainty, and
  - An additional 5% is added to take into account the differences in the jet energy corrections between b and light jets
  - these gives a combined 6%
- **Migration**: small effect:
  - vary small DR contribution by +-50% yields only a 2.1 % systematic effect on purity correction.
- **Monte Carlo statistics**: bin-to-bin systematic uncertainty from limited #MC evts
  - Use conservatively maximum value of either the statistical uncertainty of simulated
    or half of the largest bin-to-bin fluctuation observed in the correction function over DR.