B-Tagging

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ATLAS-D Meeting
20.9.2007
DESY Zeuthen

Outline

- Motivation & Introduction
- Overview of the b-tagging algorithms and new developments
- Performance Issues
- Calibration on Data
- Summary & Outlook

All Results shown in this talk are preliminary!

Motivation

Why b-tagging?

- BR (t -> Wb) ≈ 1

  1 b-quark per top decay

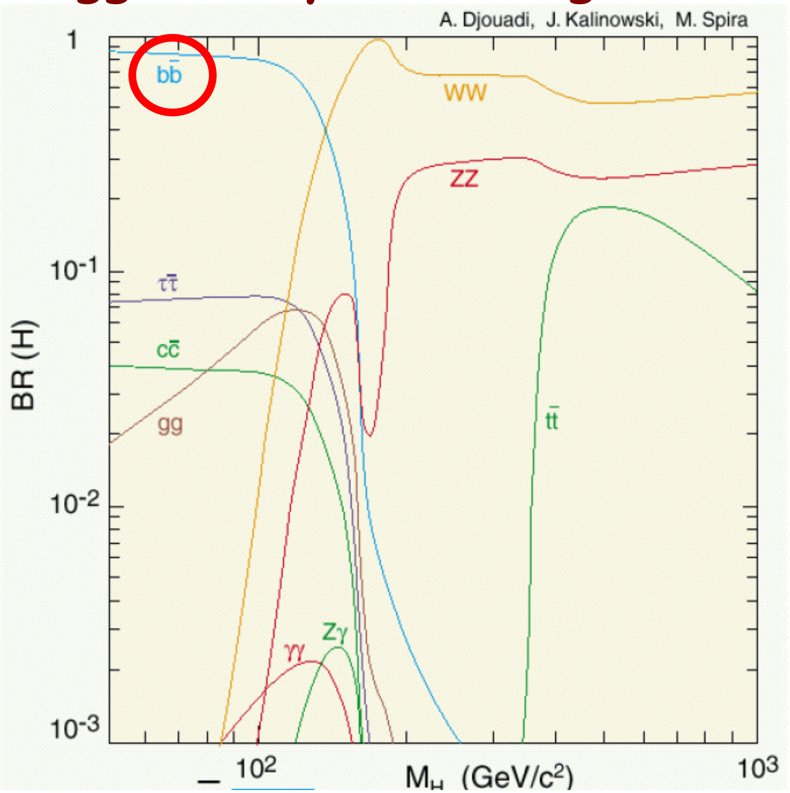
- SM Higgs boson:

  decay into bb favoured for light Higgs bosons ($m_H \leq 135$ GeV);

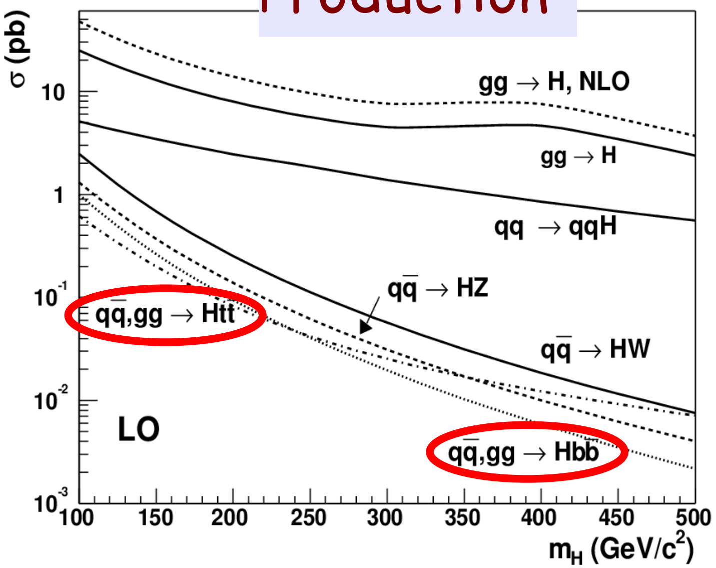
  additional b-quarks in associated production

- SUSY, ...

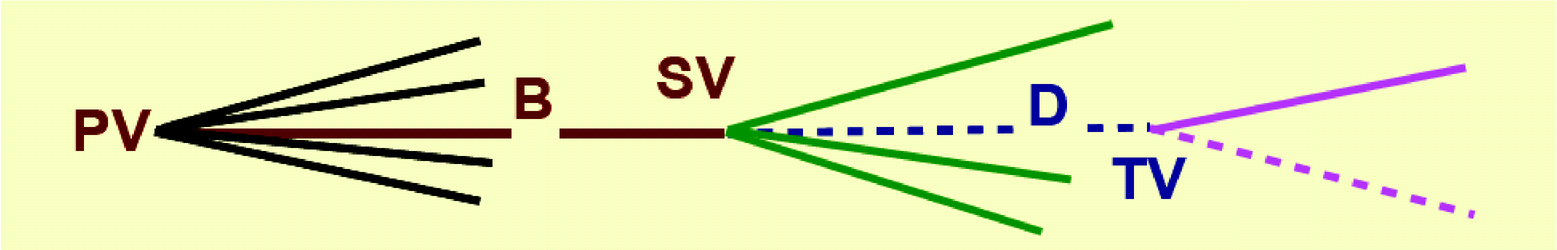
Higgs decay branching ratios



Production



B-Tagging Basics



Exploit (weak) decay and production properties of b-hadrons:

- **Lifetime of about 1.5 ps**
  -> secondary (tertiary) decay vertex; displaced tracks
  $c\tau \approx 450\ \mu m$: E(B)=50 GeV -> flight length ≈ 5 mm

- High mass and decay multiplicity

- Hard b-quark fragmentation function

- Decay kinematics (e.g. rapidities)

- Semi-leptonic decays (≈ 11% direct; ≈ 10% from c)

But: Similar for charm!

Track Impact Parameter

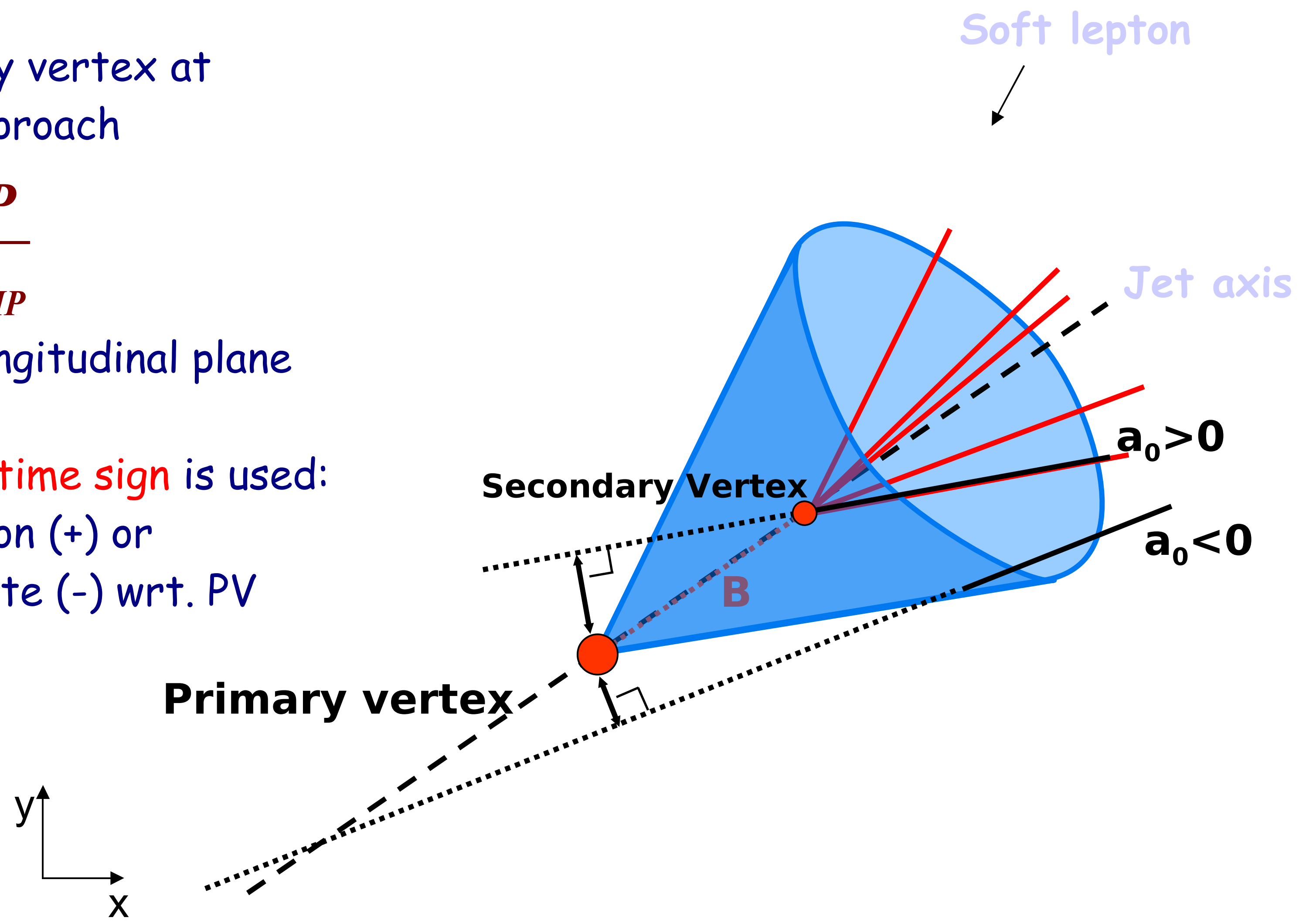
Impact parameter:

- distance to primary vertex at point of closest approach

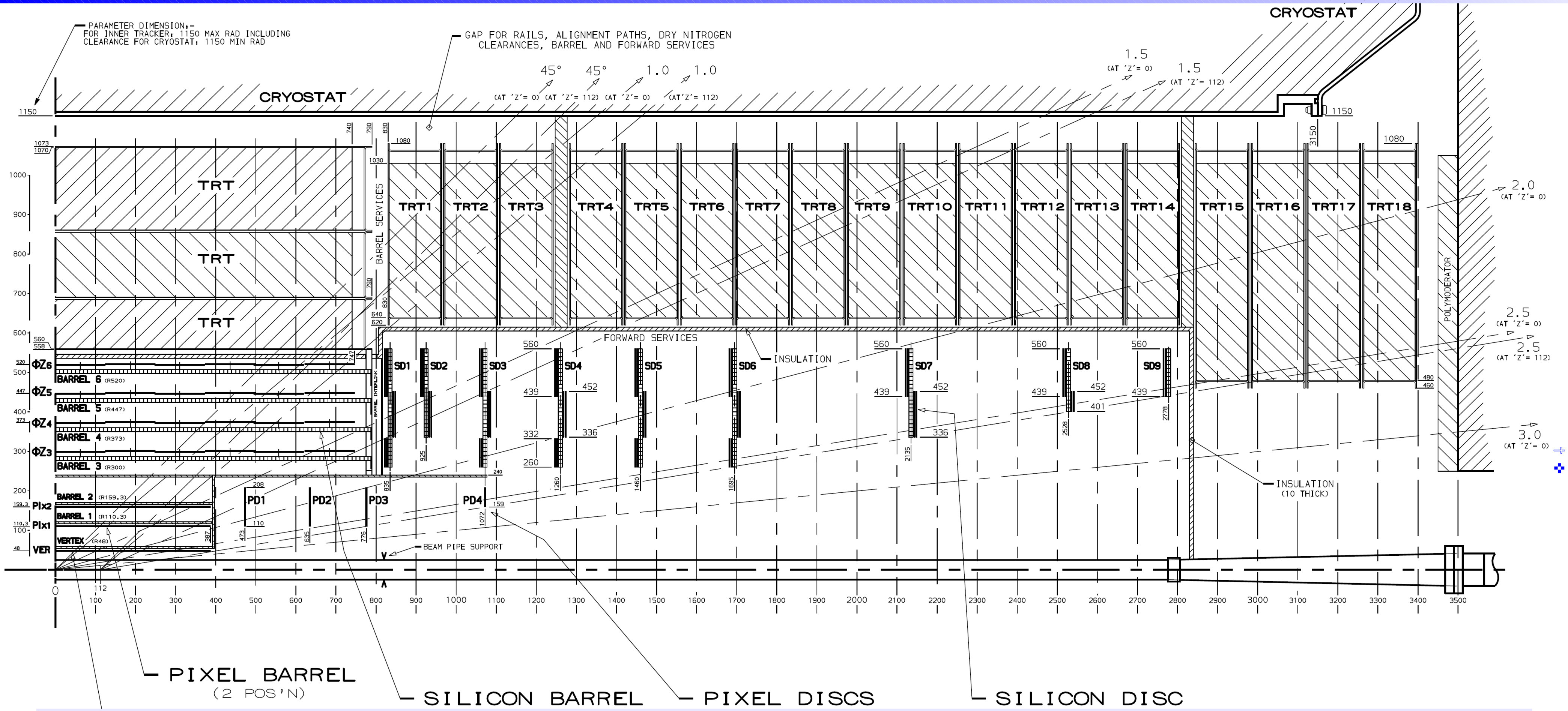
- IP significance: $\frac{IP}{\sigma_{IP}}$

