b/c-quark flavor tagging and identification: past, present and future

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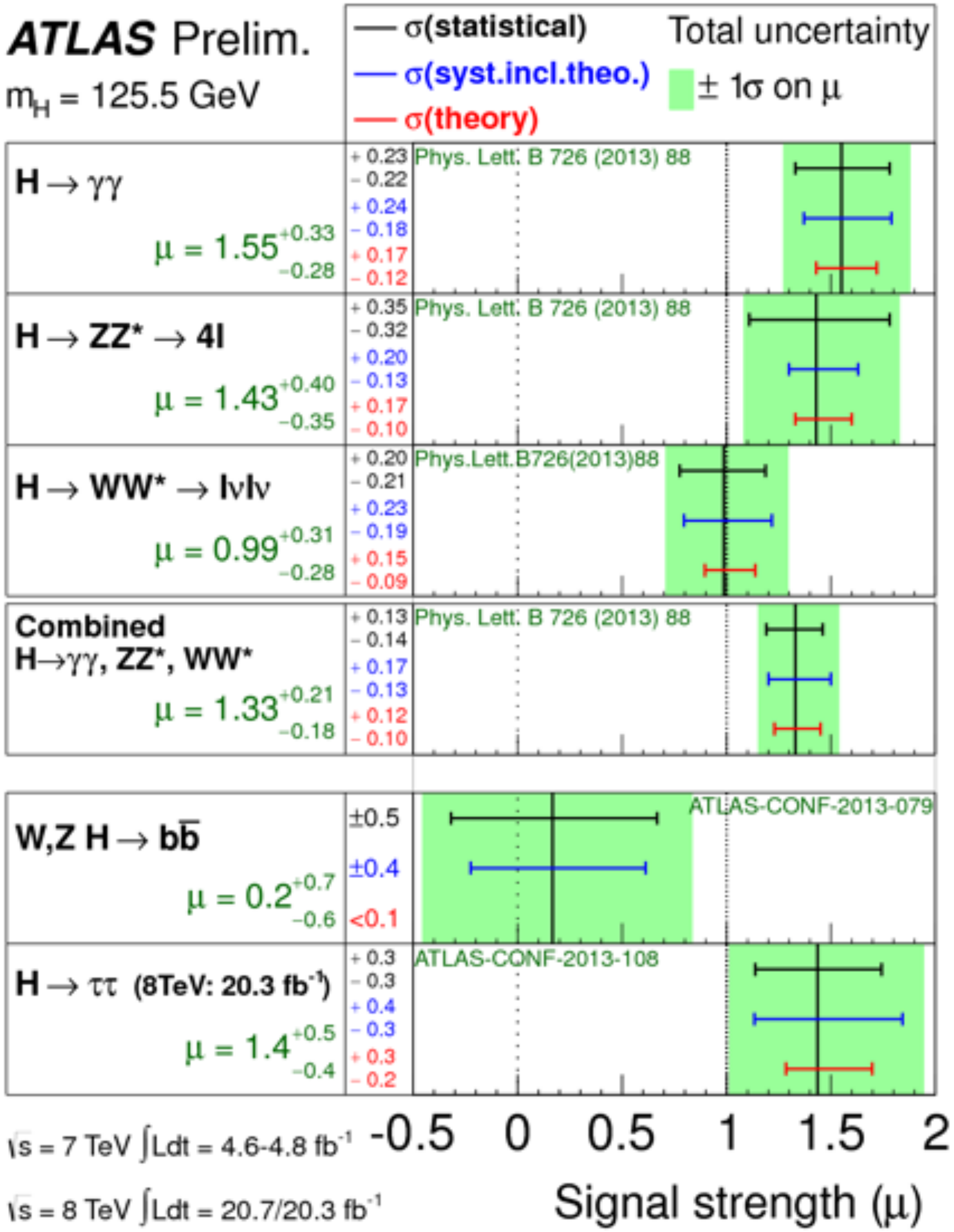
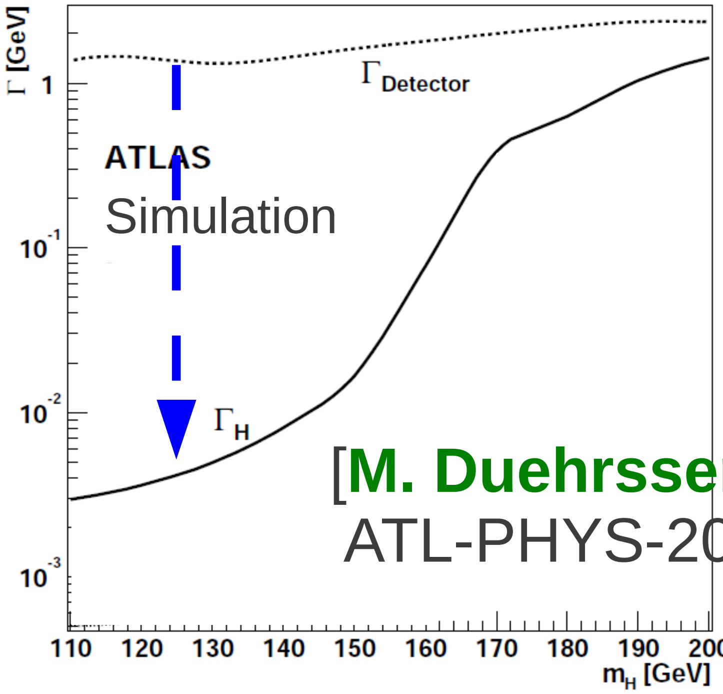
Experimental status

