Non-SM Higgs Search at DØ

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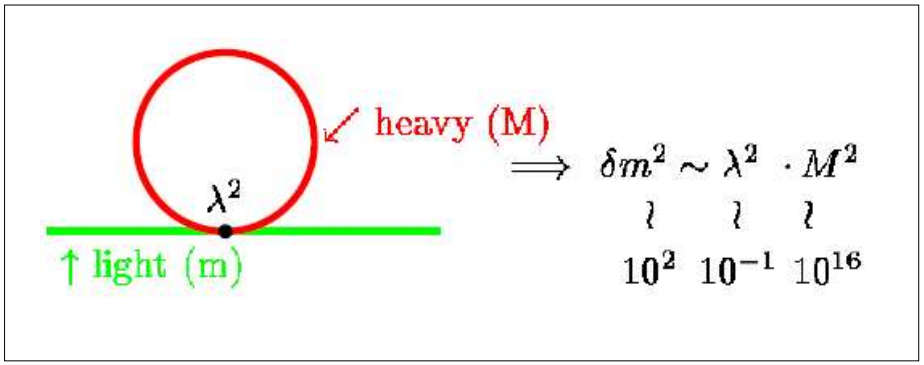
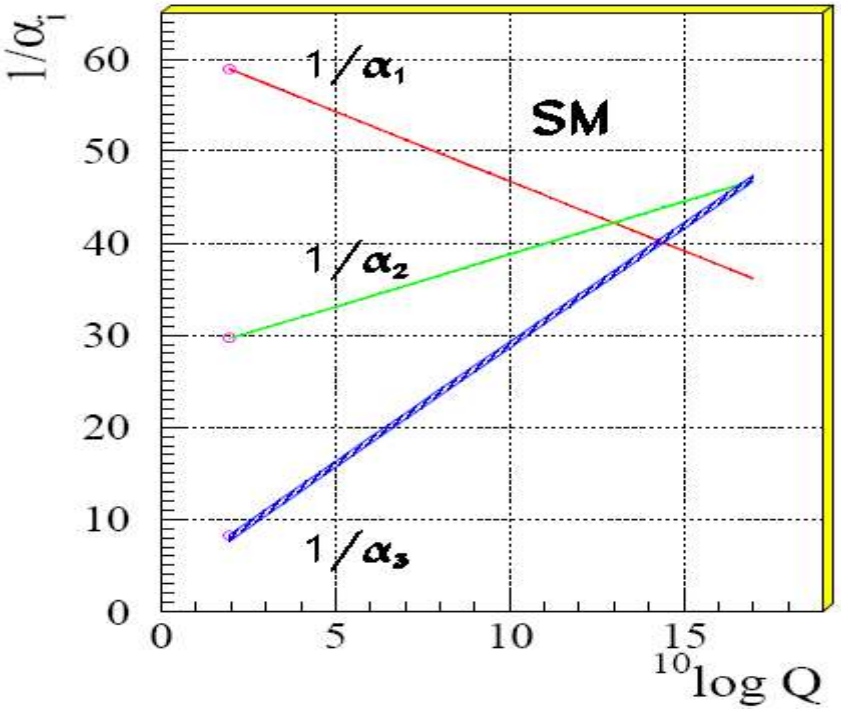
DØ Experiment

SUSY '05
Durham, UK

Going Beyond the SM Higgs

- Hierarchy stability problem:
  - QFT predicts radiative corrections
  - How does m_h stay << m_{pl} ?
- Can the gauge couplings unify?
-
- Supersymmetry enriches the Higgs sector and provides new opportunities for discovery at the Tevatron
  - **Higgs at high tanβ**
  - Enhanced rare decays (h→$\gamma\gamma$)

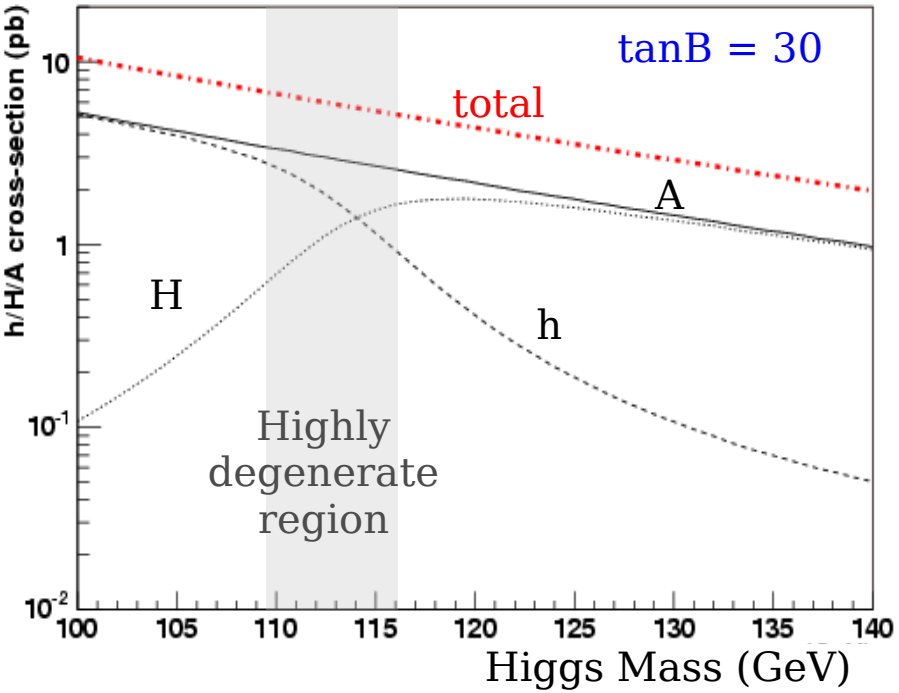


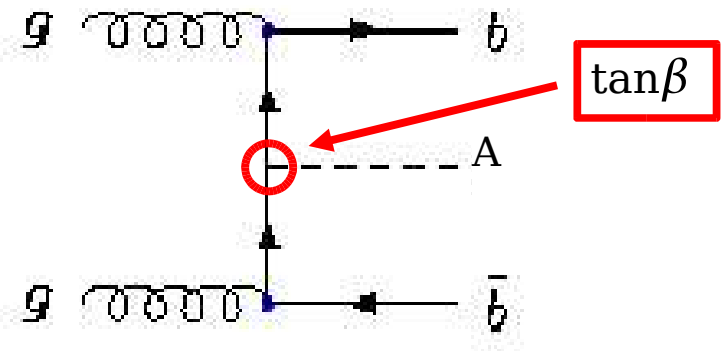


Higgs Bosons in Supersymmetry

- Higgs fields come in pairs (H_u and H_d)
  - 5 Higgs bosons : h, H, A, H+, H-
- $\tan\beta = H_u / H_d$
  - Cross-sections for pp→bbh grow like $\tan^2\beta$!
- The h is predicted to be light, <~135 GeV
  - LEP limits on Higgs mass ~ 92 GeV (not the usual 114 GeV like in the SM...)
  - LEP limits are much looser (~50 GeV) if CP-violation is allowed in the Higgs sector...
    we assume a CP-conserving Higgs!
- At high $\tan\beta$ (>~20), the A is nearly degenerate with the h/H:
- BR(A,h/H→bb) =~ 90%
  We have focused on bbh(→bb) so far

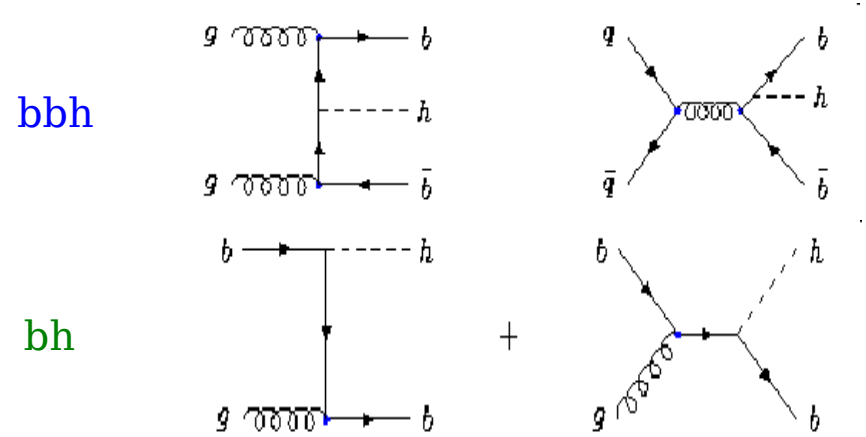
  BR(A,h/H→$\tau\tau$) =~ 10%
  Will be explored in h→$\tau\tau$ and bbh(→$\tau\tau$) soon

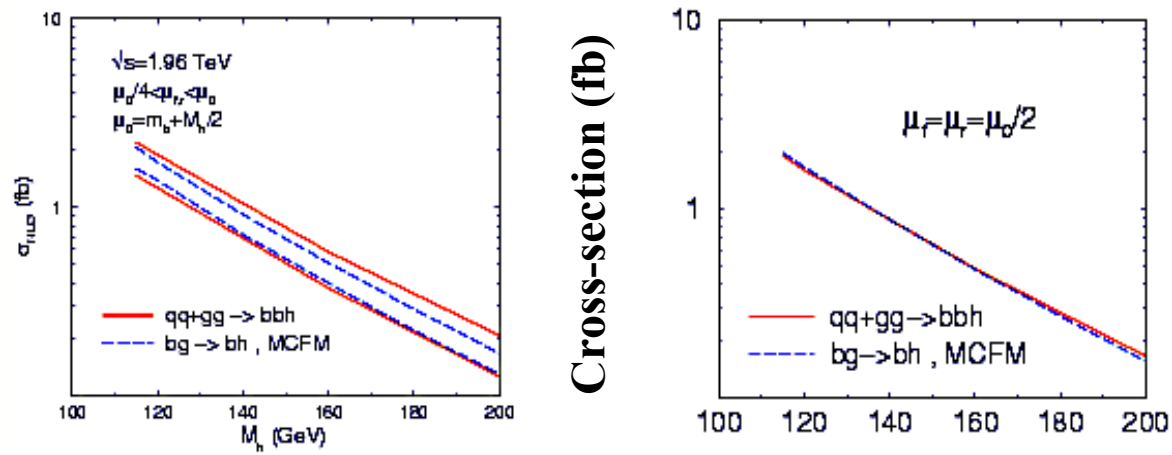




Signal at NLO in QCD

- There are two ways to calculate the signal production at a ppbar collider:
  - ppbar->bbh (4-flavor scheme)
  - ppbar->bh (5-flavor scheme) : use b-PDF
  - Both methods now agree at NLO
  - Uncertainties from PDF are comparable in size
- D0 has performed a measurement to test the predictions of the b-quark PDF calculations
  - Z+b / Z+j

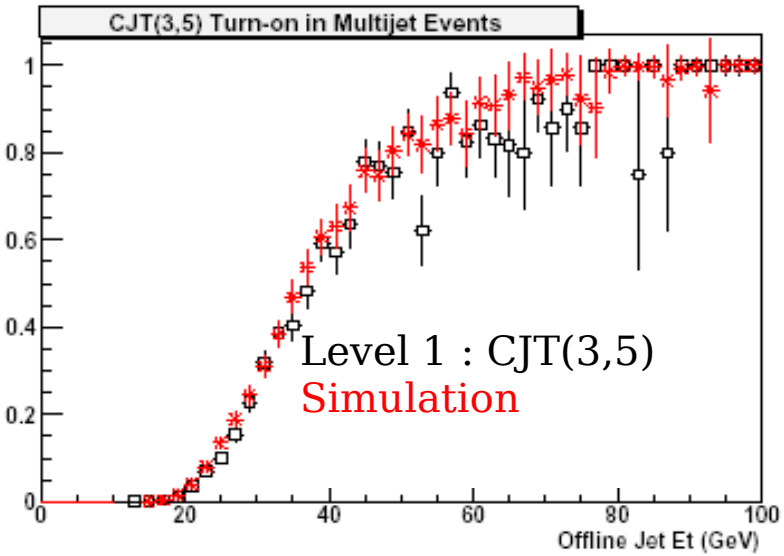




Z+b is a probe of b-quark PDF ⇒
σ(Z+b) / σ(Z+j) = 0.021 ± 0.005
= 0.018 (CTEQ6 prediction)
(DØ – hep-ex/0410078) - PRL. 94, 161801 (2005).