- in transverse or longitudinal plane

- for b-tagging a lifetime sign is used: decay in jet direction (+) or opposite (-) wrt. PV



The ATLAS Tracking Detector



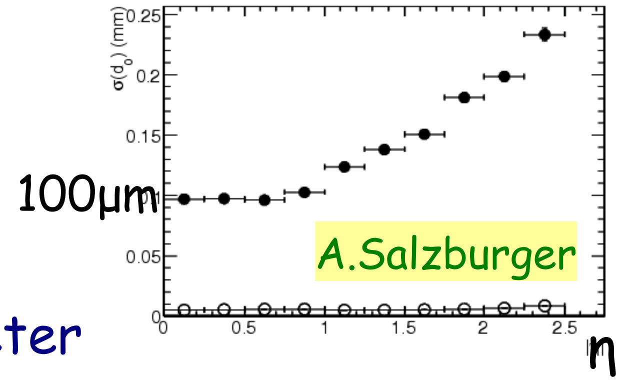
► Pixel detectors close to interaction point
pixel size 50 x 400 μm
first "b-layer" at r ≈ 5 cm

+ TRT (Transition Radiation Tracker)

► Silicon strip detectors
pitch: 80 μm (barrel)
strip length: 12 cm (barrel)
all layers double sided
(stereo angle 40 mrad)

Ingredients for B-Tagging

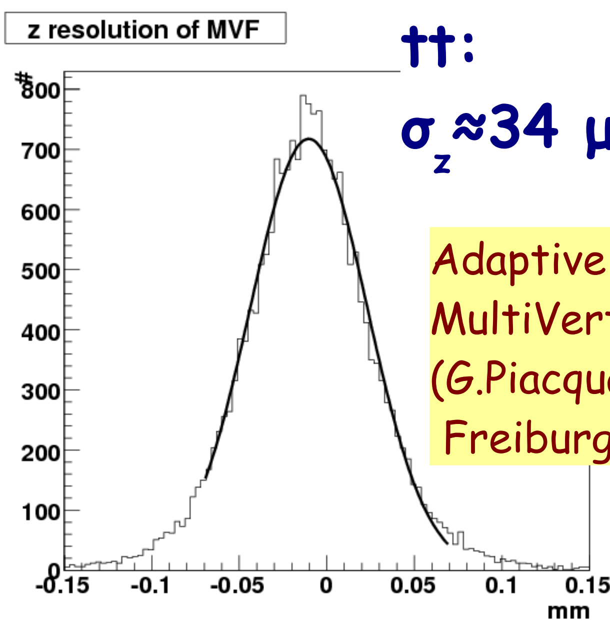
- **Tracks:**
  Impact parameter resolution!



- **Jets:** the objects to be (anti-)tagged!
  Direction: - (lifetime) sign of the track impact parameter
  - kinematical variables (e.g. lepton transverse momenta, rapidities)

- **Vertices:**
  Primary Vertex: (impact parameters, flight distances defined wrt. PV)
  - Find the signal vertex (Pile-Up)
  - Determine z-position

  Secondary vertex:
  (inclusive **vertex finding** and fitting in jets)
  - Good spatial resolution
  - High track association efficiency



tt:
$\sigma_z \approx 34$ μm

Adaptive MultiVertexFinder (G.Piacquadio, Freiburg)

Some Definitions

- Tagging efficiencies: $$\epsilon_q = \frac{Number\ of\ jets\ of\ flavour\ q\ tagged\ as\ b}{Number\ of\ jets\ of\ flavour\ q}$$

- Rejection: $1/\varepsilon_{light}$

- Typical cuts: $E_t^{jet} > 15$ GeV, $|\eta| < 2.5$

- Cone based track to jet assignment: $\Delta R < 0.4$

"True" jet flavour: (sometimes "purified")

- match to "final state" partons (after showering, radiation)
- label in the following order:

  if there is a b quark (pt > 5 GeV) within the jet cone: label as b

  c … c

  tau … tau

  else: u

Algorithms

The following b-tagging algorithms are available in ATLAS
(not the complete list; the most commonly used ones!):

- Lifetime I: Impact parameter based
  - IP2D
  - IP3D
  - JetProb

- Lifetime II: Secondary vertex based
  - SV1, SV2
  - JetFitter **NEW!**

+ combinations with IP based, typically SV1/2 + IP3D, JetFitter + IP3D

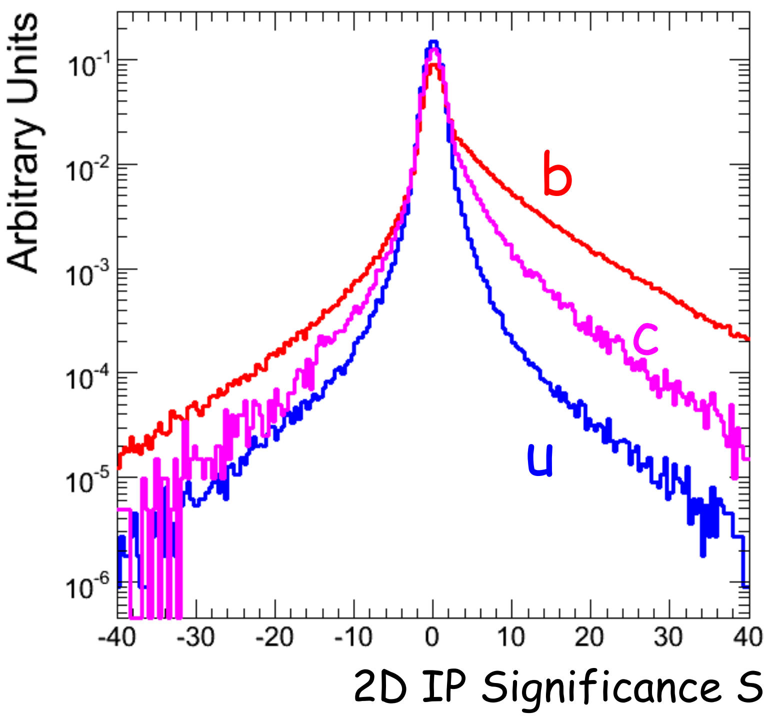
- Semileptonic decay: Soft lepton tags (μ and e)

Impact Parameter Based Algorithms

The standard methods: **"IP2D", "IP3D"**

Combination of track impact parameters using a Likelihood ratio method

3D: transverse and longitudinal impact parameter treated separately
(but combination uses 2-dim. PDF to take into account correlations)

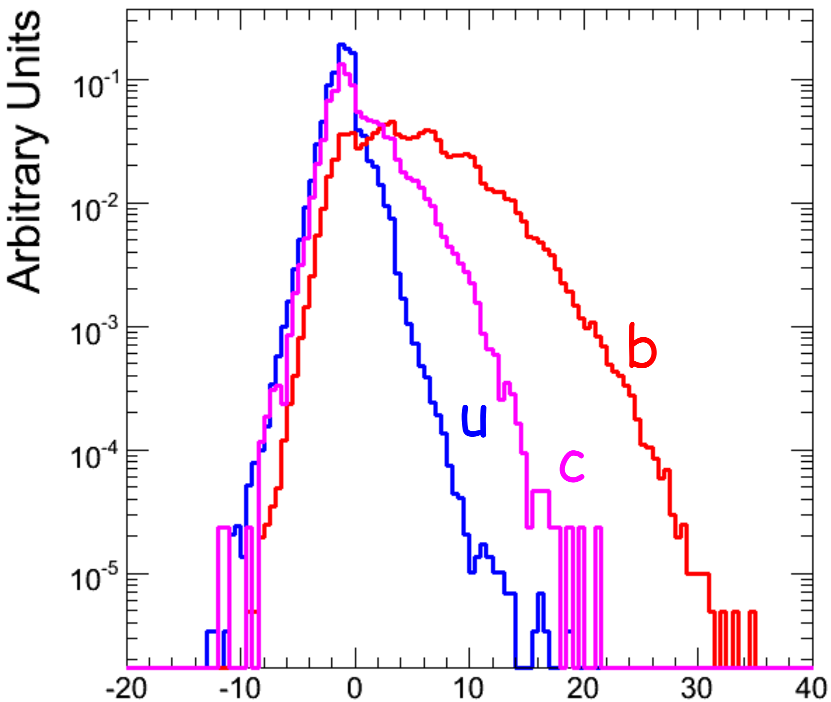


Track weight:

b(S)/u(S)

Jet weight:

$$W_{jet} = \sum_{i=1}^{N_{tr}} \ln \frac{b(S_i)}{u(S_i)}$$

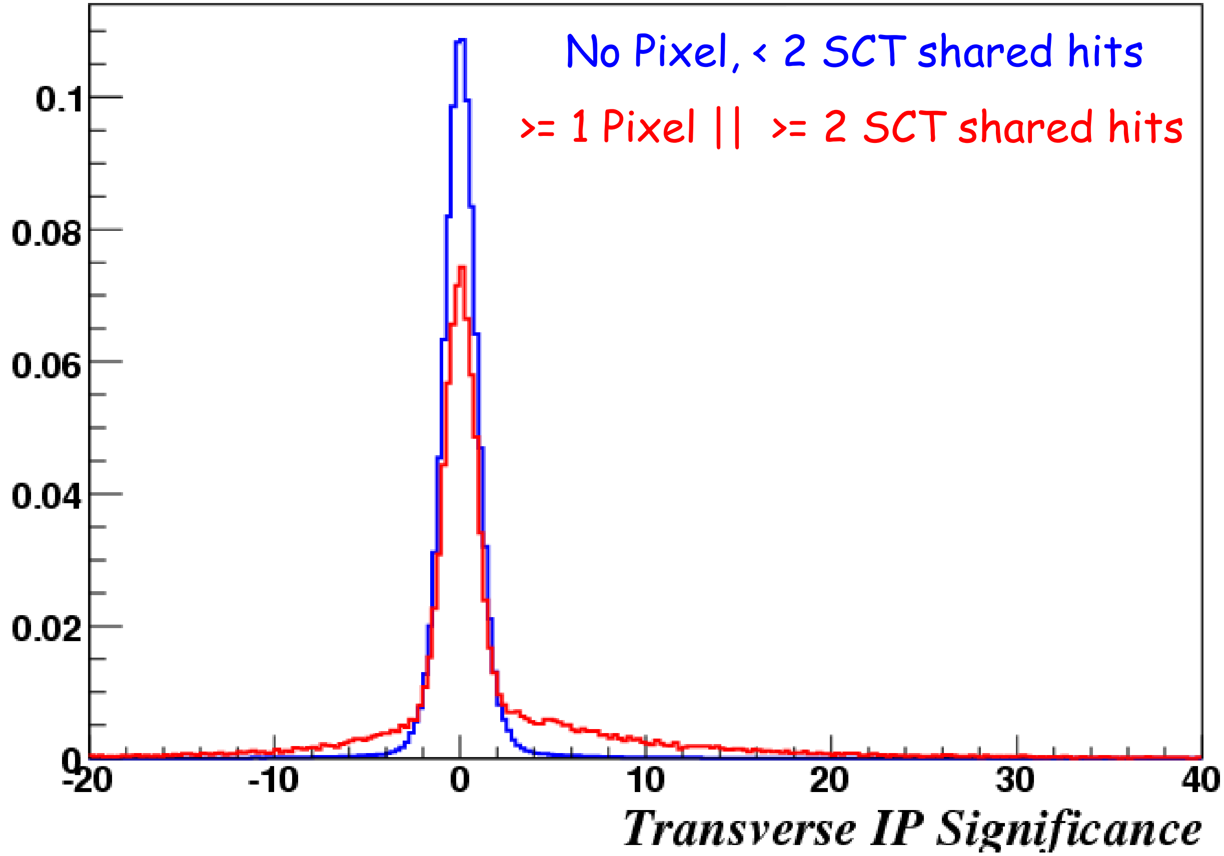


Track Categories

Crucial: Track selection and categorisation!