- Higgs boson discovery established by ATLAS and CMS at m(H) ~125 GeV.
- Discovery relies on clear signal observation in bosonic channels ($\gamma\gamma$, WW, ZZ).
- Fermionic channels:
  - Recently >3σ signal in H to tau tau
  - No 3σ observation yet in H to bb
- The main question today:
  - is it the Standard Model Higgs boson?
  - can we find deviations from SM predictions which hint at physics beyond SM?



Higgs couplings



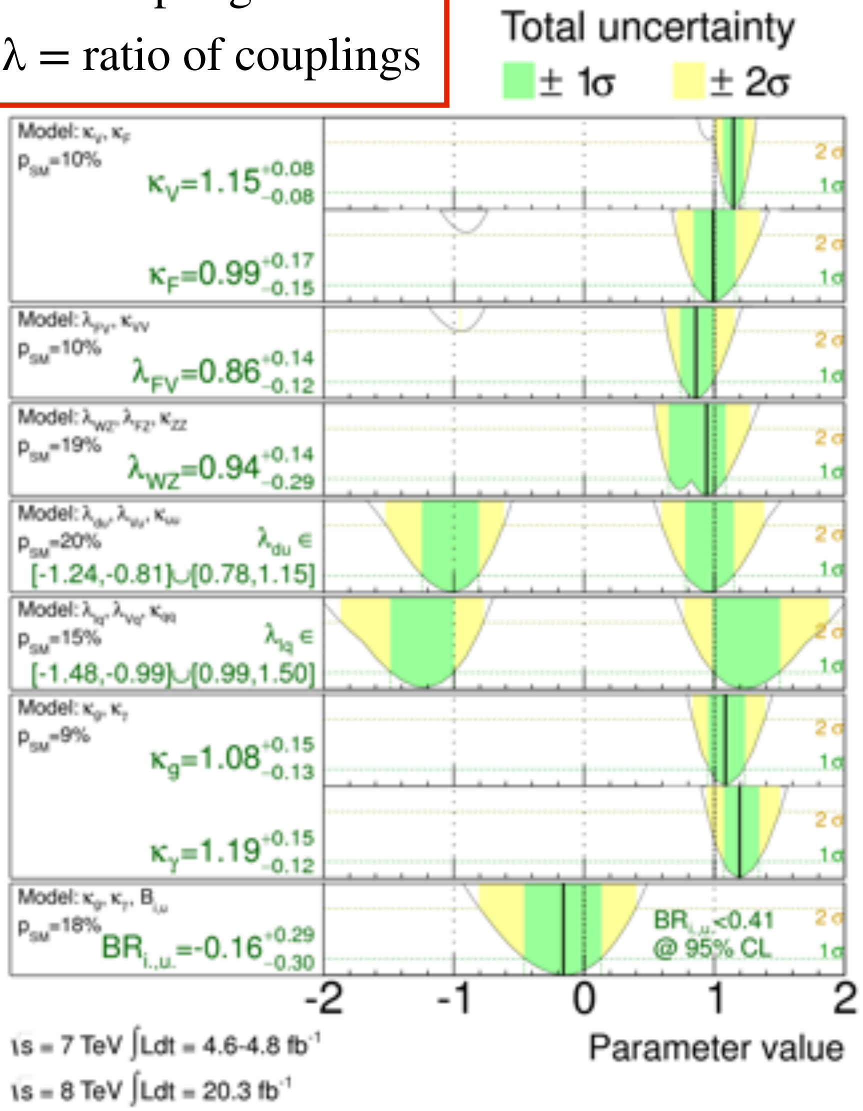
[**M. Duehrssen**, ATL-PHYS-2003-30]