bbh(⇒bb): Data / Triggering

- Custom multi-jet triggers
  - Level 1:
    Three towers with TOT E_T > 5 GeV
  - Level 2:
    Three clusters with E_T > 8 GeV
    and H_T >50 GeV
  - Level 3:
    Three jets with E_T > 15 GeV with two above 25 GeV in |eta|< 3.0
- 260pb^{-1} of good data
  - 87.5 Million events
- Includes Run II data up to June 2004

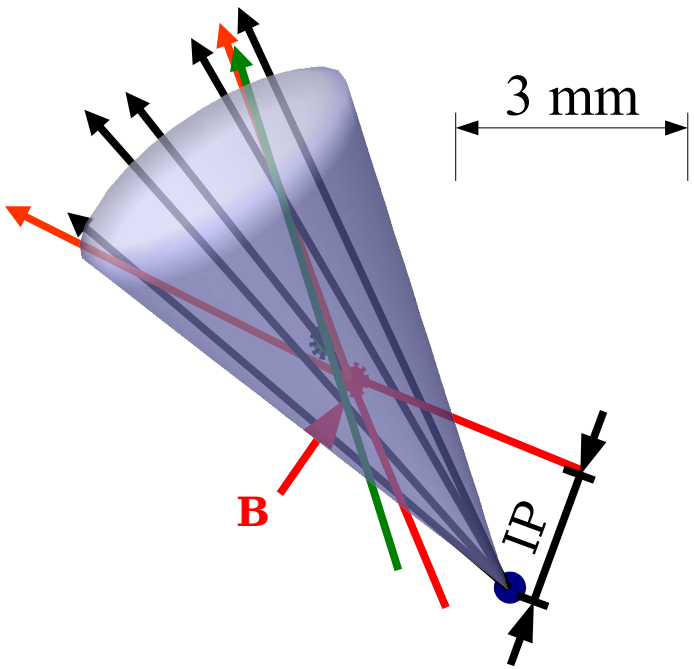


Trigger efficiencies measured using data:
> mu-based unbiased trigger for L1/L2
> special run for L3 study

68-80% efficient for m_A of 90-150 GeV

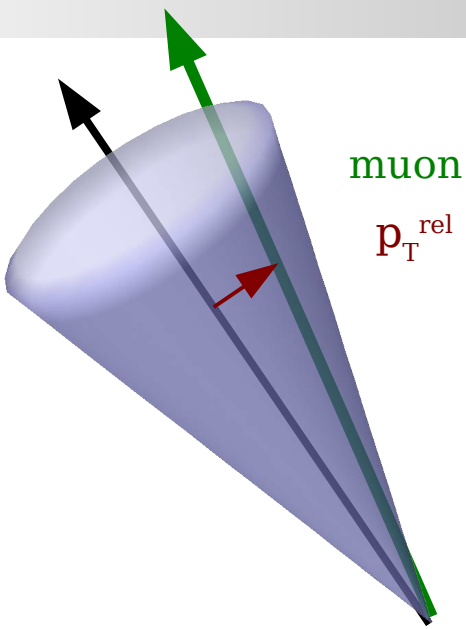
b-Jet Identification

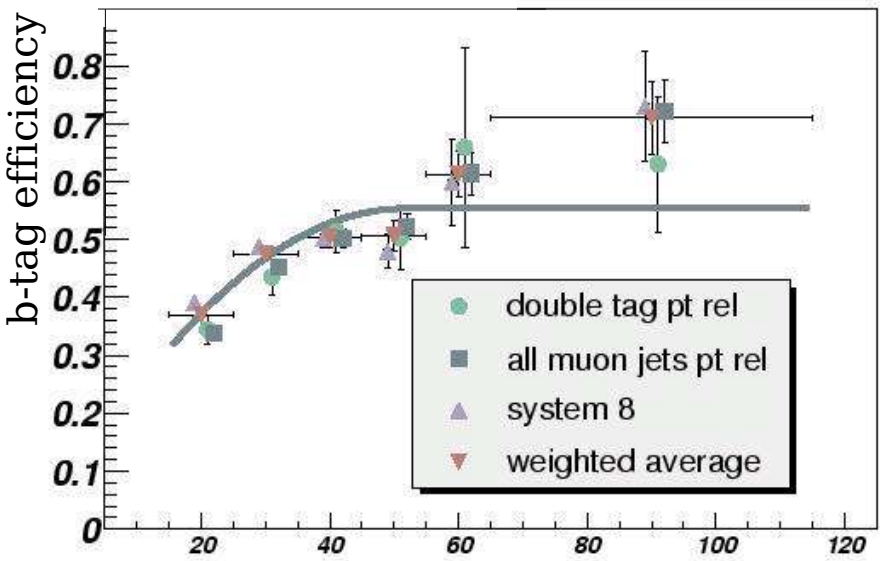
- Identify jets containing bottom hadrons
  - main weapon again the huge QCD background
  - b-hadrons travel ~3 mm before decaying
  - Their mass leads to an opening angle between tracks --- large IP significances
  - Additional large IP significance tracks may arise from daughter decays (charms, tau)
- High-IP-significance tracks are used to find the secondary vertex(es)
  - Jets with a secondary vertex in $\Delta R<0.5$ are "tagged" as b-jets
- Backgrounds consist of:
  - mis-tags: poorly reconstructed tracks which randomly happen to form a vertex
  - long-lived strange / charm decays or photon to e^+e^- conversions
  - "gluon splitting" into nearly collinear charm or bottom pairs

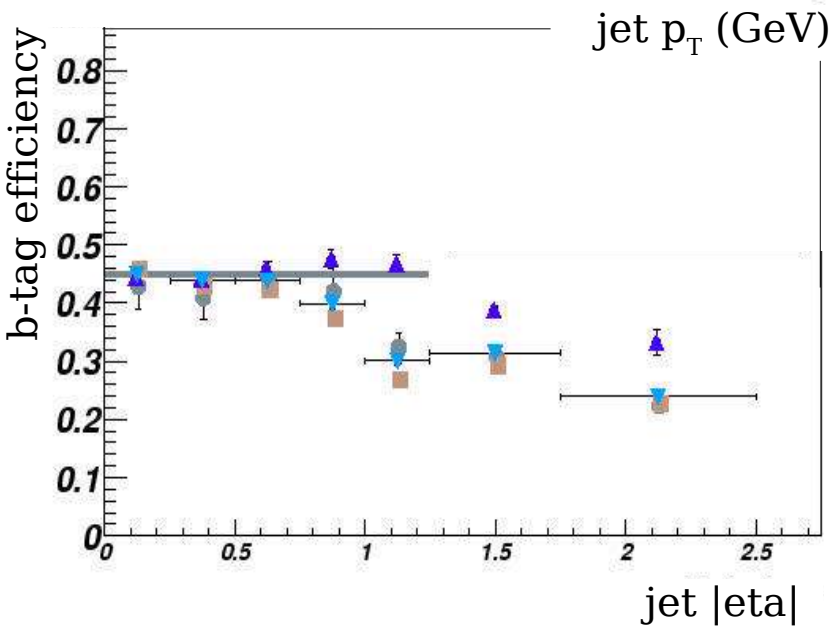


b-Tagging Efficiency

- The b-tagging efficiency is measured in data and compared to simulations
  - Very difficult!
    (no pure b-jet data sample)
- Use the fact that the p_T^{rel} spectrum of muons is different for b, c, light – jets
- Compare vertex tags to muon tags and extract vertex tagging efficiencies

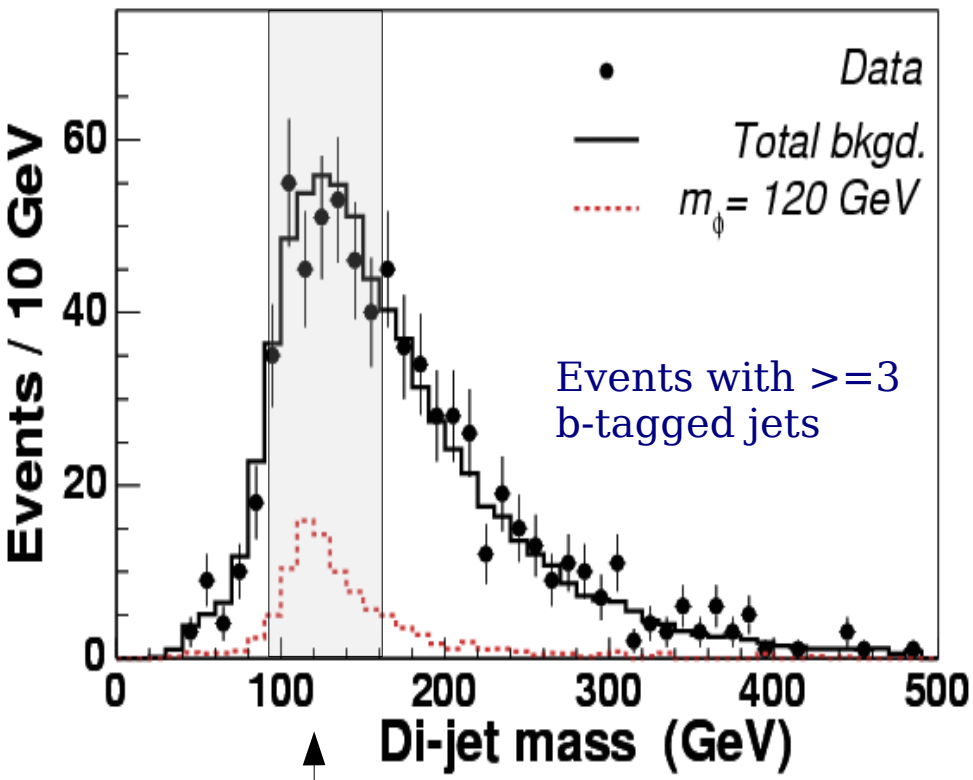






bbh(⇒bb): Analysis Method

- Signal:
  - 3 or more b-tagged jets
  - Invariant mass of leading jets is peaked at m_A
- Backgrounds:
  - Determined from data!
    - Shape estimated from the double b-tagged data sample (taking into account the kinematic bias from requiring a 3rd b-tag)
    - Normalized outside the "signal region"
  - Also modeled in MC as a cross-check
    - "fakes": all light-quark/gluon jets (measured from data)
    - "heavy flavor": (ALPGEN) bbj(j), ccj(j), bbcc, cccc, bbbb
    - "other": tt, Z(→bb)+jets (Pythia)



"Signal window"