Currently, two sets of PDFs are used for tracks w/wo shared hits or ambiguities

More track categories to come (contributions from Bonn, Dresden)



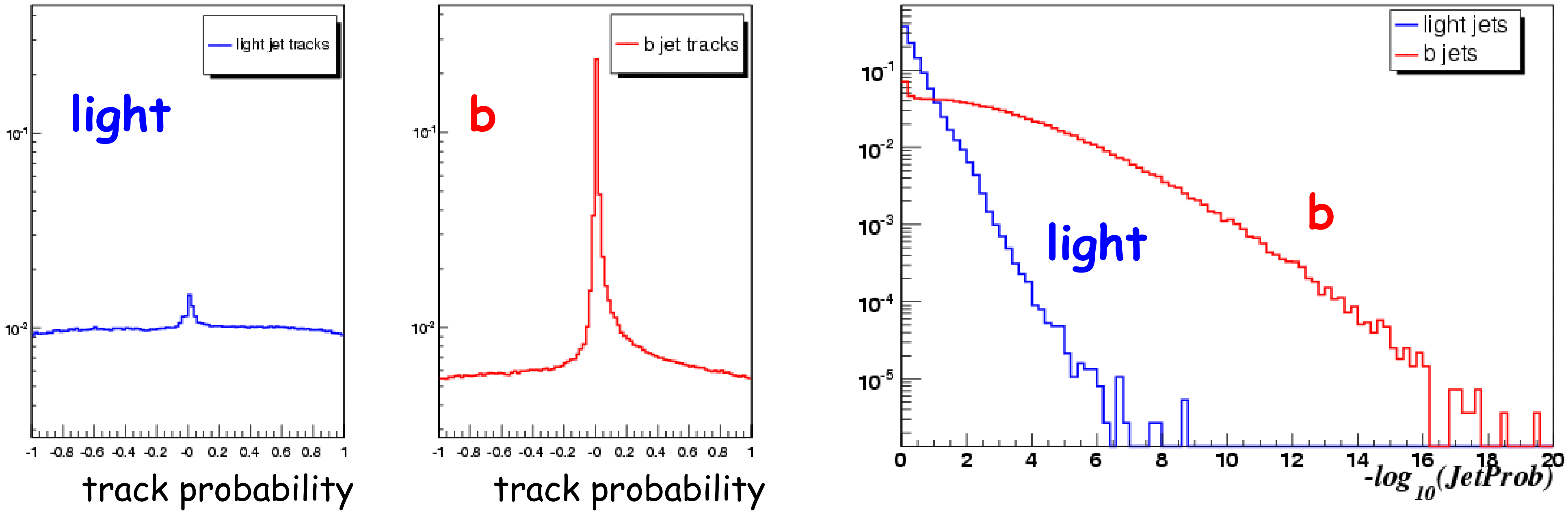
The "classical" LEP Method

"IP2D", "IP3D" require PDFs for both "signal" and "background"
-> b-jet PDFs not as easy to get as light jet PDFs from data

-> "JetProb" method: only needs IP resolution of tracks from PV
-> easier to calibrate on data

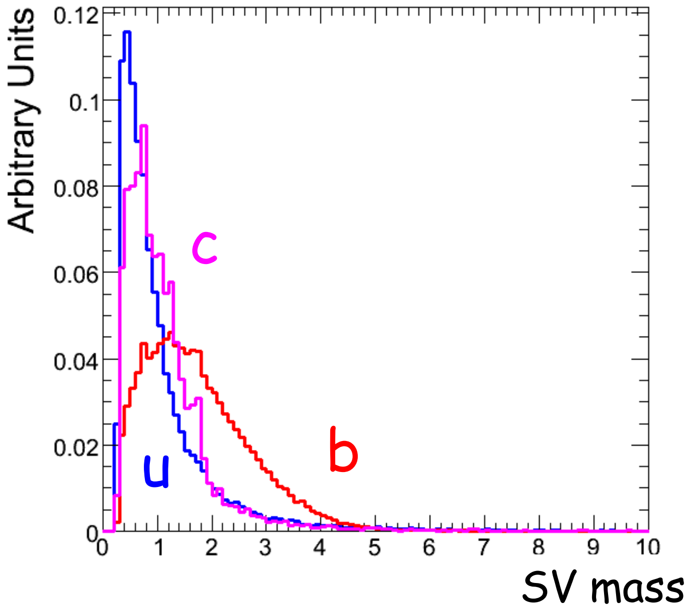
Not reaching the performance of IP2D, IP3D
(but less effort spent in optimisation etc.)

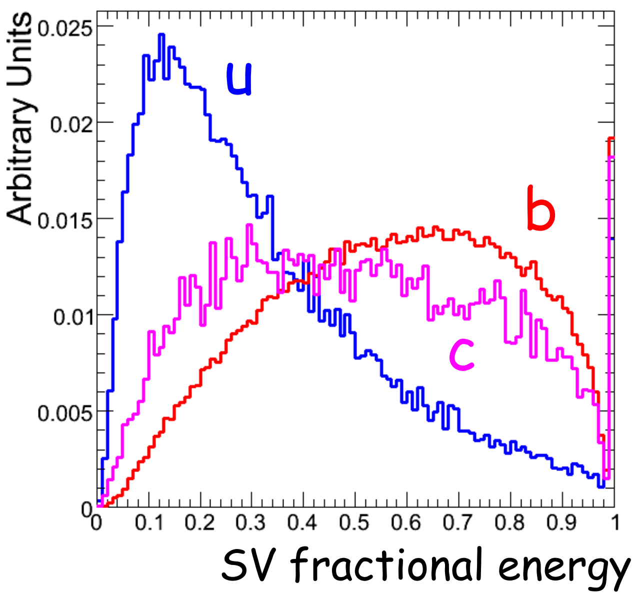
$$P_{jet} = \Pi \cdot \sum_{j=0}^{N_{tr}-1} \frac{(-\ln \Pi)^j}{j!}, \quad \Pi = \prod_{i=1}^{N_{tr}} P_{tr_i}$$

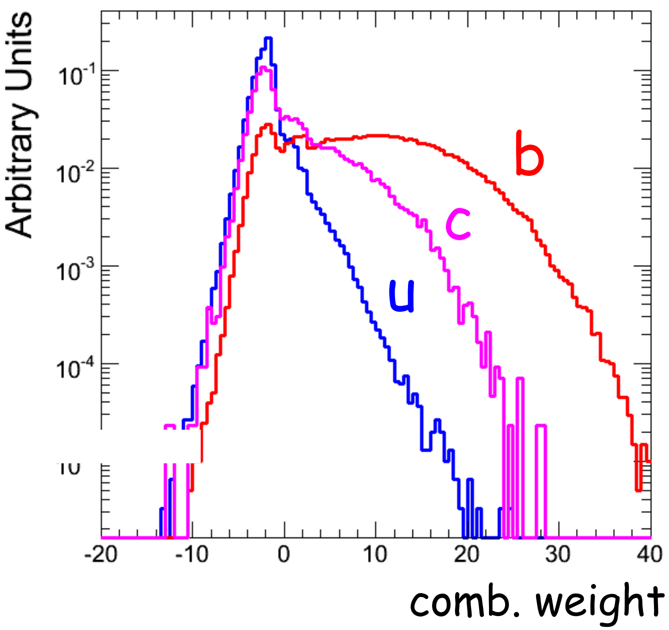


Secondary Vertex Based Taggers

"Classical" vertex reconstruction







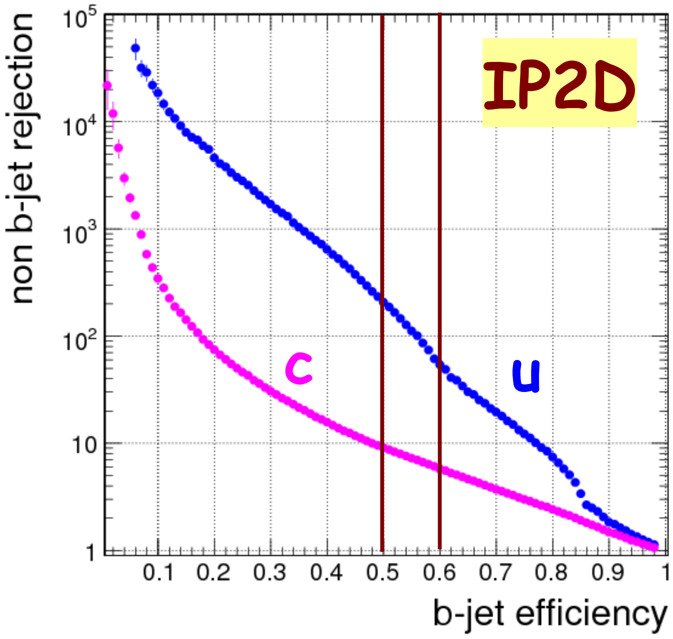
+ number of 2-track vertices

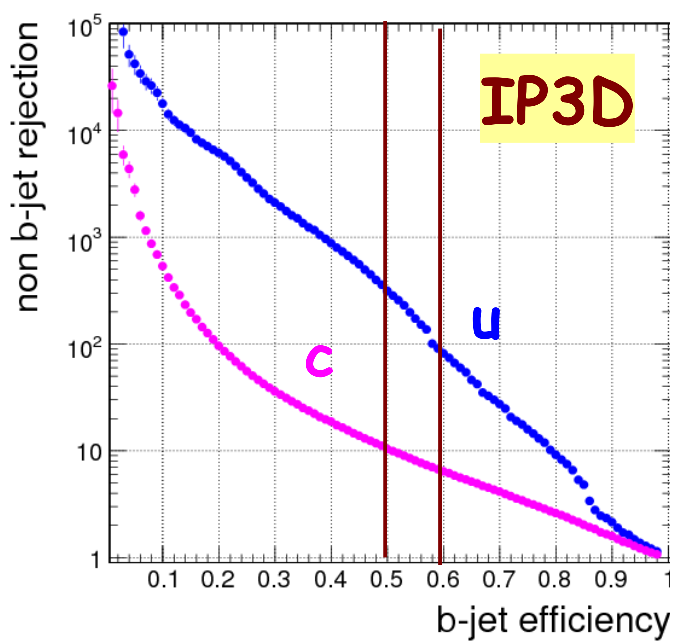
"SV1" uses 2D PDF for mass & efrac + 1D for 2-track vertices

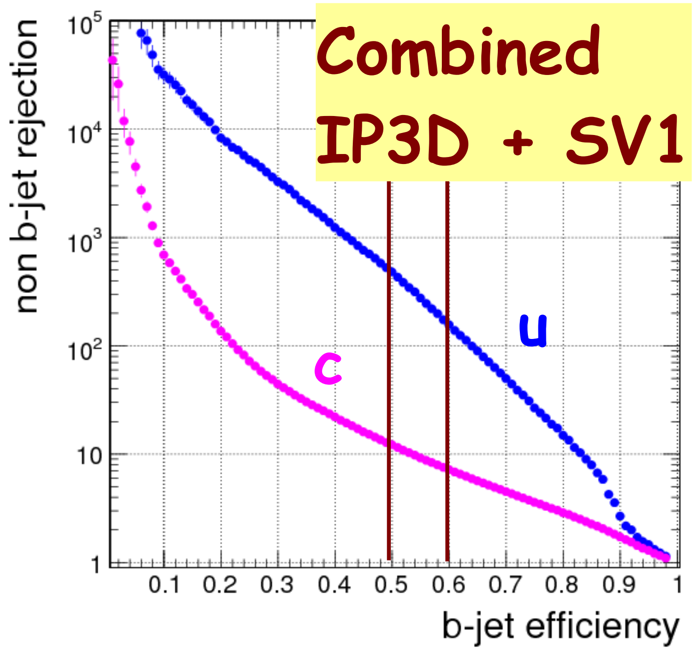
Combination with IP3D:

$$W_{jet\ comb.} = W_{jet,IP3D} + W_{SV1/2} = W_{jet,IP3D} + \sum_{i=1}^{3} \ln \frac{b(x_i^{SV})}{u(x_i^{SV})}$$