- Deviations from SM are presently looked for by defining multiplicative scale factors ***κ*** for the coupling parameters (SM expectation = 1), leaving the tensor structure unchanged.

$$\mathcal{L} \;=\; \kappa_W \frac{2{m_W}^2}{v} W^+_\mu W^-_\mu H + \kappa_Z \frac{{m_Z}^2}{v} Z_\mu Z_\mu H - \sum_f \kappa_f \frac{m_f}{v} f\bar{f}H$$
$$+ c_g \frac{\alpha_s}{12\pi v} G^a_{\mu\nu} G^a_{\mu\nu} H + c_\gamma \frac{\alpha}{\pi v} A_{\mu\nu} A_{\mu\nu} H$$

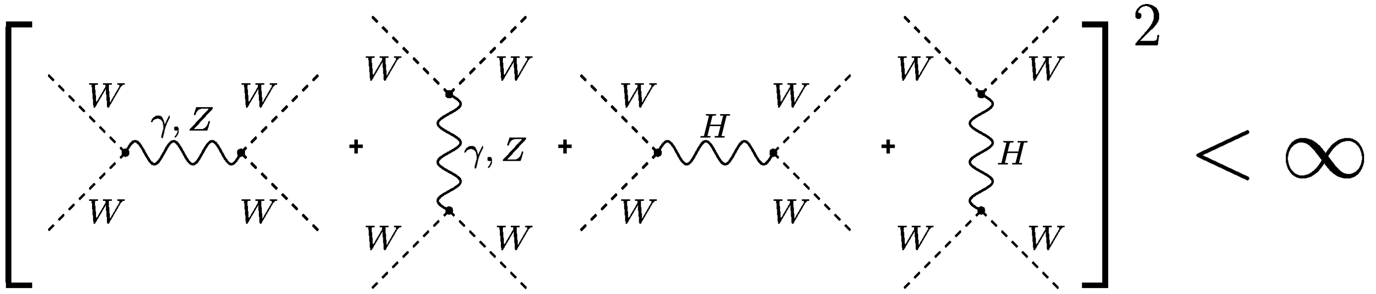
κ = coupling

λ = ratio of couplings



ATLAS-CONF-2014-009

- Test of absolute couplings difficult
  - Total decay width not directly accessible at LHC.
- A measurement of absolute couplings is possible if the total width is bound
  - **NEW!** Measurement through interferometry, but has assumptions!
  - Upper limit from fulfilling unitarity in WW scattering (valid for SM and a large class of BSM models)