Triple b-tagged Background

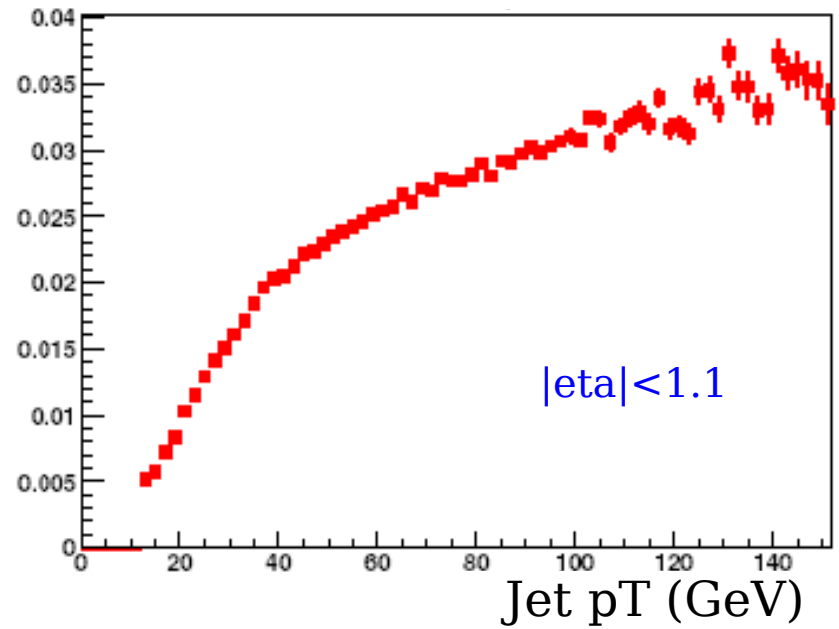
Full multi-jet data sample → Calculate TRF (E_T & 3 regions of η)

Double b-tagged data sample → Apply TRF to un-b-tagged jets

↓

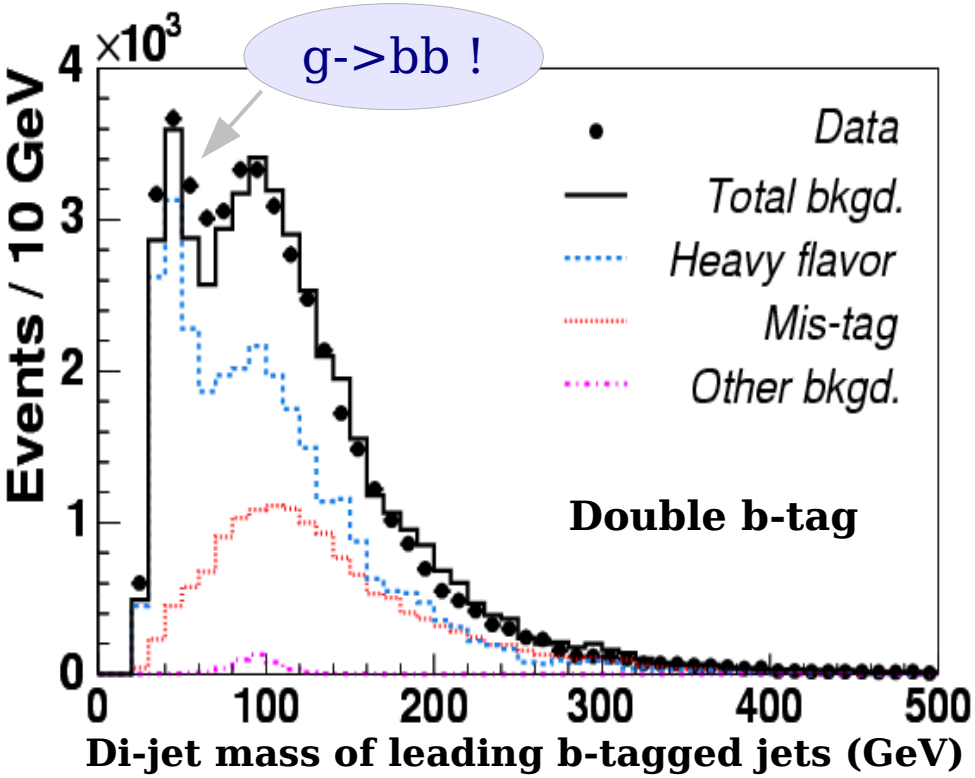
Triple b-tagged background shape → Fit outside the signal region to data → Triple b-tagged background

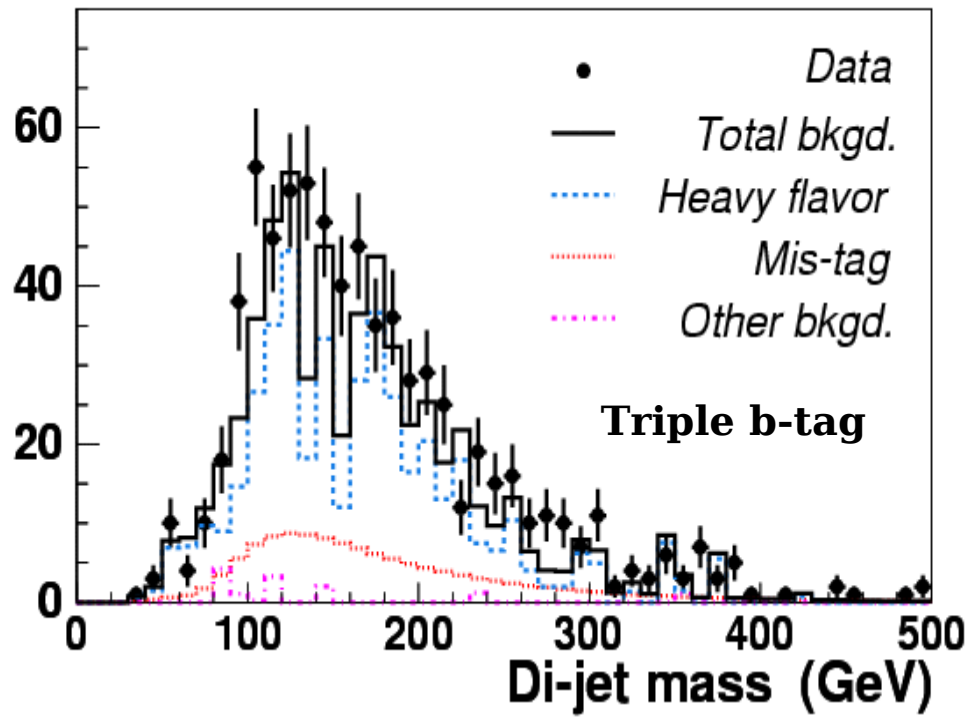
Tag-rate-function (TRF)



Background is completely determined from data !

MC Cross-checks



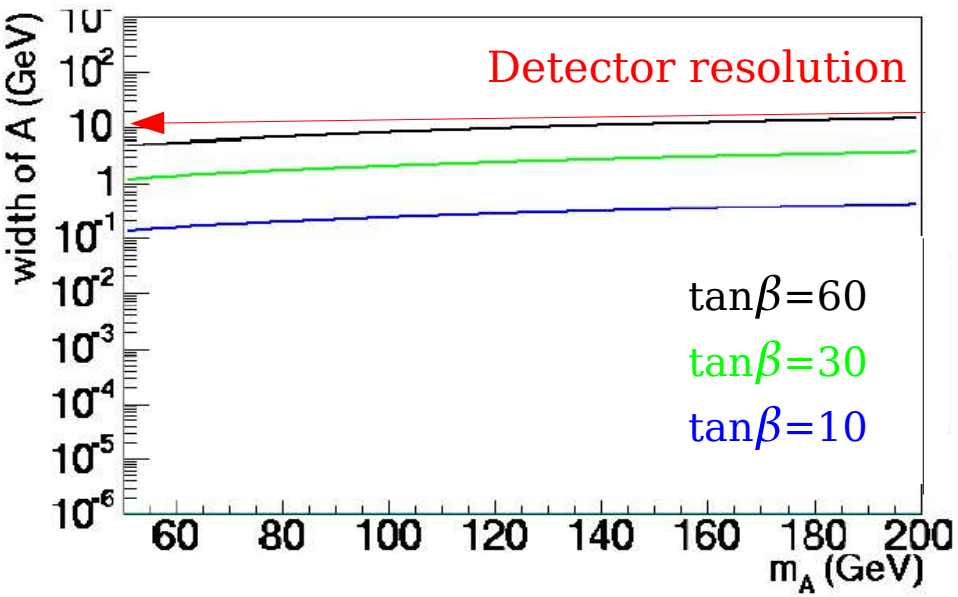


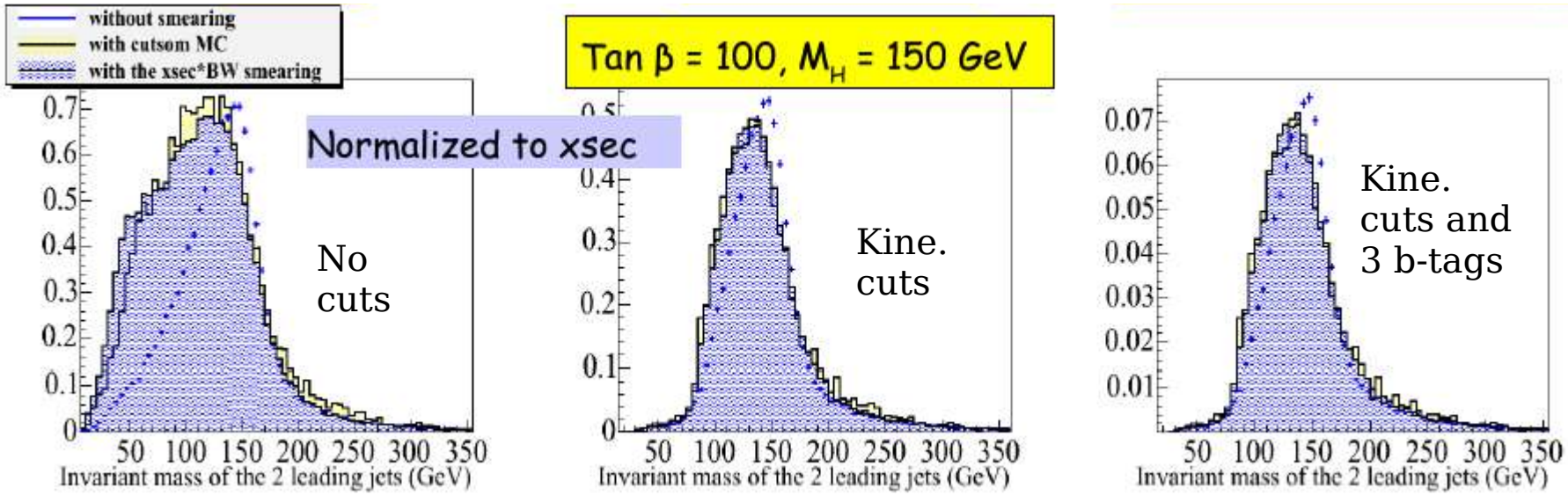
Monte Carlo can model many other distributions in the double b-tagged data as well.

Monte Carlo predicts a background shape and normalization in good agreement with the triple b-tagged data.