Performance







tt
Athena 12.0.6
"non-purified" jet label
no Pile-Up

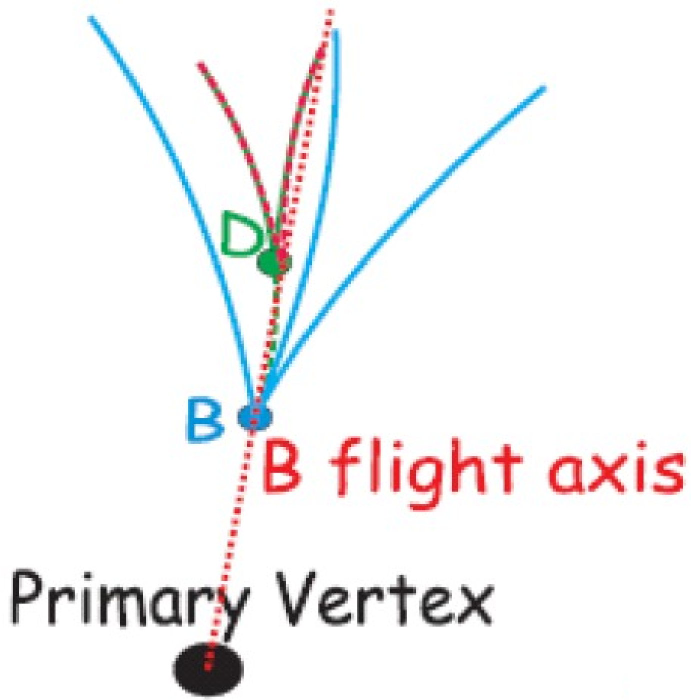
Light/charm jet rejection at 50% / 60% b-efficiency:

	ε_b = 50%	ε_b = 60%
IP2D	**206 / 9.1**	**54 / 5.8**
IP3D	**314 / 10.4**	**81 / 6.4**
IP3D + SV1	**479 / 12.1**	**156 / 7.2**

A New Approach: JetFitter

G.Piacquadio, CW (Freiburg)

Drawbacks of "conventional" methods:
- Hypothesis of a single geometrical vertex not correct (only in few cases secondary/tertiary vertices are resolved)
- Some topologies (e.g. 1-1) difficult to access



b and c vertices approximately on same line of flight

-> intersect b-hadron flight direction with tracks

(principle used by SLD in "ghost track" algorithm)

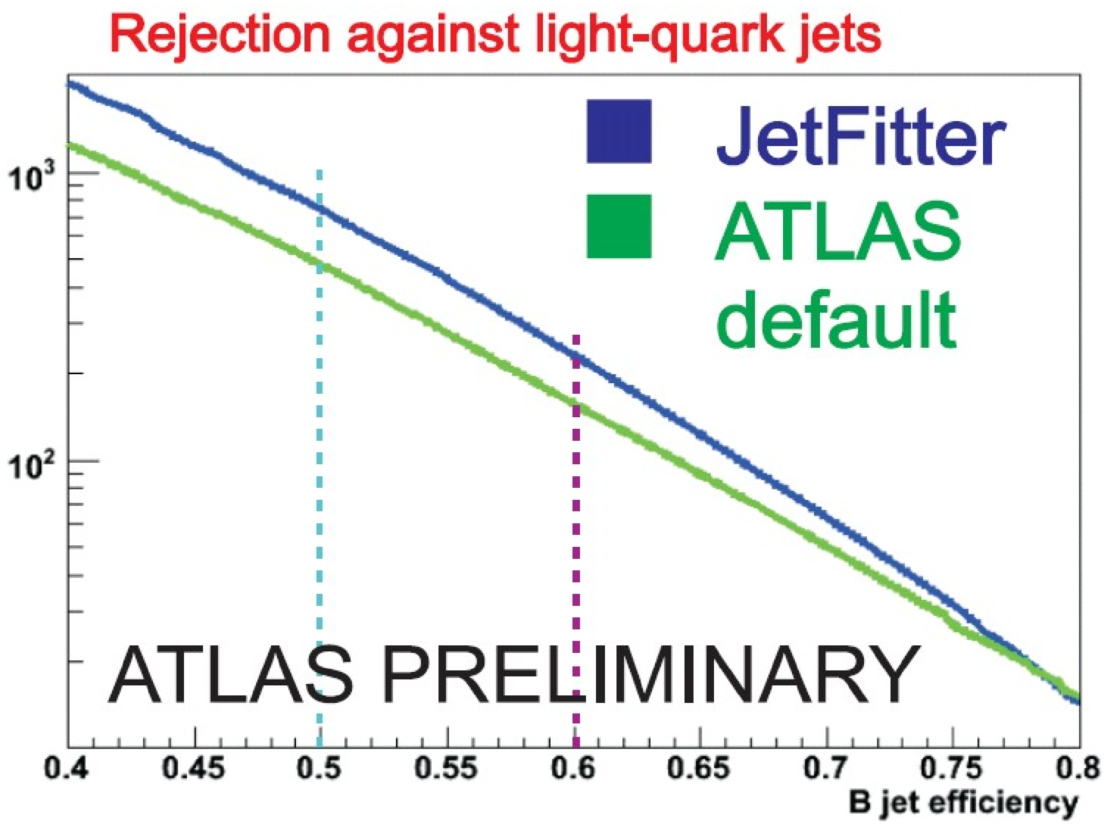
JetFitter
first Kalman filter based implementation

available since Rel. 13.0.20

JetFitter (II)

Likelihood discriminator based on topology coefficients and other variables (charged SV mass, charged energy fraction at SV, flight length sign.)

$$L(x) = \sum_{\{cat\}} coeff(cat) \cdot P_{\{cat\}}(mass) \cdot P_{\{cat\}}(en.Fract.) \cdot P_{\{cat\}}\left(\frac{\sigma(d)}{d}\right)$$



Rejection against light-quark jets

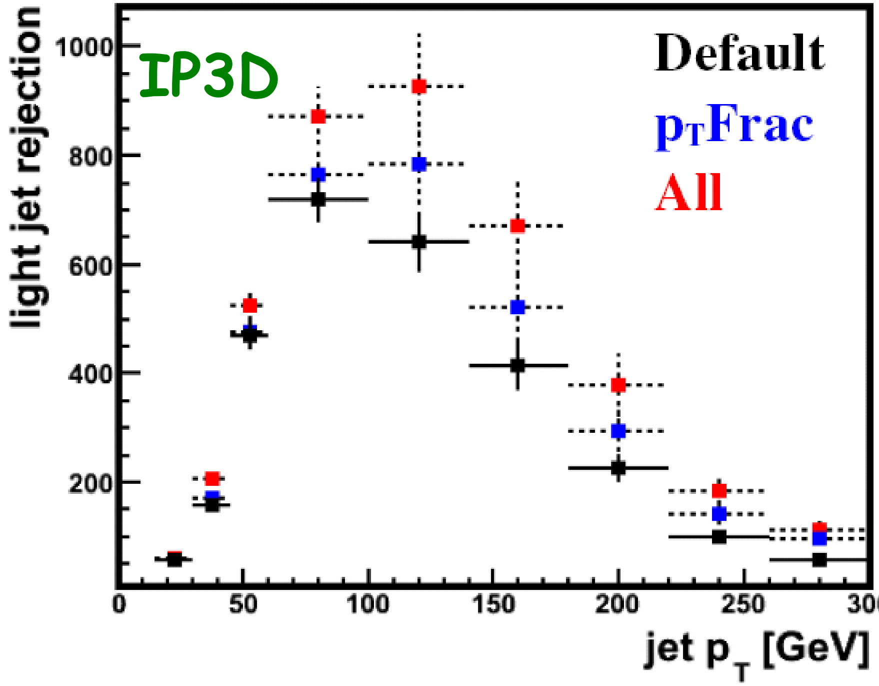
B-jet efficiency	default	JetFitter
50%	477±9	765±18 (+60%)
60%	156±2	228±3 (+45%)

other ongoing activity:
"Topological Vertex Finder"
(T.Lenz, Wuppertal)

Further Improvements

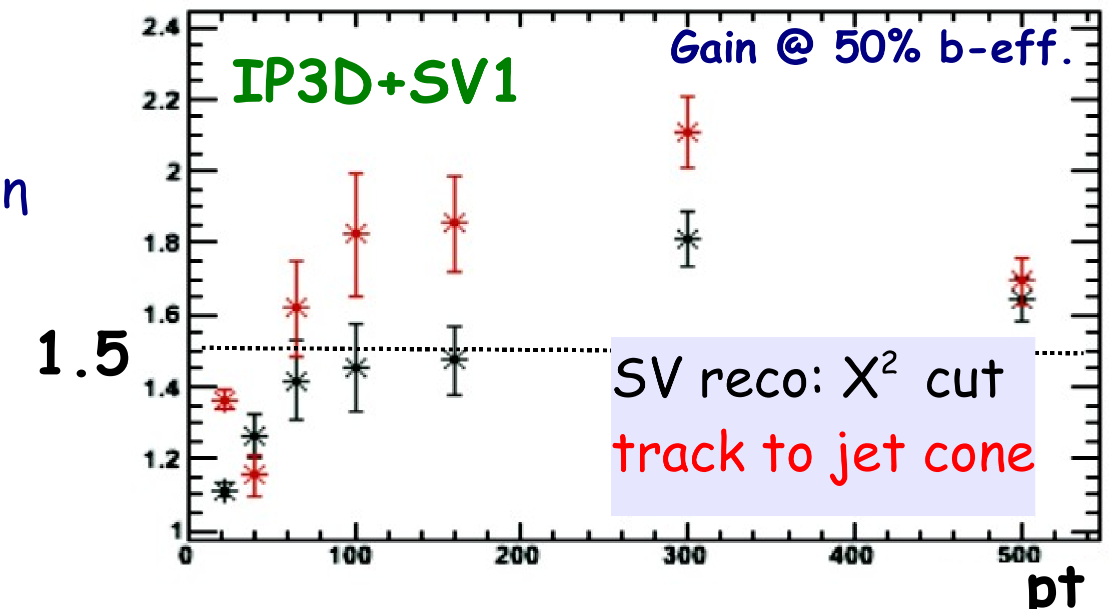
Understand tracks in detail, categories:

- Define additional track categories for b/u PDFs
  - M.Lehmacher (Bonn),
  - Th.Göpfert(Dresden)



Tuning algorithm parameters:

- Cuts, associations depending on pt,η
  - S.Lai (Freiburg)



Soft Lepton Tagging Algorithms

A-priori limited efficiency because of semi-leptonic branching ratio:

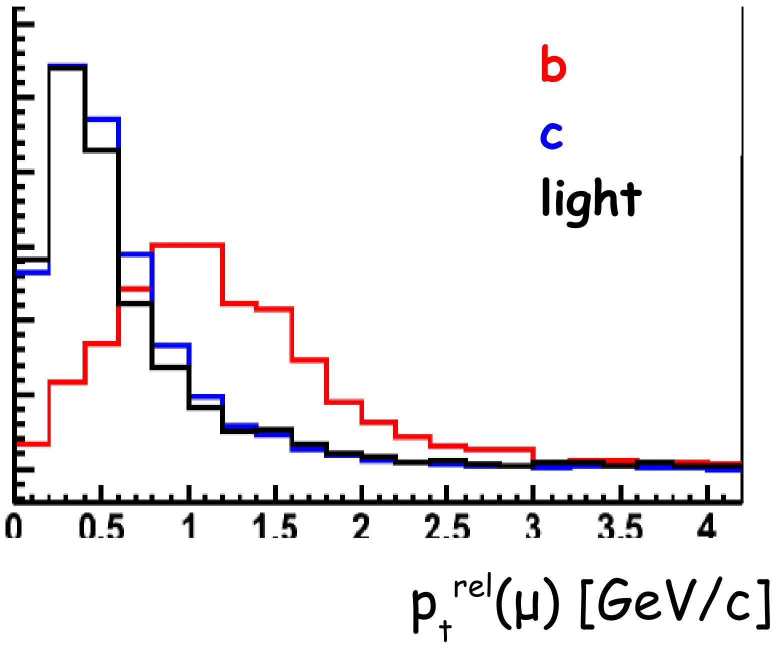
BR(b->l+X) ≈ 11%, BR(b->c->l+x) ≈ 10%

- Not relying so much on tracking performance, alignment etc. as the lifetime based tagging algorithms
- Largely uncorrelated to lifetime information -> ideal for cross calibration methods
- Combination with lifetime algorithms for ultimate performance (e.g. for ttH, H->bb)