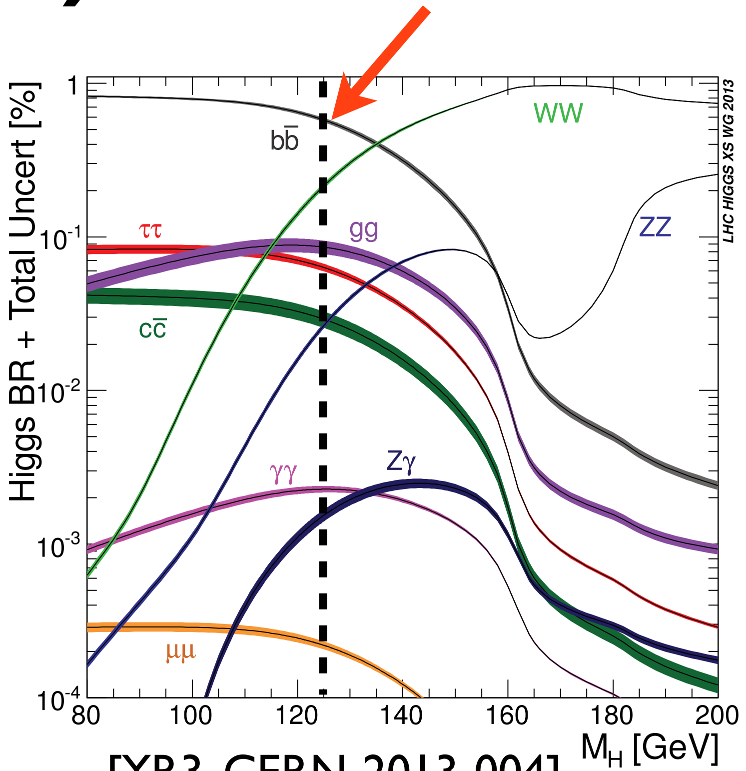
$$\kappa_W \leq 1,\ \kappa_Z \leq 1$$

Higgs couplings (II)

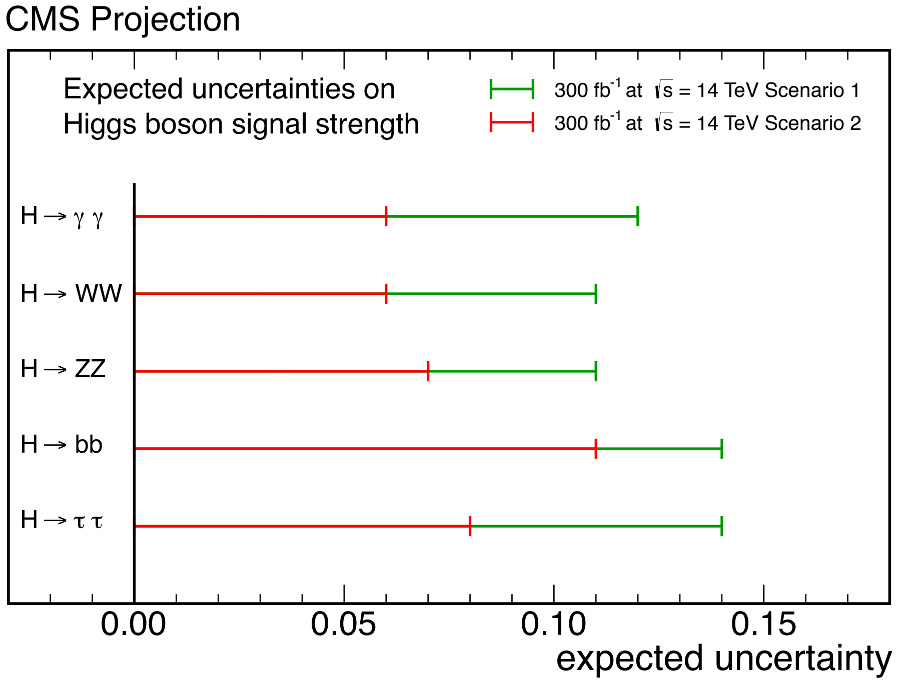
- Lower limit from sum of all “visible” decay modes

$$\Gamma_H \geq \Gamma_W + \Gamma_Z + \Gamma_g + \Gamma_\tau + \boxed{\Gamma_b}$$

- At ~125 GeV Higgs boson width is expected to be dominated by H to bb (BR ~ 60%)
  - Precise determination of H to bb would be important for extracting absolute couplings!
- Most sensitive channel is VH, H to bb (V=W/Z)
  - Leptonic signature to trigger / reduce backgrounds
  - Excellent b-quark ID required to reject light- and c-jets
  - Expected sensitivity at the end of Run-I LHC:
    - ~2σ (CMS), ~1.7σ* (ATLAS)
  - <15% error on H to bb signal foreseen by CMS with 300 inv. fb. of data



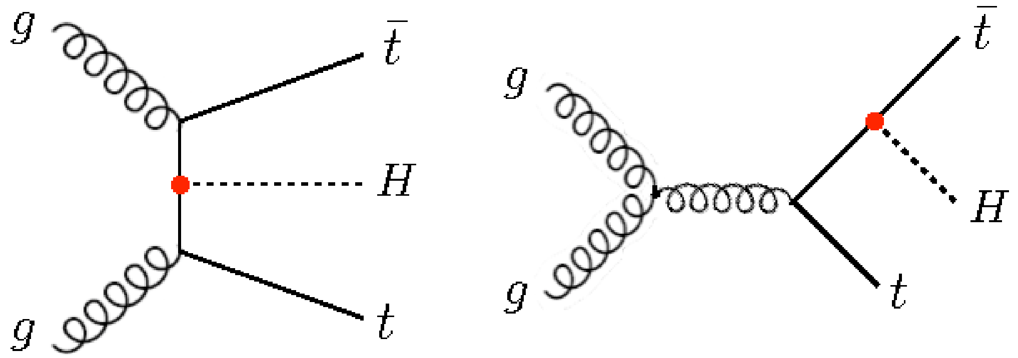
[YR3, CERN-2013-004]