Higgs Widths

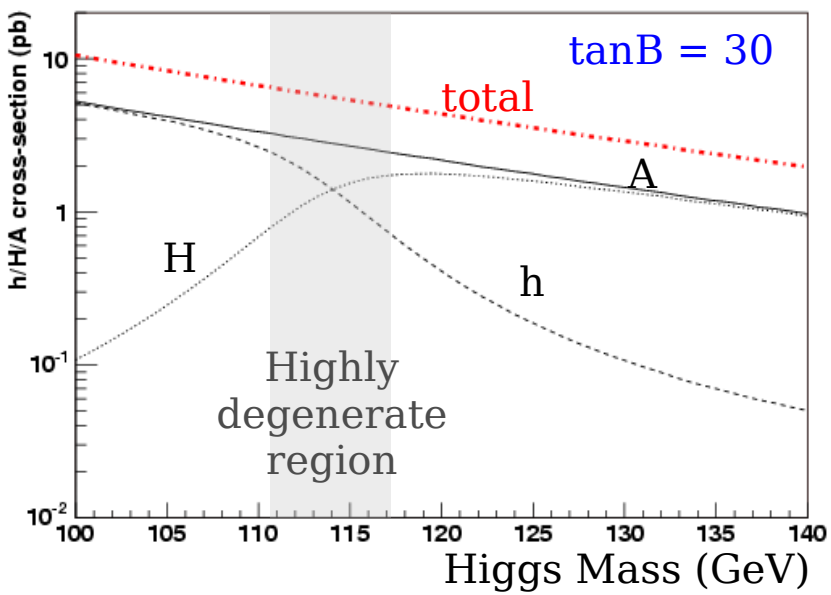
- Higgs bosons get wider, proportional to $\tan^2\beta$
- Widths are modeled with BW shape, weighted by cross-section
- Not a large effect on sensitivity, for reasonable $\tan\beta$ values, after considering kinematic criteria

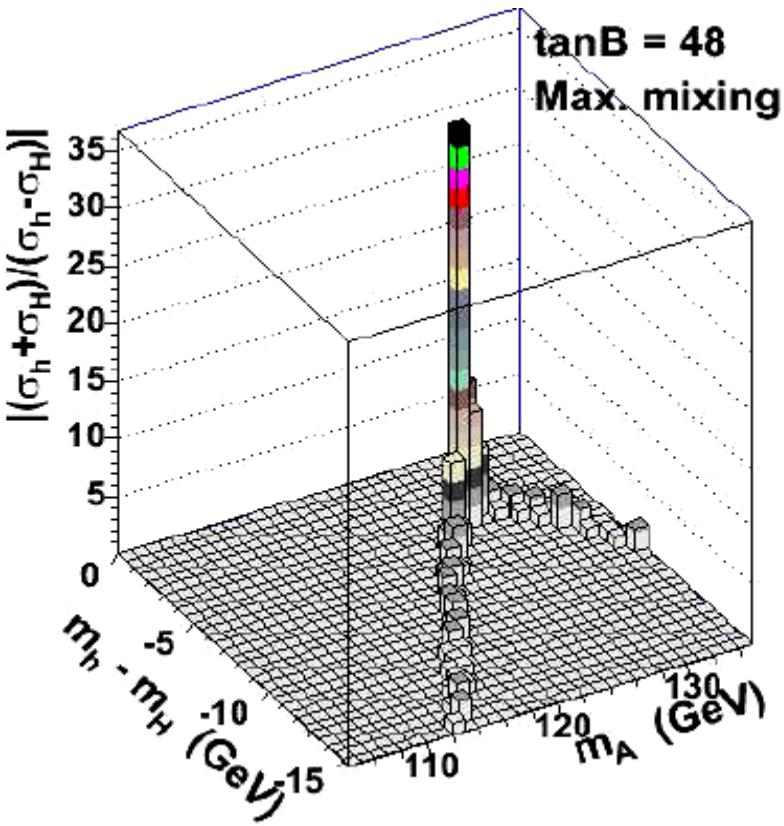




Mass-splitting of the Higgses

- What about when all 3 Higgs are nearly degenerate?
- What matters is the shape and height of the invariant mass peak
- When cross-sections are significant, the mass-splitting is small compared to the detector resolution

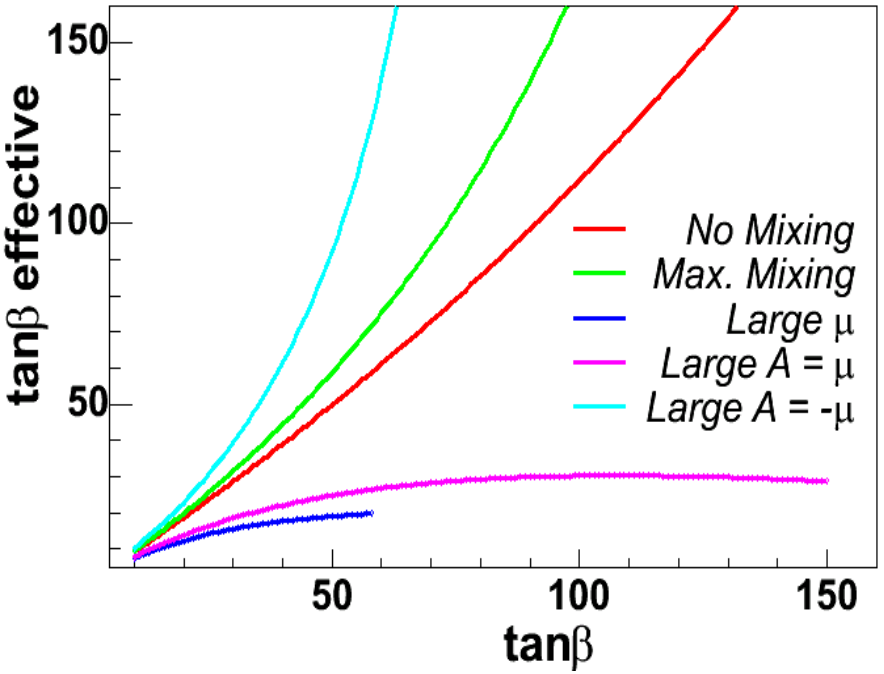




Mass splitting, weighted by inverse cross-section difference, of h and H

MSSM Beyond Tree-Level

- Supersymmetric loop corrections are calculated using "CPSuperH"
  - Production doesn't scale like $\tan^2\beta$... can be faster or slower depending on the supersymmetric model and its parameters
- We set limits on $\tan\beta$ vs. m_A in two of the "benchmark scenarios":
  - no mixing and maximal mixing in the stop-quark sector



$$\sigma \times BR_{SUSY} = 2 \times \sigma_{SM} \times \frac{\tan\beta^2}{(1+\Delta_b)^2} \times \frac{9}{[9+(1+\Delta_b)^2]}$$

Δ_b is a function of various SM/SUSY parameters:

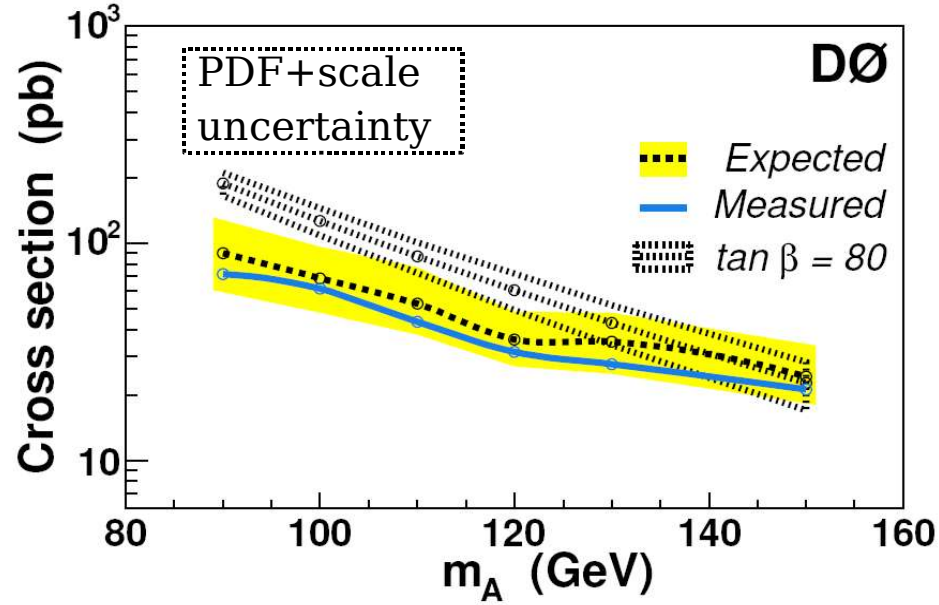
$X_t = A_t - \mu \cot\beta$, μ, M_g, M_q, etc.

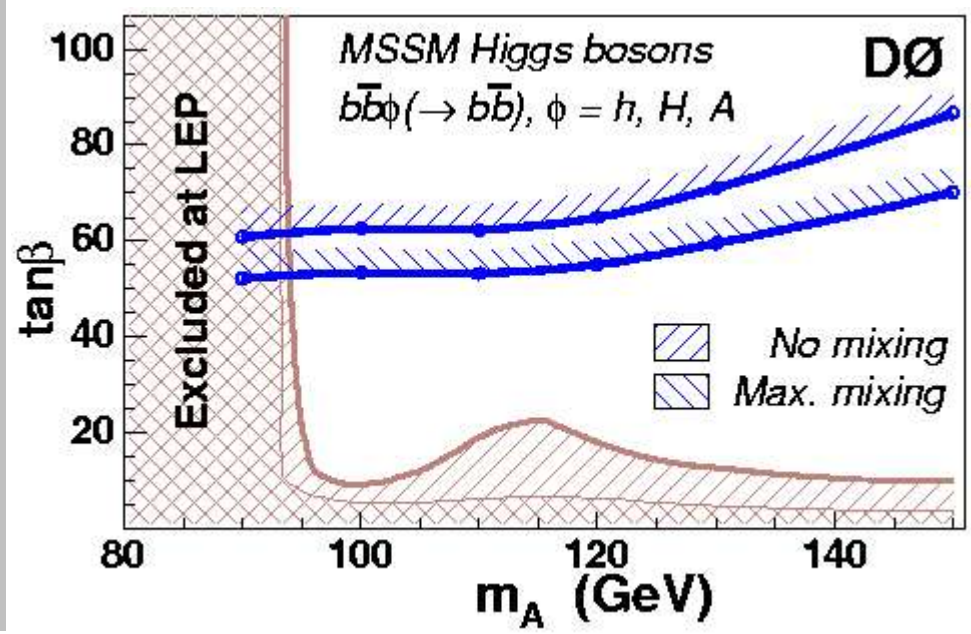
bbh(→bb) is more sensitive for $\mu<0$. But still is still sensitive to $\mu>0$.