Identify μ or e in jet
(e.g. 80% e-ID efficiency -> π rejection ≈ 200)

discriminating variables: p_t^{rel}, signed IP

typical light jet rejections
r ≈ 200-300 for ε_b ≈ 10% / 6% (μ / e)



Dependence on Kinematics (I)

At the LHC a wide kinematical range has to be covered

e.g. associated SUSY Higgs (high mass) production H/A bb:

high p_t (up to several 100 GeV) central jets + low p_t forward jets

Physics:

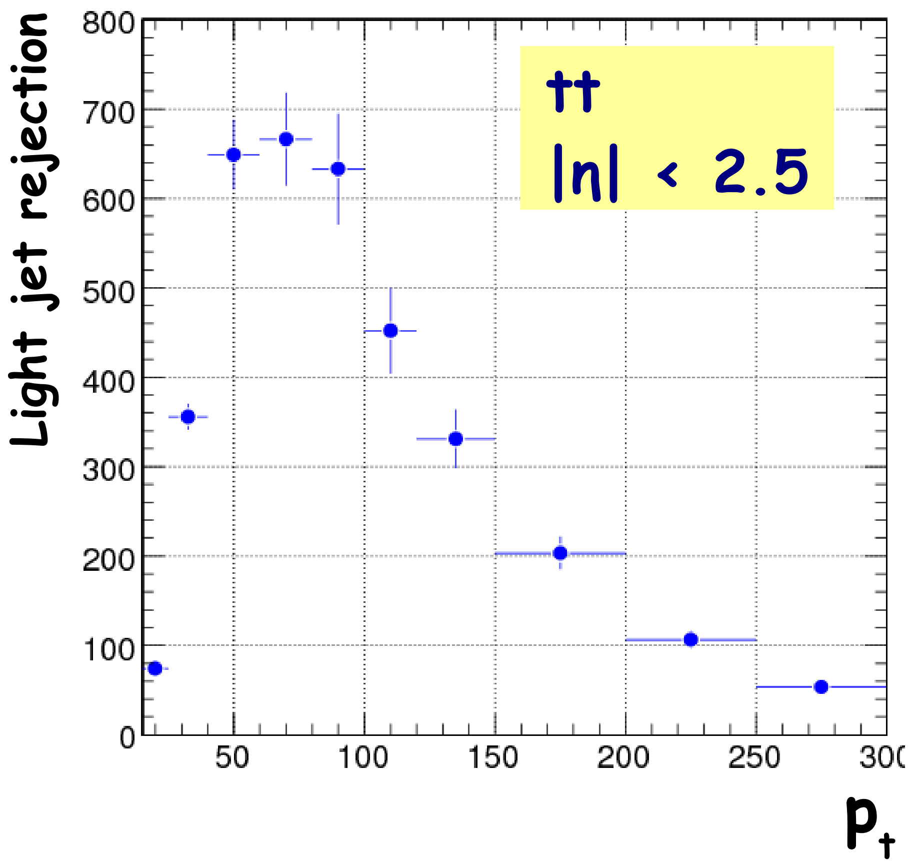
- b-hadron decays close to the PV or with very low charged multiplicity
- gluon splitting to heavy quark pairs (c,b);
  decays of very long-lived particles, e.g. V^0 (K^0_s, Λ^0)
- fragmentation multiplicity

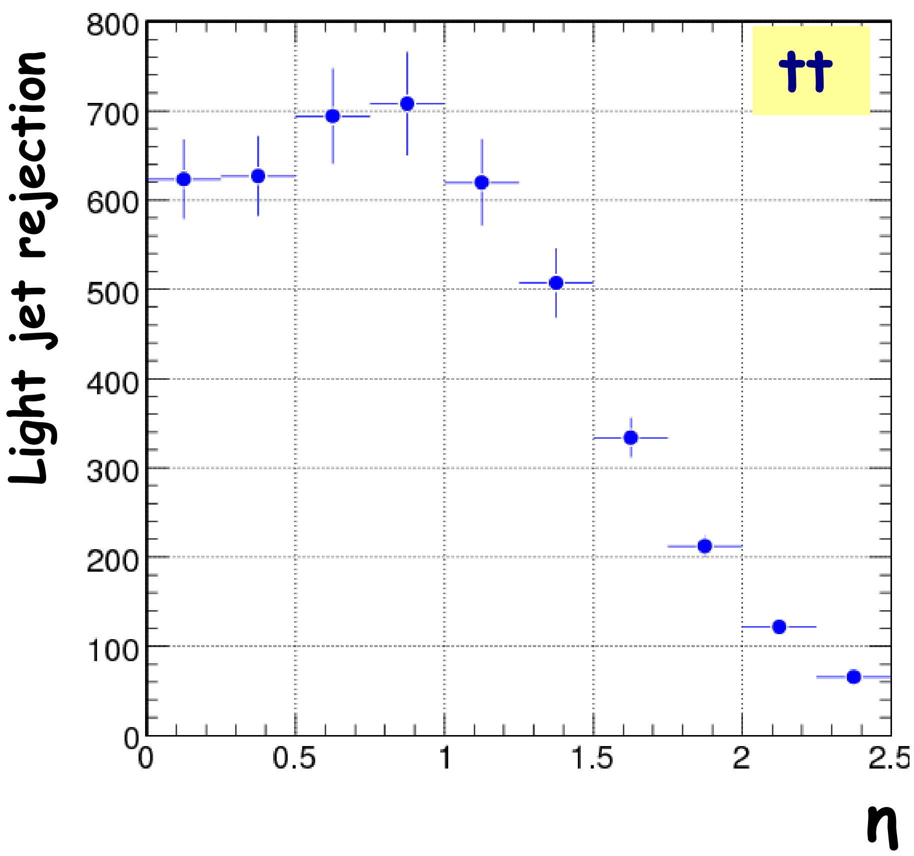
Instrumental:

- Resolution of tracking detectors
- Interaction with detector material:
  multiple scattering, photon conversions, nuclear interactions
- Pattern recognition: track density in jet

Dependence on Kinematics (II)

Light jet rejection for fixed b-tagging efficiency of 50% (Combined IP3D + SV1)

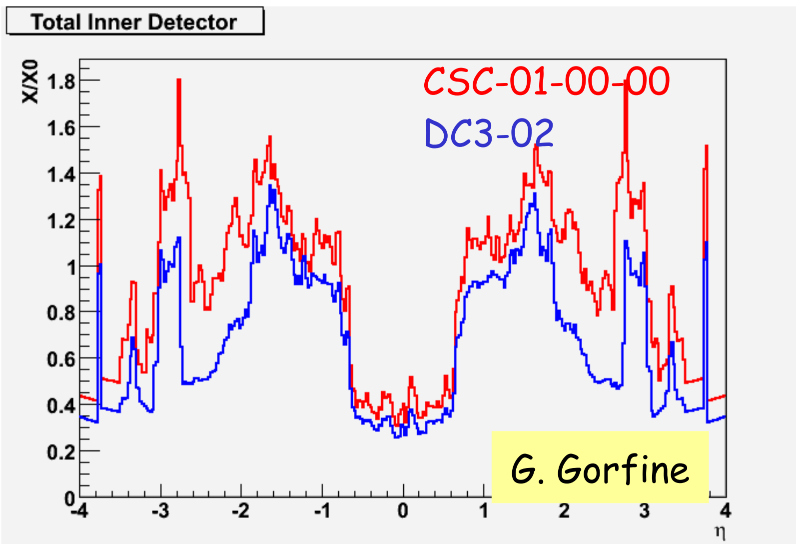




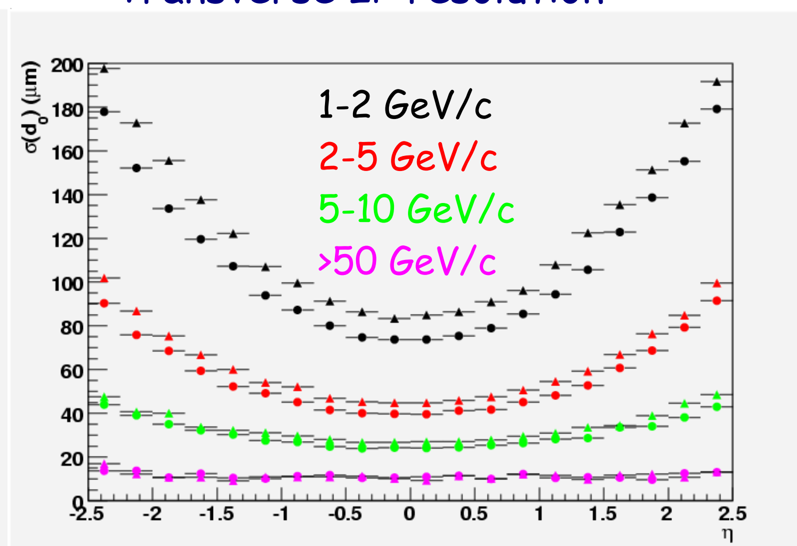
Towards Real Life .....

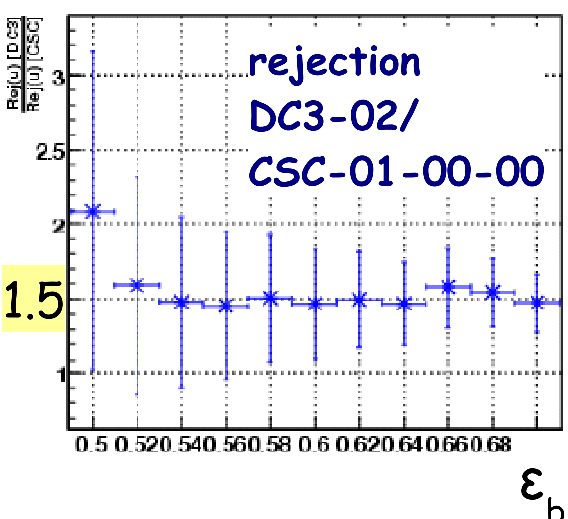
B-Tagging is very sensitive to effects like misalignment, material, ..

Inner Detector material



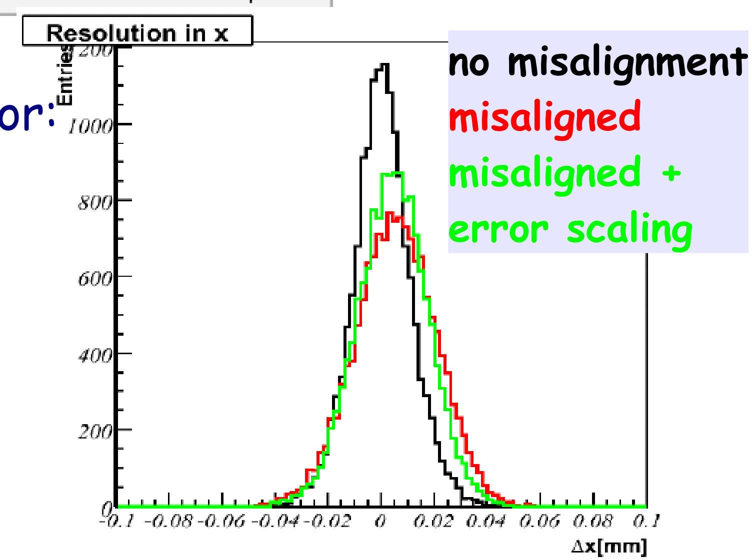
Transverse IP resolution





Misaligned Detector:
PV resolution
(V.Sipica, Siegen)

also: Pile-Up
(K.Grybel, Siegen)



Calibration on Data

Currently relying on Monte Carlo simulation.

VEEEERY unlikely that our MC will describe data well from day 1

-> need to develop methods to calibrate b-tagging performance and extract relevant distributions (IP resolutions, PDFs, ...) from data using dedicated samples

-> need jet samples of well defined flavour content:

1) Independent tagging algorithms: Lifetime & Soft Lepton

2) Kinematic selection (e.g. top events)

"System 8"

used in D0

need: **- 2 samples with different flavour composition**

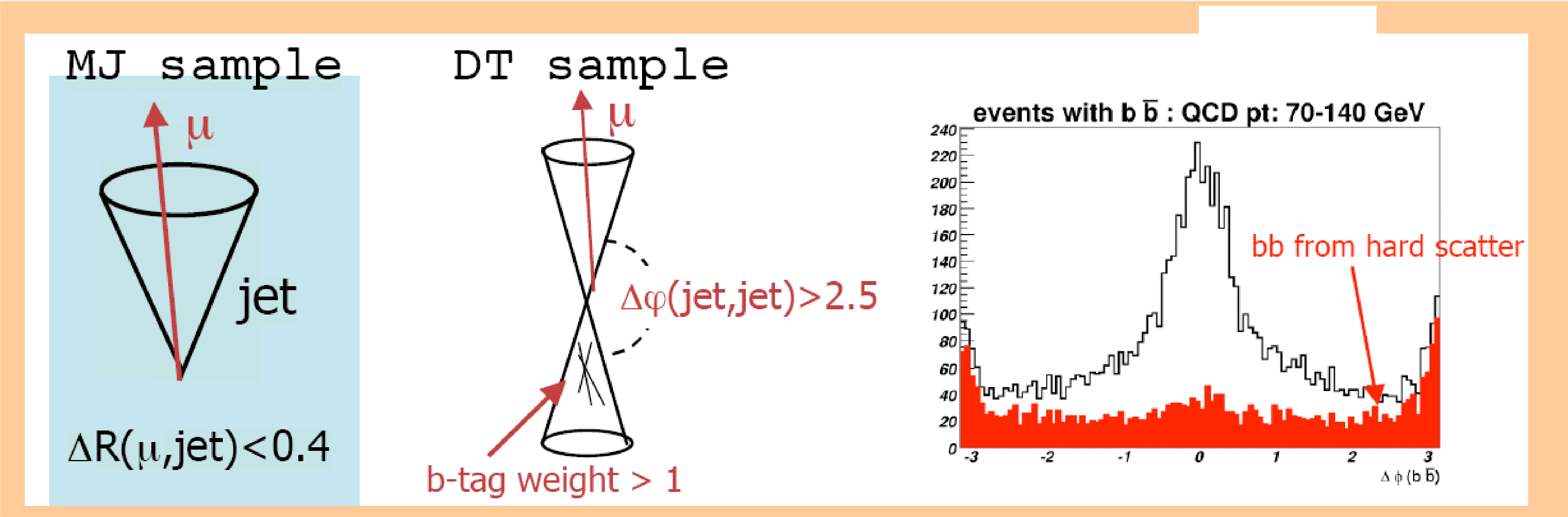
-> jet with lepton

-> jet with lepton + lifetime tagged jet in opposite hemisphere

- 2 (uncorrelated) taggers:

soft lepton + lifetime tag

-> solve for b-tagging and mistagging efficiencies

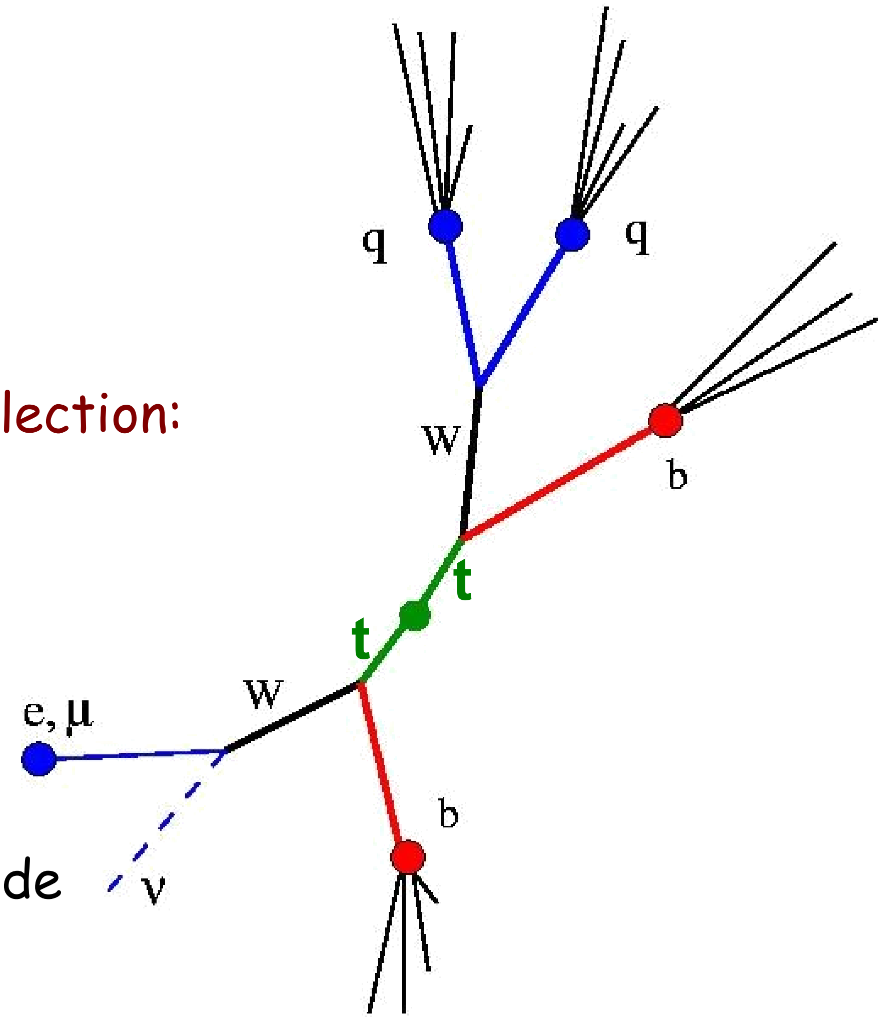


Calibration on Data: tt

Several approaches

here: **"Kinematic Fit"**
(G.Gorfine et al., Wuppertal)

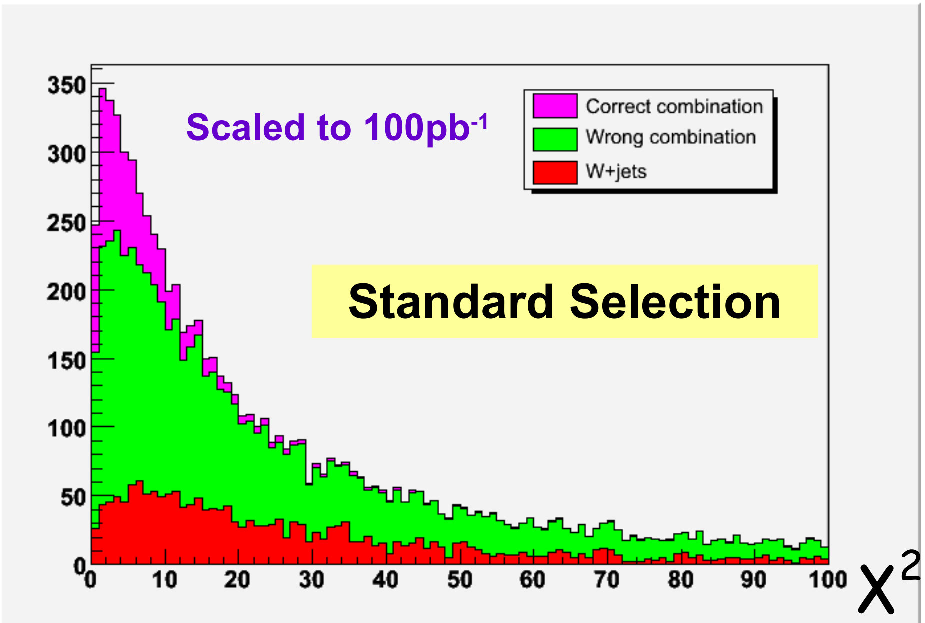
Enriched b-tag sample through kinematic selection:

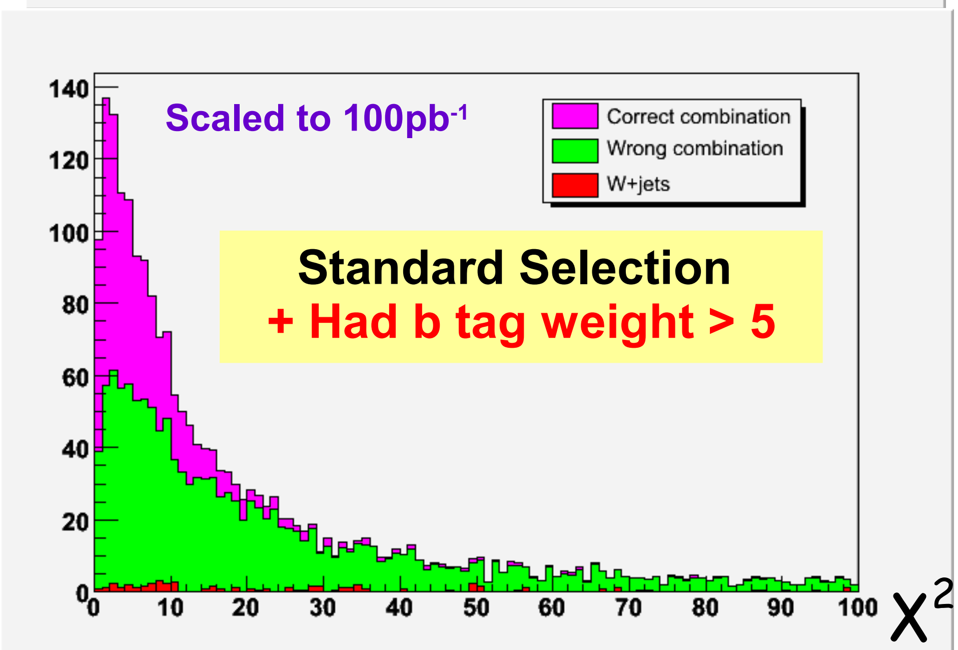


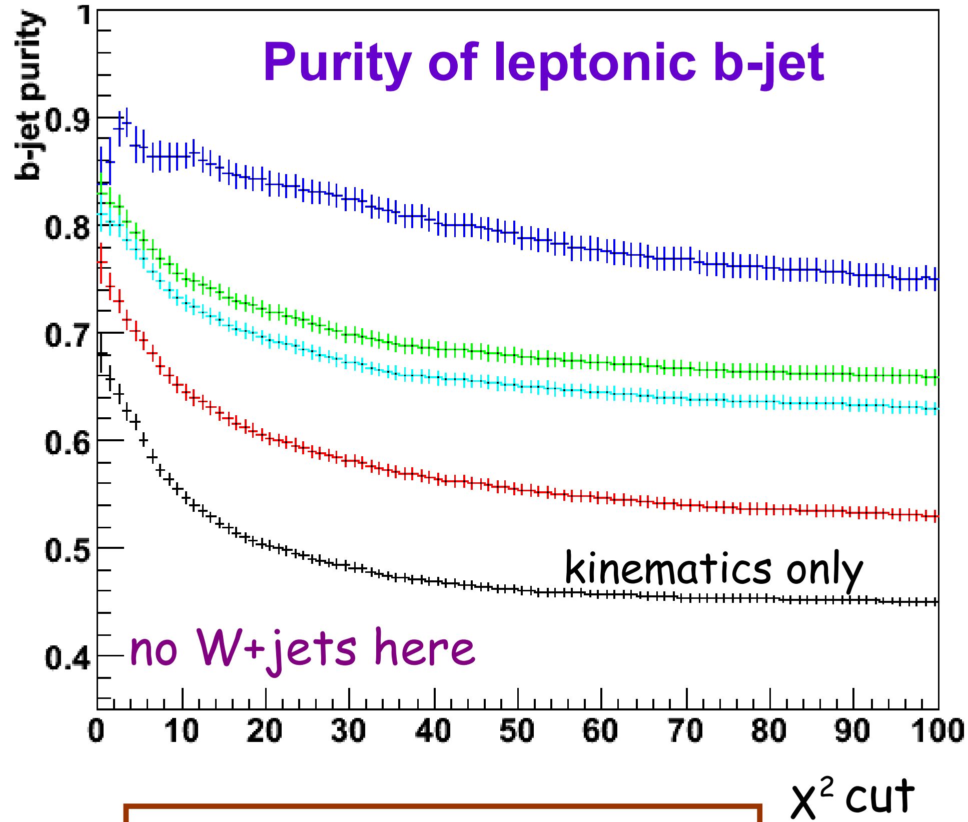
- Full kinematic fit,
  select combination with lowest X^2
- Optionally tag one side
  -> use unbiased b-jet candidate on other side
- Defines in principle also light and charm
  jet sample (W->ud, W->cs)

Calibration in tt (II)