Note: h(→$\tau\tau$) loses less sensitivity for $\mu>0$, since BR(h→$\tau\tau$) increases

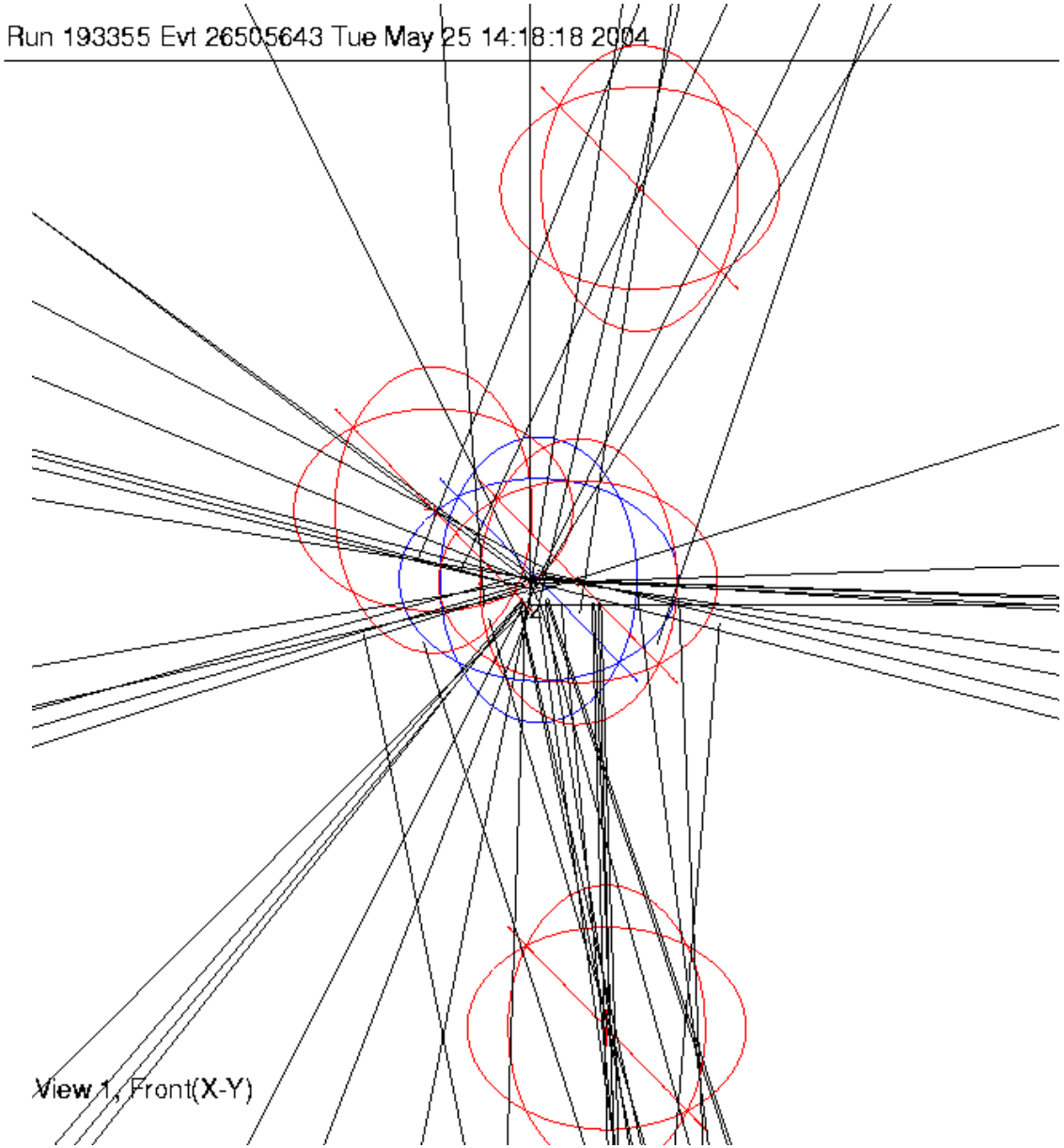
MSSM Limits

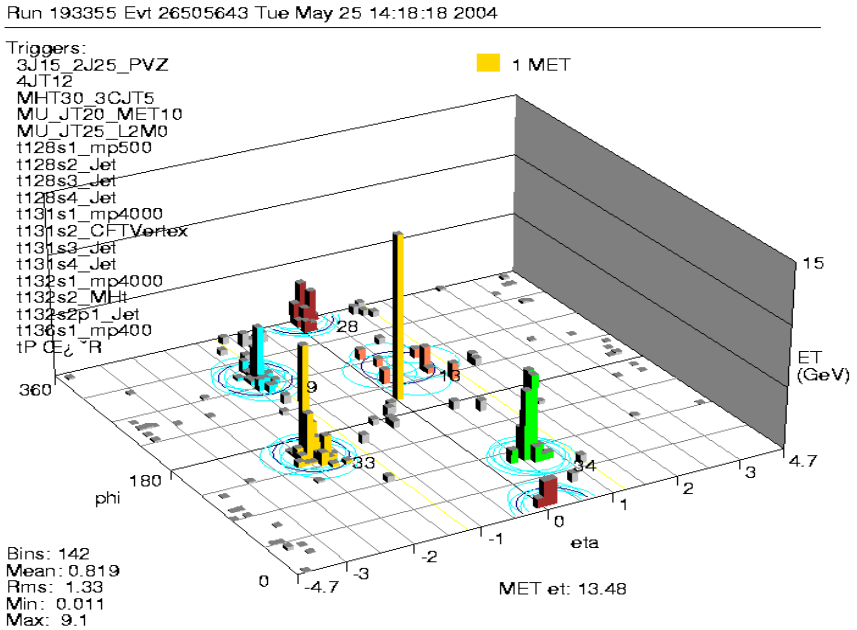
- Limits set using CL_S method (from LEP)
  - For each m_A, set a cross-section limit at 95% C.L.
- Cross-section uncertainties are calculated by varying the factorization / renormalization scales, and the PDF sets (CTEQ6)
- The current result excludes much more parameter space than our preliminary result from last year
  - Similar analysis, with more data
  - Much more rigorous
    - better reconstruction
    - improved theoretical understanding

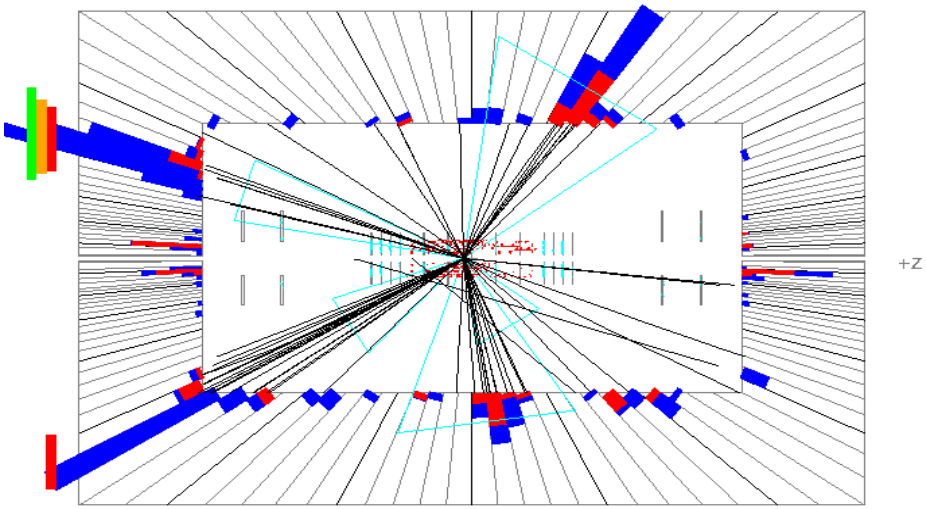




A Quadruple b-tagged Event

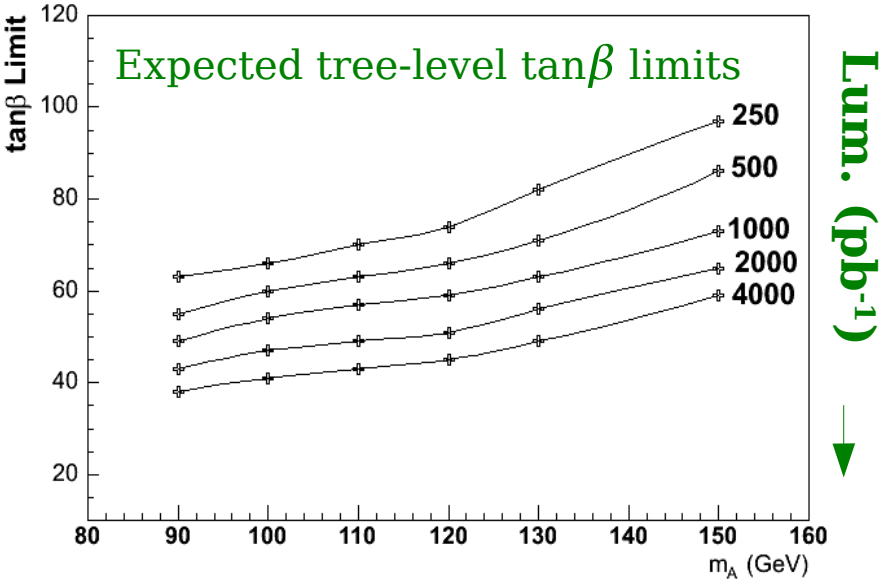






Future of the Analysis

- With no analysis improvements, expect to exclude down to tanβ=40 with 4fb^{-1}
- But we also look forward to a much improved analysis with next year's data set (1fb^{-1})
  - Inclusion of more triggers
  - Better calorimeter and jet energy calibration / resolution
  - Improved b-tagging
  - Use quadruple b-tagged events
  - Neural network?
- Combine with h($\rightarrow\tau\tau$) channels?
- Combine with CDF?

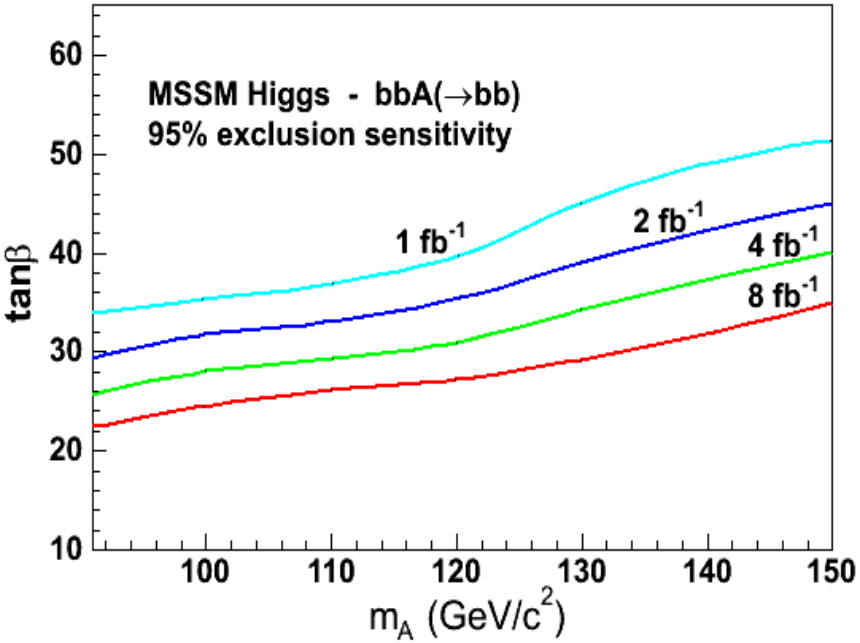


Improving the b-tagging

- This analysis is very sensitive to the b-tagging efficiency and the background tagging rate
- One obvious way to improve the b-tagging S/B is to use more information about the secondary vertex(es) in each jet
  - number of tracks on vertex
  - the χ^2
  - the “mass”
  - decay length significance
  - number of secondary vertices
  - … combine into neural network?
- Initial studies show large gains in performance are possible

Improved Expectations

- Use of a NN for b-tagging and addition of silicon "Layer 0" for Run IIb (this fall!)
  - About a 30% improvement in b-tagging efficiency at the same background rate
- Can also decrease the systematic uncertainties by a factor of ~2
  - More statistics for measuring b-tagging efficiency
  - Smaller jet energy scale uncertainty