G.Gorfine







Black: Standard Selection

+ had b tag weight >5

+ had w jets tag weight < 5

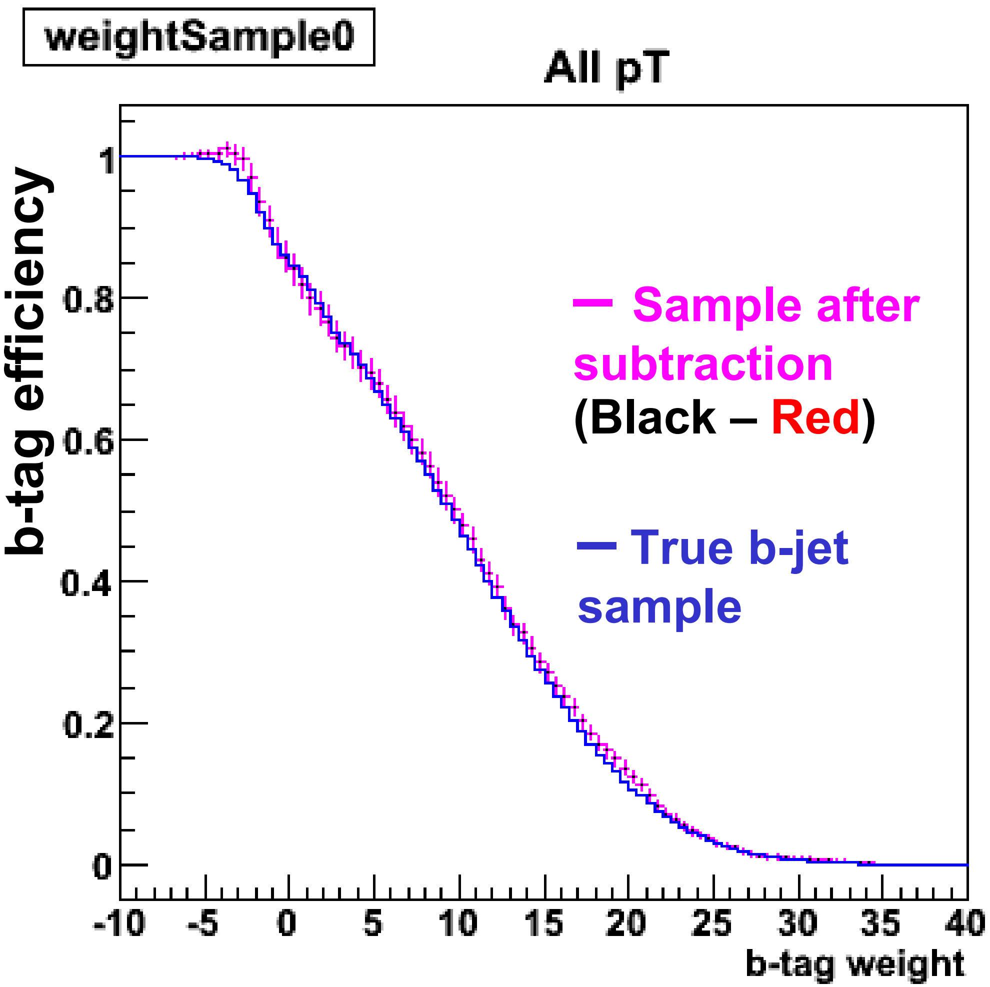
+ num jets <=6

+ had top pt > 150 GeV

Calibration in tt (III)

after (combinatorial) background subtraction

-> b-efficiency versus
jet weight cut



German B-Tagging Activities

Bonn: Track Selection & Categories

Dresden: Track Performance Studies

Freiburg: Vertex Reconstruction, B-Tagging Algorithm, Soft E-Tag, Algorithm Tuning

Siegen: Pile-Up & (Mis-)Alignment Studies

Wuppertal: Vertex Reconstruction, (Mis-)Alignment, Calibration in top events

Significant contributions to four B-Tagging CSC Notes

B-Tagging Parallel Session

Today, 16:30 – 18:30

16:00	[64] **Track Categories** by Marc LEHMACHER (Univ. Bonn) (SR1: 16:30 - 16:45)
	[65] **Track based Performance Studies** by Thomas GöPFERT (Univ. Dresden) (SR1: 16:45 - 17:00)
17:00	[66] **Topological Vertex Finder** by Tatjana LENZ (Univ. Wuppertal) (SR1: 17:00 - 17:20)
	[67] **Inclusive Secondary Vertex Finding and JetFitter** by Giacinto PIACQUADIO (Univ. Freiburg) (SR1: 17:20 - 17:40)
	[68] **Misalignment Studies using Error Scaling: Impact on B-Tagging** by Valentin SIPICA (Univ. Siegen) (SR1: 17:40 - 18:00)
18:00	[69] **Charm Tagging in Top Events** by Sebastian REUSCHEL (Univ. Wuppertal) (SR1: 18:00 - 18:15)

Summary & Outlook

- Signatures involving b-quarks in the final state will play an important role at the LHC, both for precision measurement (top) and searches (Higgs, SUSY, ...)
  -> need well performing and understood b-tagging algorithms

- Track and vertex reconstruction the most important ingredients
  -> relies on tracking detector

- Several well performing algorithms available, based on the lifetime of b-hadrons or their semileptonic decay.

- Very interesting new developments, e.g. JetFitter

- German b-tagging community gives significant contributions!

- **Focus now on methods how to calibrate performance on data, get resolutions and PDFs from data etc.**

BACKUP

German Contributions to CSC Notes

b-tagging performance (BT0): Bonn, Freiburg

Primary, secondary vertexing and beam spot in b-tagging (BT1): Freiburg, Siegen, Wuppertal

b-tagging performance with ID misalignment (BT2): Siegen, Wuppertal

b-tagging calibration using ttbar events (BT8): Wuppertal

b-tagging performance with soft electrons (BT4):

b-tagging calibration with di-jet sample using soft lepton b-tagging (BT10):

b-tagging performance with soft muons (BT3):

HLT b-tagging performance and strategy (BT5):

b-tagging performance in SUSY (BT6):

b-tagging performance for ttH->bb (BT7):

b-tagging performance using bbH->tautau events (BT9):

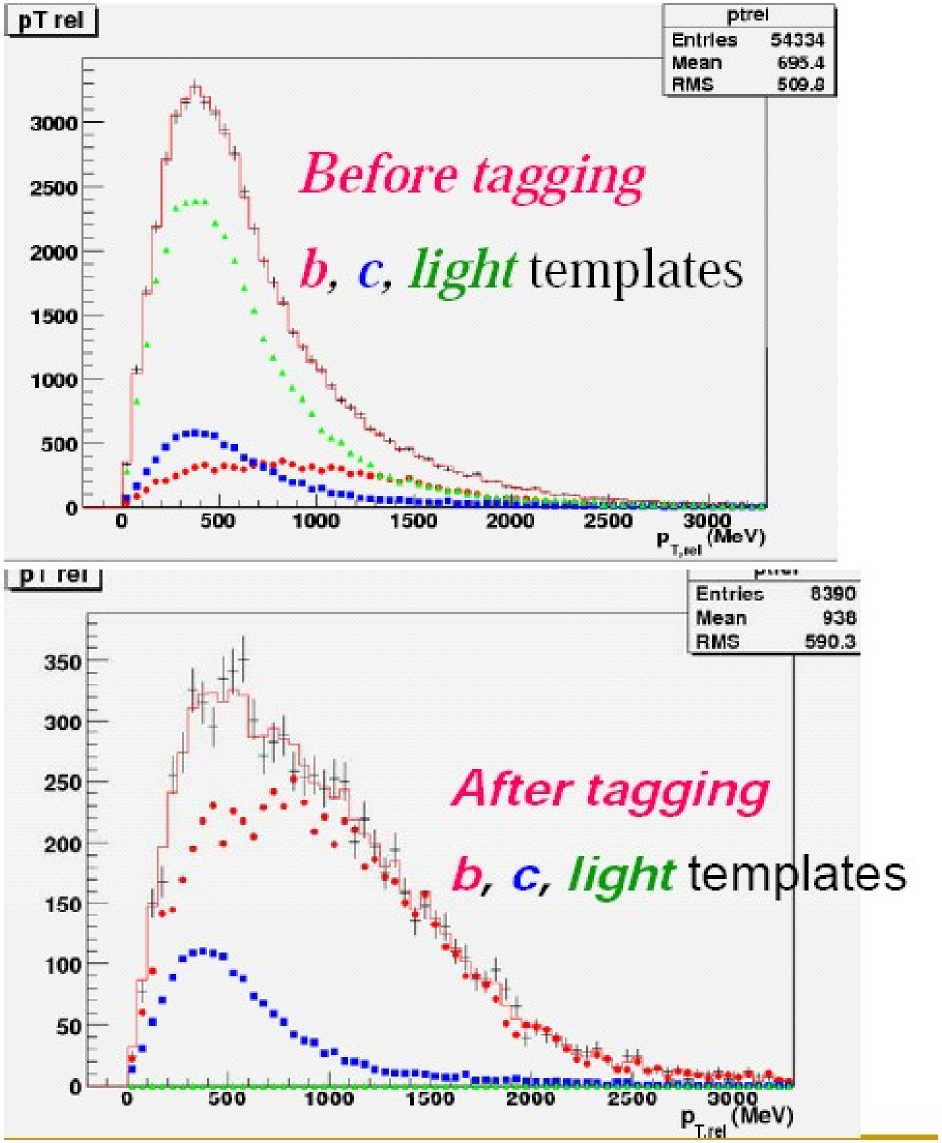
QCD (Di-)Jets

Lifetime + soft lepton tagger

- fraction of b-jets by fitting templates to lepton p_t^{rel} spectra before / after applying lifetime tag

(originally intended for the 900 GeV run)

$$\varepsilon_{btag} = \frac{N_{\mu}^{tag} \cdot F_{b\to\mu}^{tag}}{N_{\mu} \cdot F_{b\to\mu}}$$



System 8

n: lepton jet sample (here only μ)
p: "double tagged" sample

ε,r: b/light tagging efficiency

$_{Tr,\mu}$: Passing track based (lifetime) or muon tag

$_{all}$: Passing both tags

β,α: correction factors for sample dependency

k_b,k_{cl}: (de-)correlation between taggers

$$n = n_b + n_{cl}$$

$$p = p_b + p_c$$

$$n_\mu = \varepsilon^\mu n_b + r^\mu n_{cl}$$

$$p_\mu = \varepsilon^\mu p_b + r^\mu p_{cl}$$

$$n_{Tr} = \varepsilon^{Tr} n_b + r^{Tr} n_{cl}$$

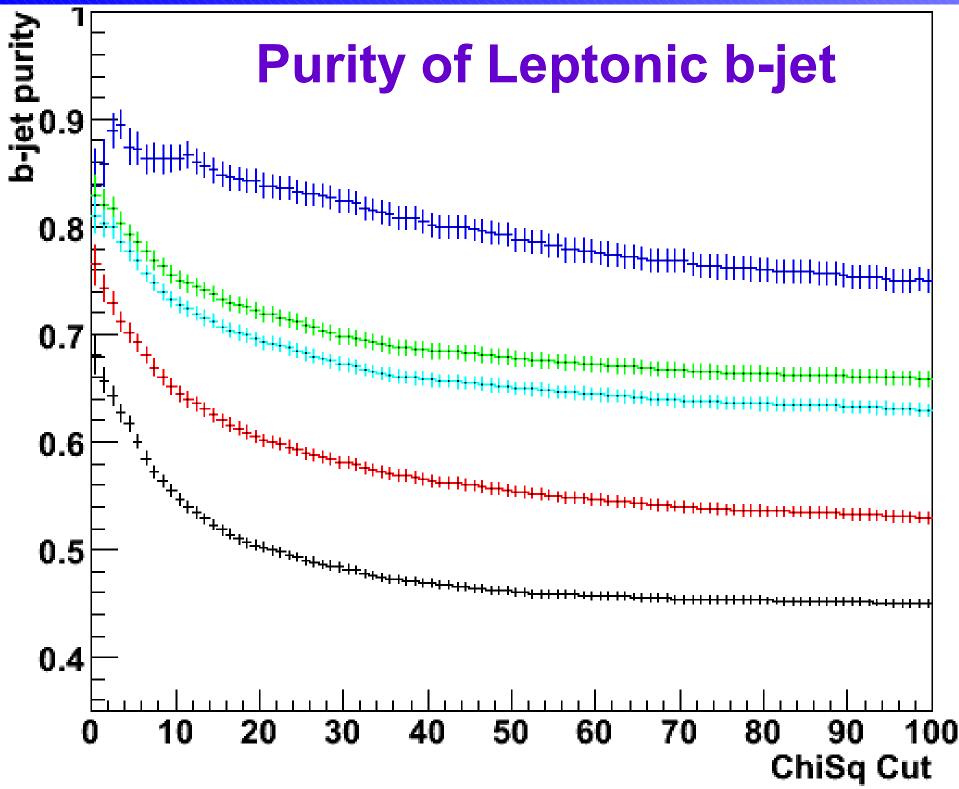
$$p_{Tr} = \beta \varepsilon^{Tr} p_b + \alpha r^{Tr} p_{cl}$$