Exclude down to tanB~25 for low m_A

Exclude up to m_A~200 GeV for tanB>~50

Some sensitivity up to m_A~300 GeV for very large tanB

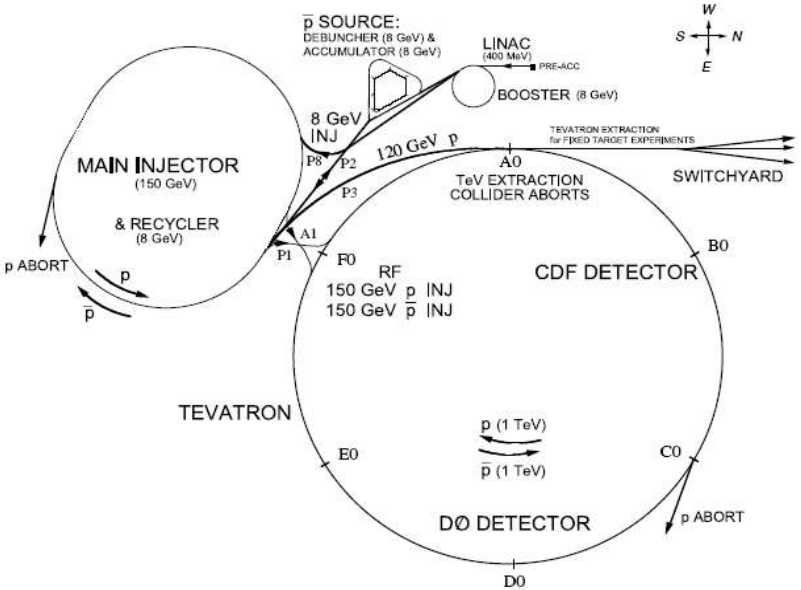
Conclusions

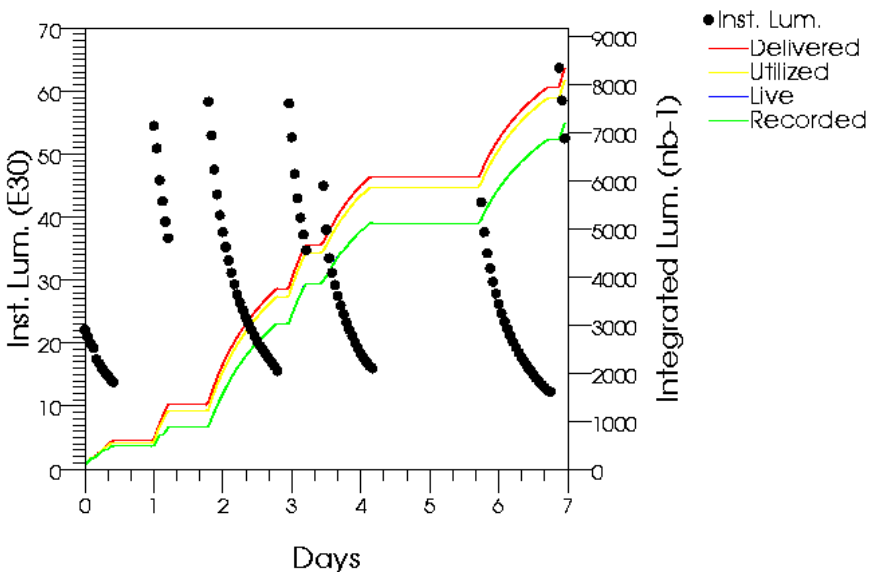
- A search has been completed for neutral Higgs bosons in the MSSM using 260 pb^{-1} of DØ Run II data
  - Good agreement between heavy-flavor multijet simulations and data
  - Solid theoretical understanding of the bbh production and decay
  - hep-ex/0504018 : submitted to PRL!
- Now that an initial analysis has been completed, we focus on improving it
  - Better b-tagging, advanced analysis techniques
  - New triggers / data – 1 fb^{-1} by this summer (now!), ~8 fb^{-1} by 2009!
- We hope to make a discovery, or place impressive limits on $\tan\beta$ vs. m_A in the next few years, while preparing for the LHC era
- Also, we are pursuing the tau channels: $h \rightarrow \tau\tau$ and $bbh(\rightarrow \tau\tau)$
  - Less loss of sensitivity for $\mu>0$, complimentary search
  - Would provide very interesting constraints on the MSSM parameters if both the b and tau decays could be measured

Backup slides...

Fermilab Tevatron Accelerator – Run II

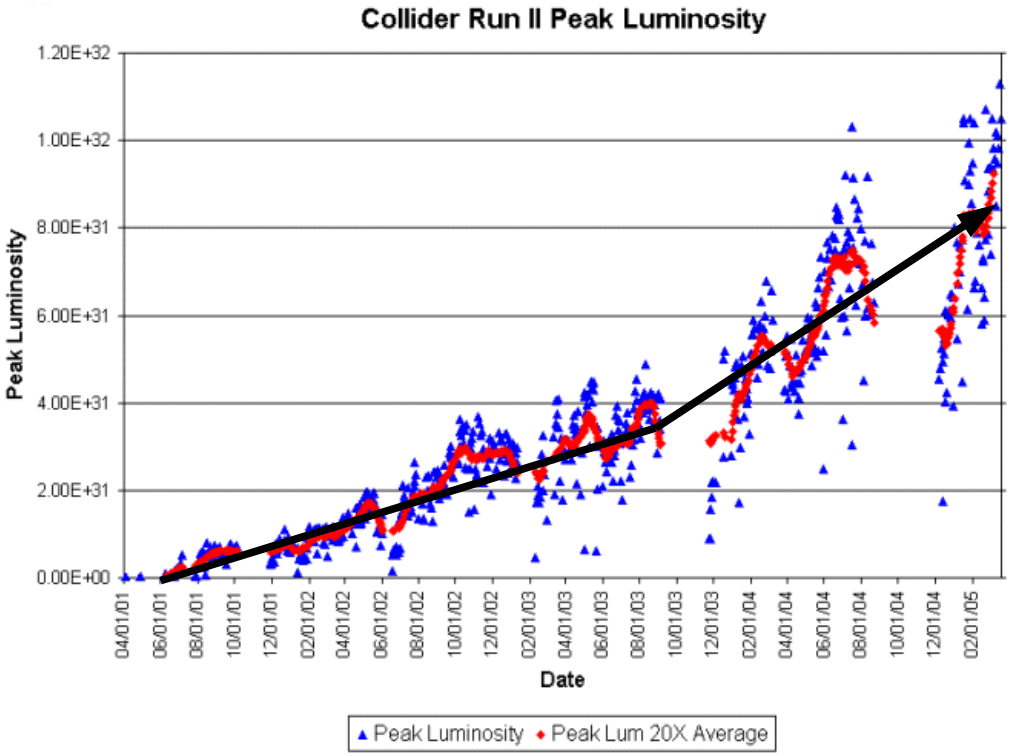
- 1 km radius p-pbar super-syncrotron
  - World's most powerful: 1.96 TeV
  - 36 bunches of p and pbar
  - 396 ns crossing period
  - 25 cm RMS interaction region
- One store every day or so...

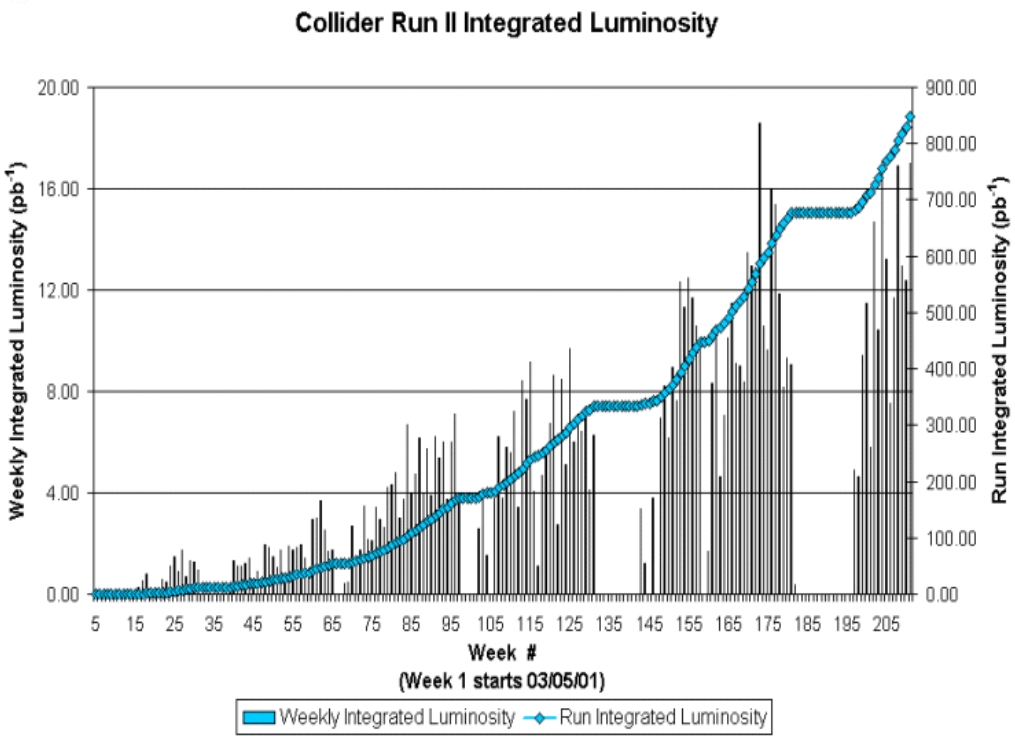




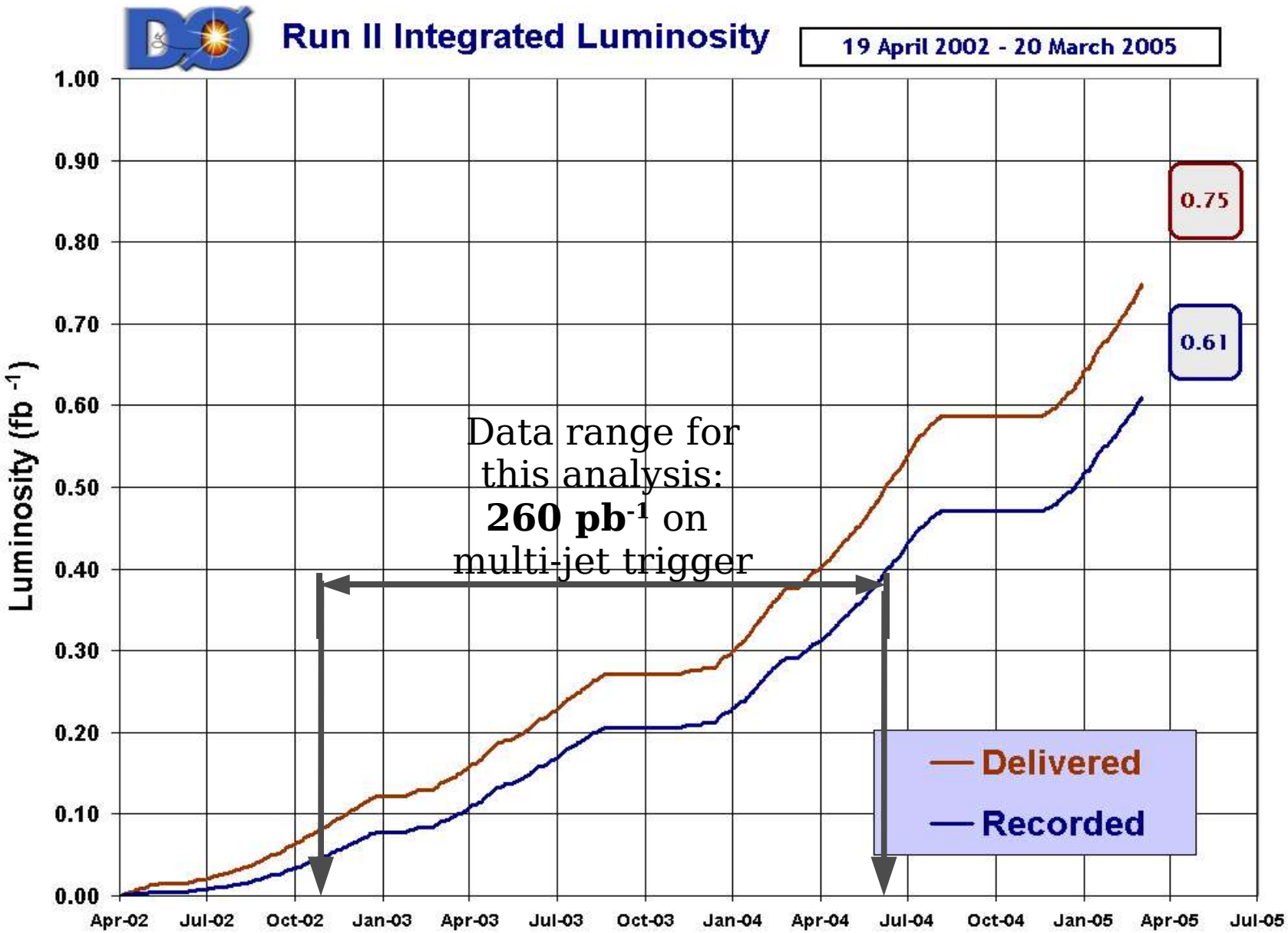
Tevatron Performance

- Run II began 4 years ago
- Instantaneous luminosity has steadily increased
- Last year was excellent, and this year is also right on track
- Almost 1 fb^{-1} delivered so far
- Should collect 4-8 fb^{-1} in the next few years

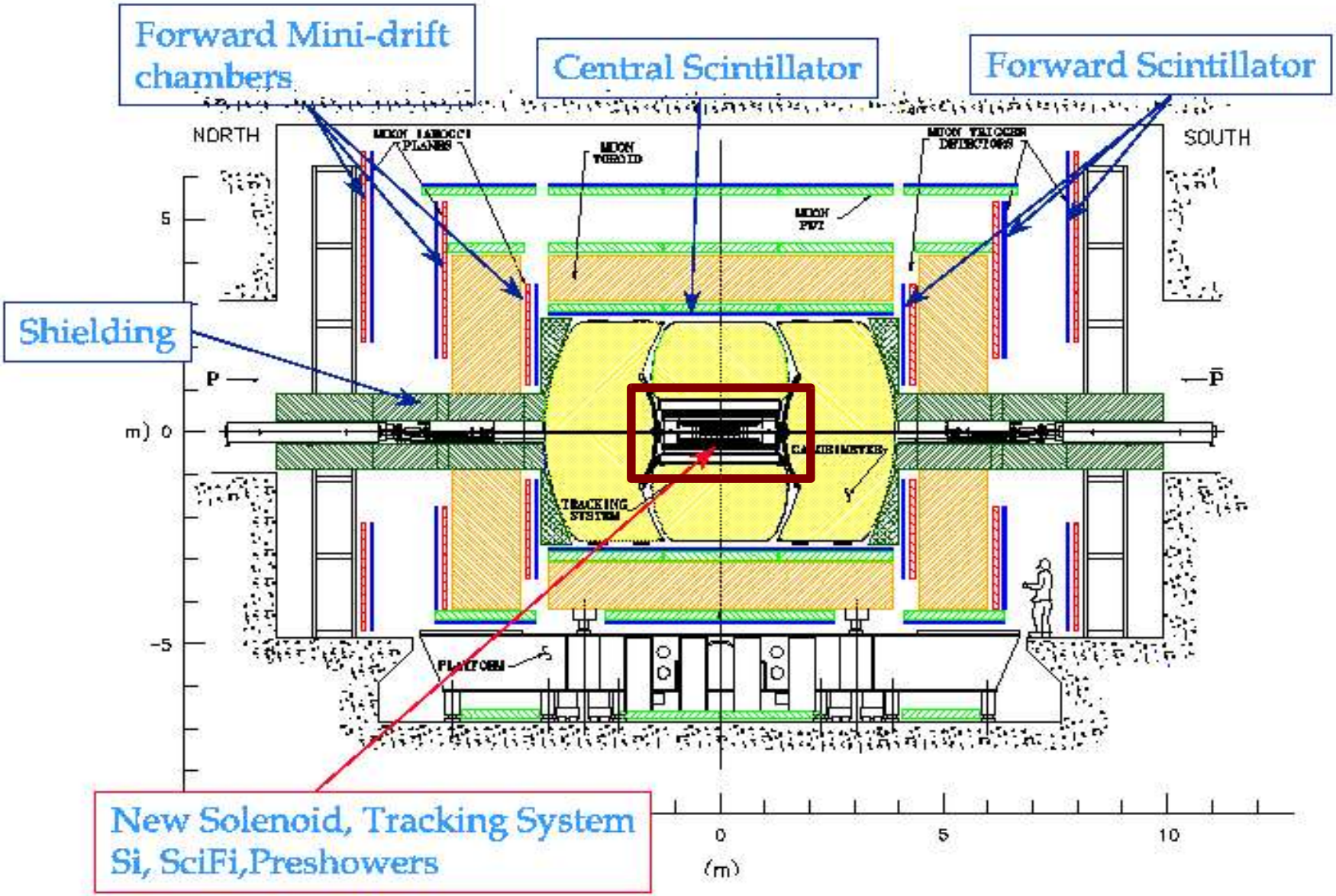




Current Detector Data / Efficiency

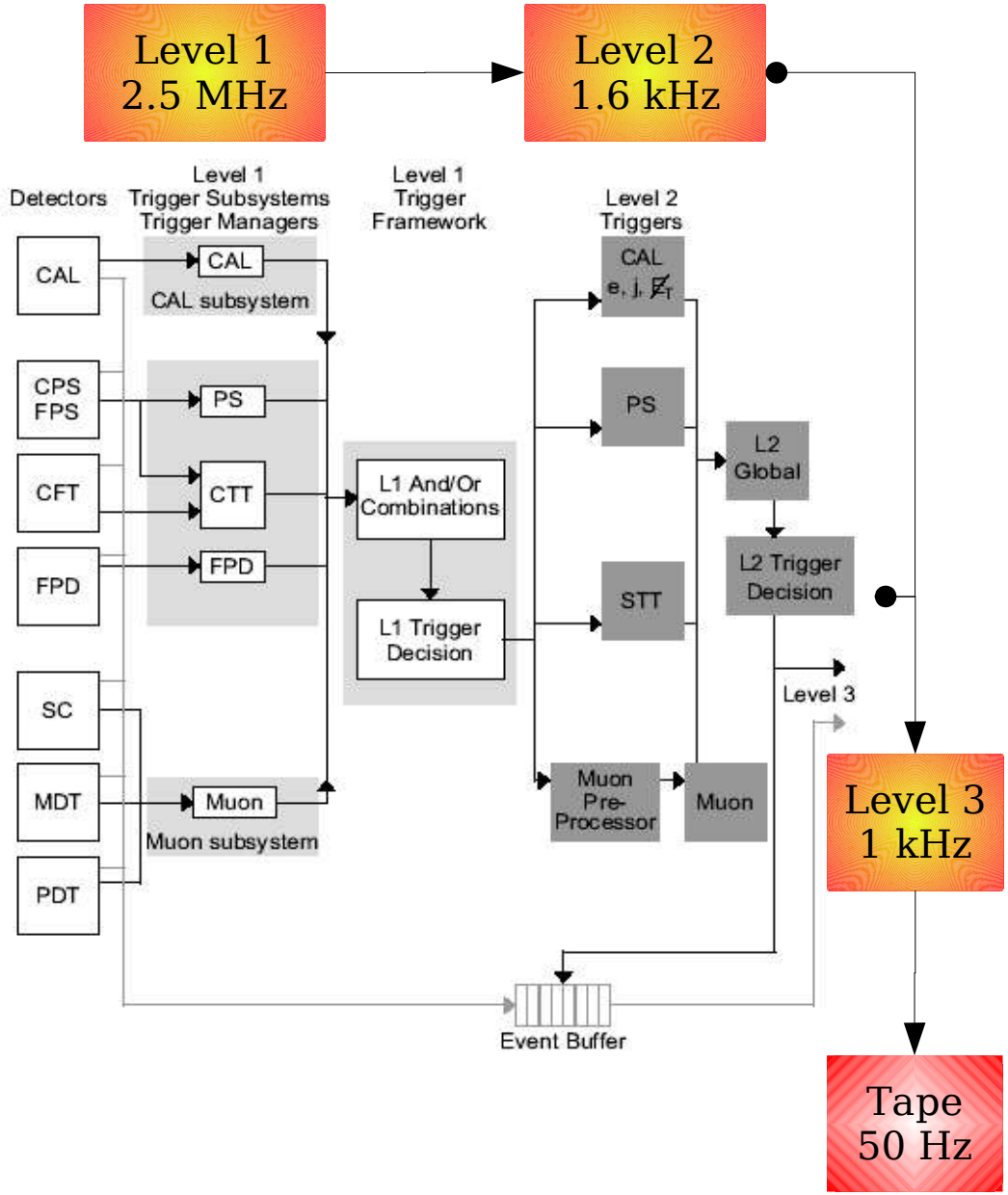


The DØ Detector for Run II

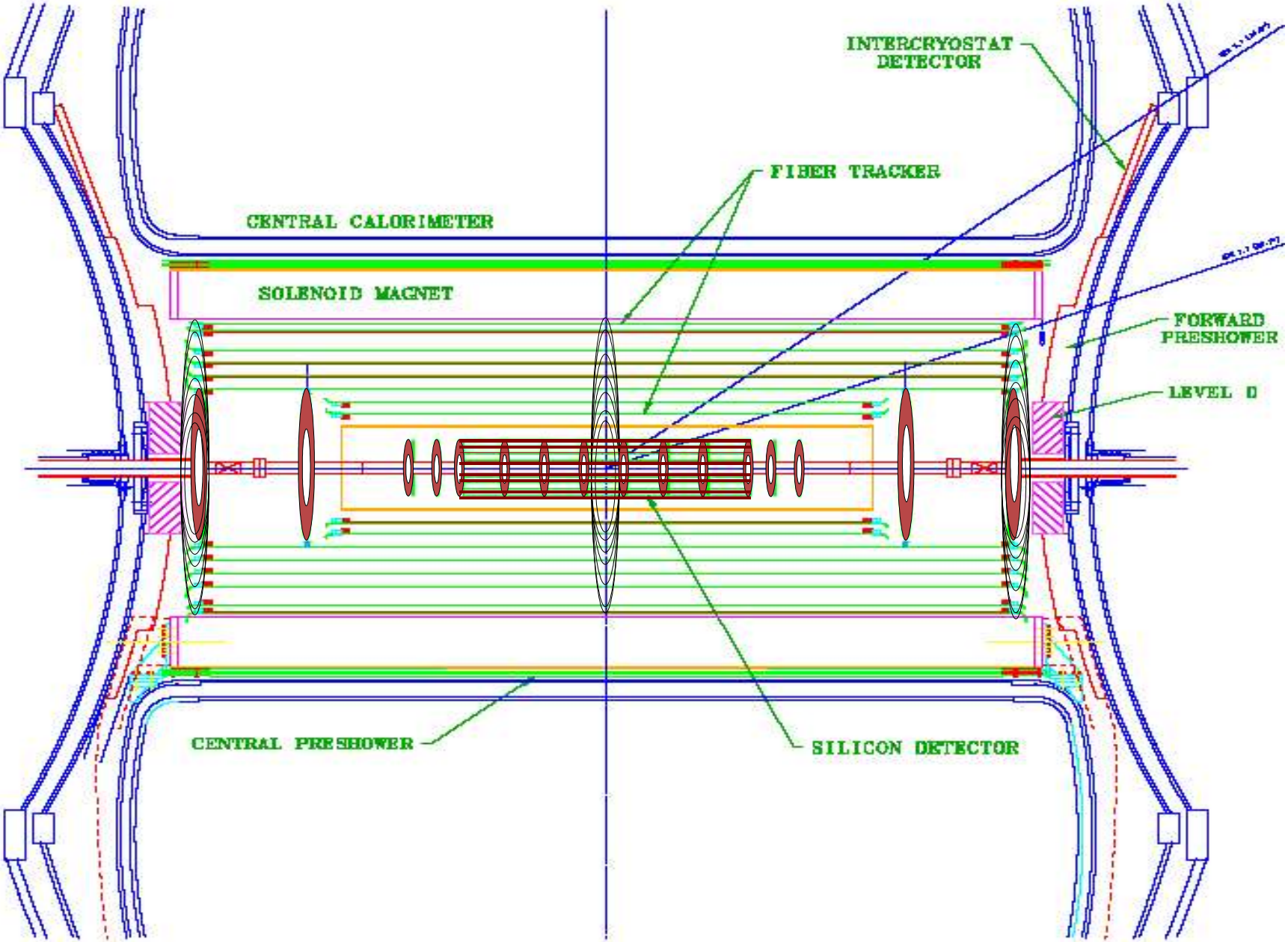


Trigger System

- Level 1
  - Calorimeter EM and TOT E_T (.2x.2)(η-ϕ)
  - Muon stubs
  - Central high-p_T axial tracks
- Level 2
  - Clustered calorimeter EM and TOT E_T
  - Missing transverse calorimeter E_T
  - Matched muon segments
  - Displaced high-p_T axial tracks
- Level 3 trigger algorithms:
  - Jets (no split/merge)
  - Central stereo tracks
  - Muons matched to central stereo tracks
  - Primary vertex
  - Jet lifetime b-tags



Tracking Systems



Cross-check Using Double b-tagged Data

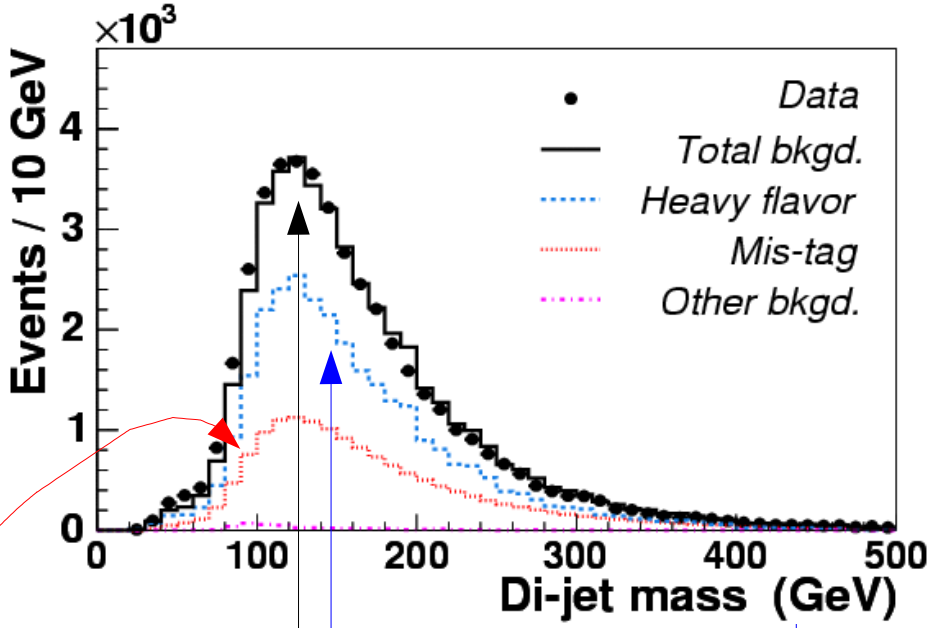
TRF is iteratively corrected for "heavy-flavor" in the un-b-tagged data sample

Full multi-jet data sample → Calculate TRF (E_T & 3 regions of η)

Full multi-jet data sample → Apply TRF to un-b-tagged jets → Double b-tagged background

Double b-tagged background ↔ Compare ↔ Double b-tagged data sample

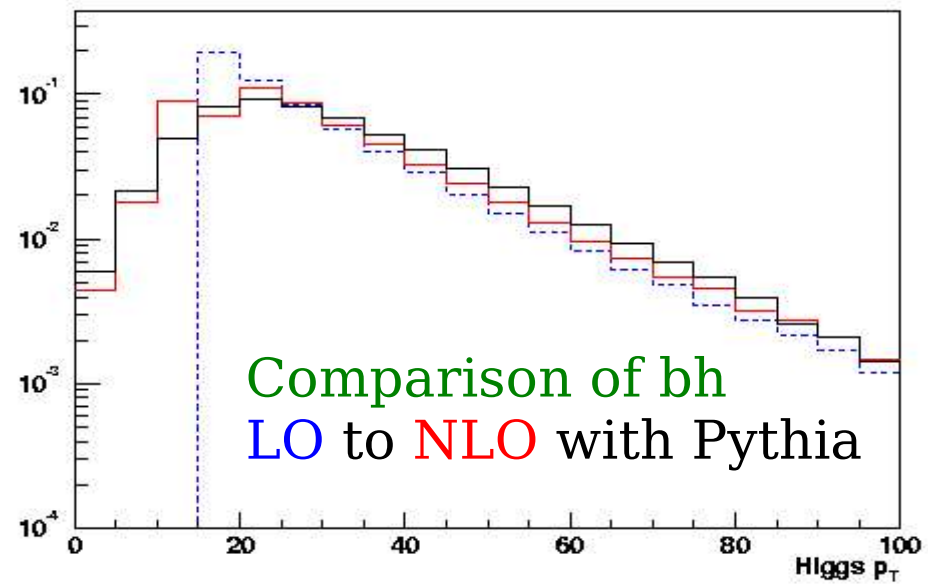