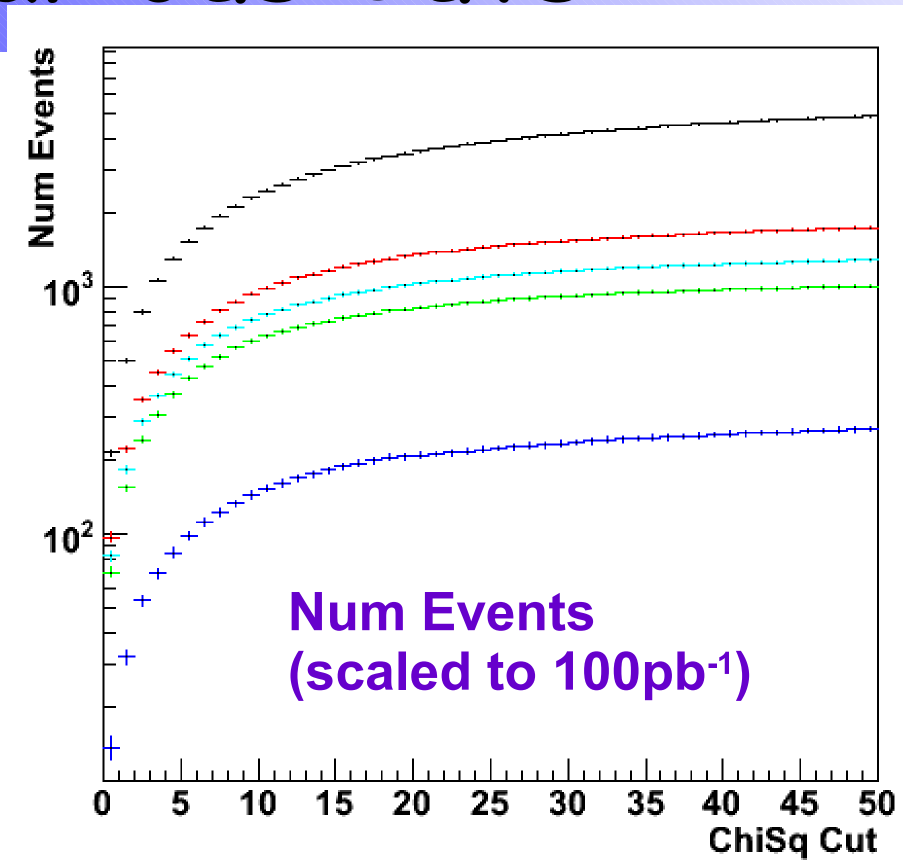
$$n_{all} = k_b \varepsilon^\mu \varepsilon^{Tr} n_b + k_{cl} r^\mu r^{Tr} n_{cl}$$

$$p_{all} = k_b \beta \varepsilon^\mu \varepsilon^{Tr} p_b + k_{cl} \alpha r^\mu r^{Tr} p_{cl}$$

8 equations, 8 unknowns

Purity for Various Cuts





Black: Standard Selection

+ had b tag weight >5

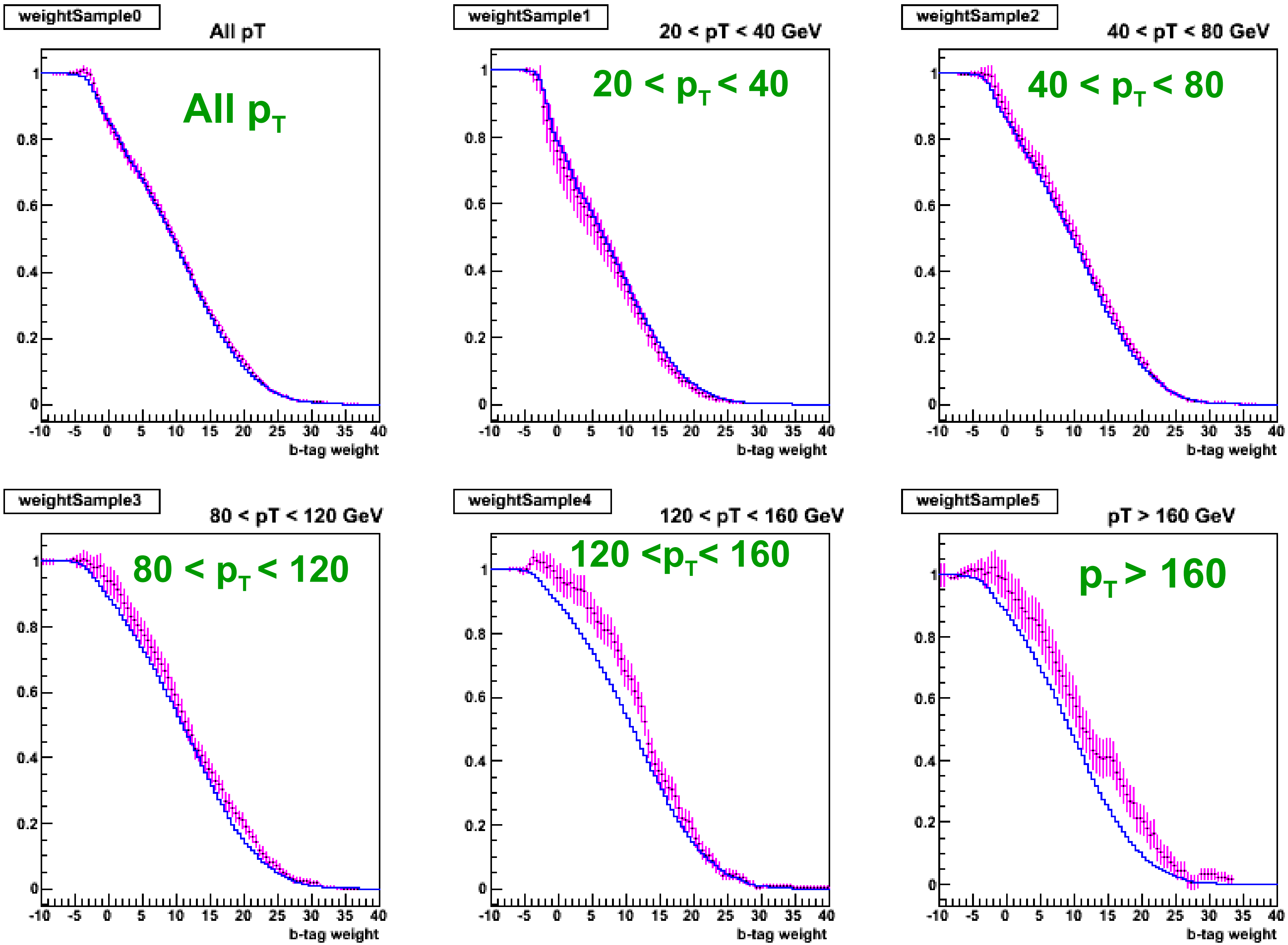
+ had w jets tag weight < 5

+ num jets <=6

+ had top pt > 150 GeV

- W+Jets not included
- For chi2 cut < 10
- Up to 90% purity with all cuts
- ~150 events left for 100pb^{-1}

B-tag efficiency vs jet p_T



Good agreement for low to medium p_T bins.

– Sample after subtraction

– True b-jet sample

Calibration On Data: tt

Tag Counting: count the number of events with 1/2/3 tagged jets

- $L = Poisson(N_1, < N_1 >) \cdot Poisson(N_2, < N_2 >) \cdot Poisson(N_3, < N_3 >)$
- $N_n =$ Number of observed events with n tags
- $< N_n > =$ Expected number of events with n tags : function of ϵ_B, ϵ_C, ϵ_L, $\sigma_{t\bar{t}}$, etc...

$$< N_n > =$$

$$(L \cdot \sigma_{t\bar{t}} \cdot A_{pre-tag}) \cdot \Sigma_{i,j,k} F_{i,j,k} \Sigma_{combi.} A_i^{i'} \cdot \epsilon_b^{i'} \cdot (1-\epsilon_b)^{i-i'} \cdot A_j^{j'} \cdot \epsilon_c^{j'} \cdot (1-\epsilon_c)^{j-j'} \cdot A_k^{k'} \cdot \epsilon_l^{k'} \cdot (1-\epsilon_l)^{k-k'}$$

$i = \#$ b-jets and $i' = \#$ tagged b-jets

$j = \#$ c-jets and $j' = \#$ tagged c-jets

$k = \#$ l-jets and $k' = \#$ tagged l-jets

$F_{i,j,k} =$ Fraction of events with i b-jets, j c-jets, k l-jets.

$A_i^{i'} = i!/(i'! \cdot (i-i')!)$

$\sigma_{t\bar{t}} =$ production cross-section

$A_{pre-tag} =$ acceptance without b-tagging

$L =$ integrated luminosity

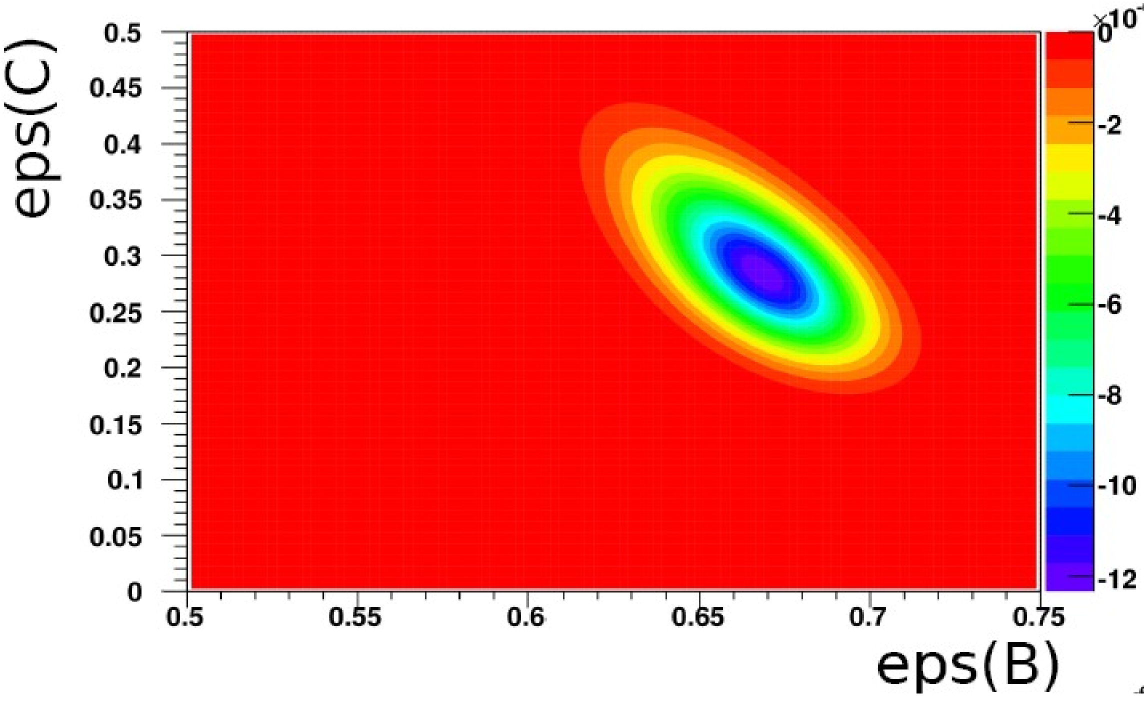
Calibration On Data: tt

Fit eps(b), eps(c) and tt x-section

statistical uncertainty expected for 100 pb^{-1}

b-eff.: ≈ 2.5 %

c-eff.: ≈ 20 %



Calibration On Data

Methods presented mainly sensitive to b-efficiency (and c-eff.)

Need also to get light quark mistags from data!

-> Definition of "negative tags" desirable

e.g.: tagger based on negative IP only

negative flight length distribution for SV based taggers

+ corrections for pos./neg. asymmetry

(resolution fake tags vs. decays in flight, material interactions)

-> work in ATLAS just started