Double b-tagged data sample → Contribution from "heavy-flavor" MC

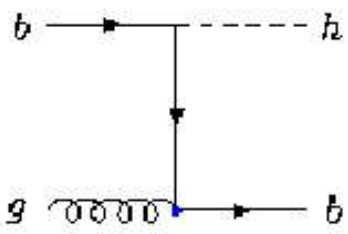


Good agreement in shape.
Normalization of "heavy-flavor" MC agrees to within 10%.

Monte Carlo Higgs Spectra

- Our Monte Carlo uses Pythia, which is semi-leading-order
- The events have been re-weighted, to mimic the NLO kinematics as closely as possible
- Comparisons of the bh and bbh processes are in good agreement





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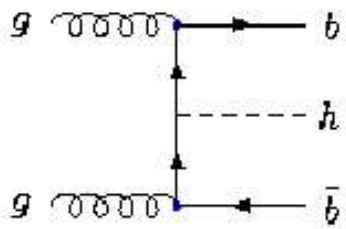
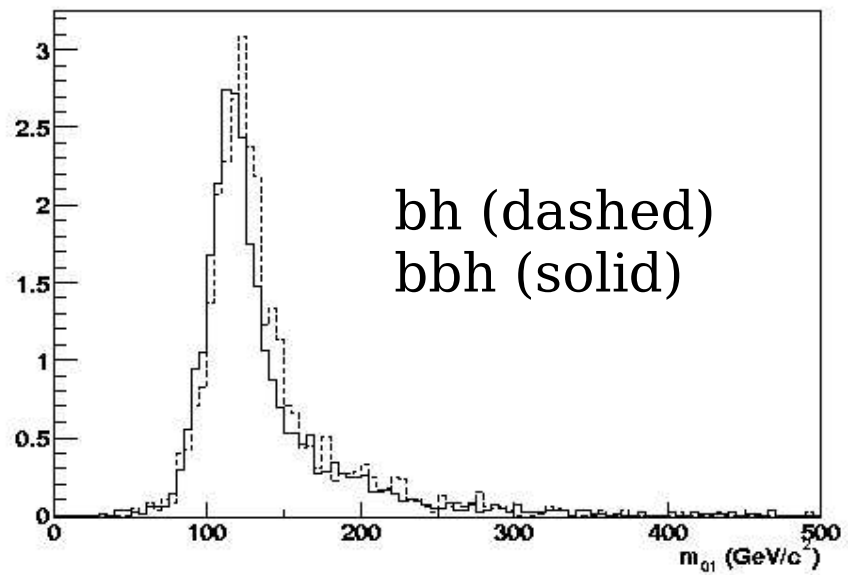
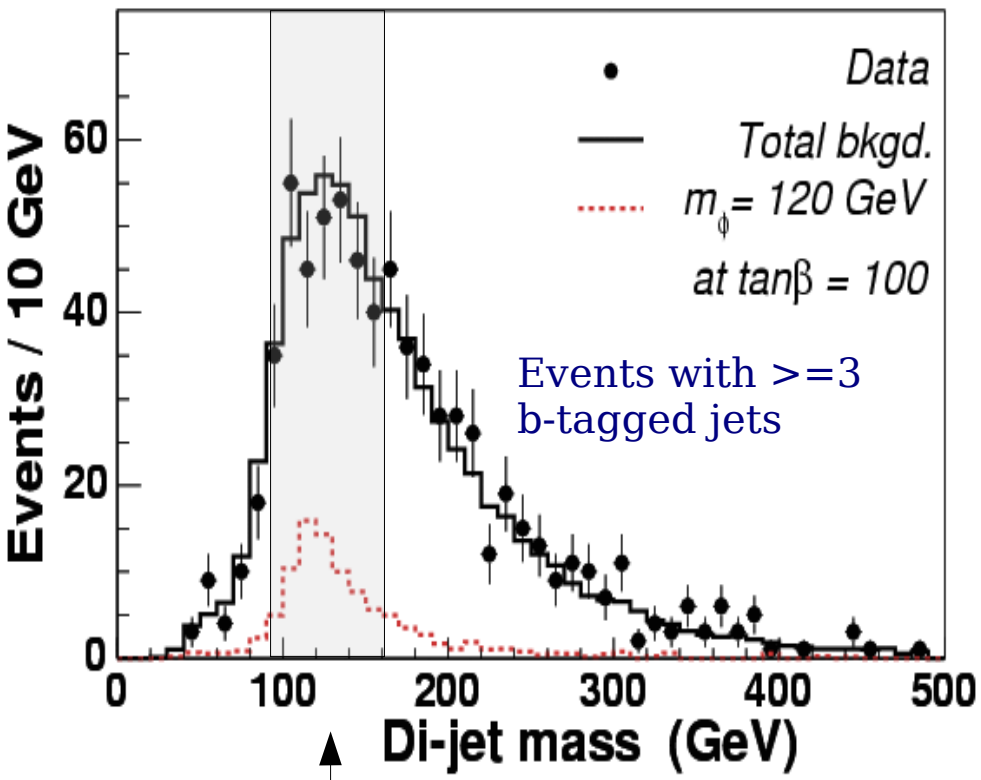


bbh



Systematic Uncertainties

- Signal efficiency uncertainties (total = 21%):
  - b-tagging efficiency (15%)
  - Trigger efficiency (9%)
  - Jet energy scale (8%)
  - Integrated luminosity (6.5%)
  - NLO kinematics (5%)
  - Jet reco/ID efficiency (4%)
  - Jet energy resolution (1%)
- Background shape / normalization uncertainties (total = 3%):
  - TRF shape (2%)
  - Statistics outside signal window (1%)
  - Width of signal window (1%)



"Signal window"