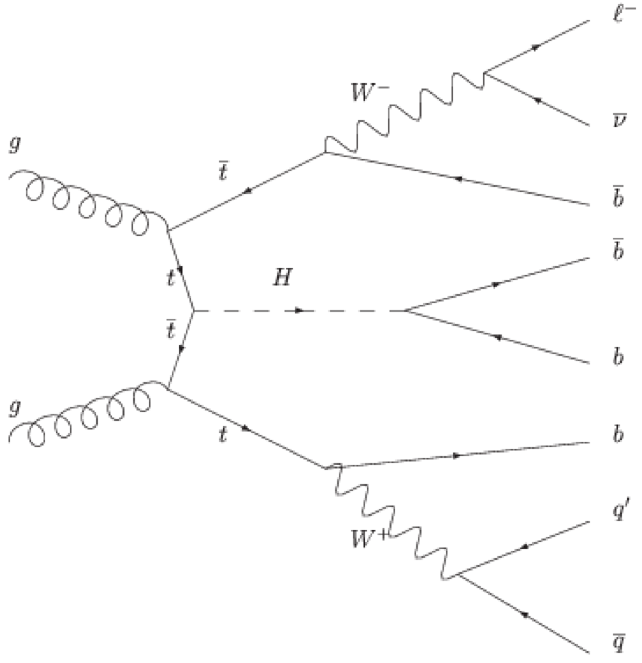
**Final ATLAS Run-I result not public yet*

Higgs couplings (III)

- Direct evidence of coupling to top-quarks implies observation of ttH production
  - at least 2 b-quarks in final state
- Most promising channel ttH, H to bb
  - Very challenging due to high backgrounds
  - Excellent b-quark ID required to suppress tt+light-jet backgrounds
  - 4 b-jets means it’s hard to reconstruct an even broad Higgs mass peak
- Presently 0.7σ/0.5σ sensitivity (ATLAS / CMS) (~1σ combining all decay modes)
- Measurement will become competitive in Run-II.



$t\bar{t}H\rightarrow$ 6 jets 4 b-jets



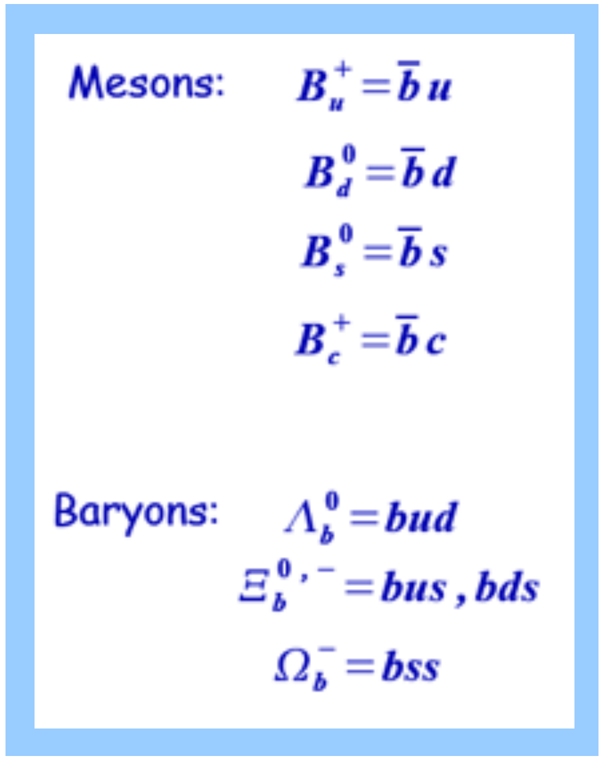
b/c-quark flavor ID

- Important role in Higgs physics:
  - H to bb searches
  - ttH production
  - as a handle to veto b-jets from top production (e.g. VBF H to WW)
- Will review:
  - What b-tagging is about and how it works
  - What we have achieved @ LHC in Run-I (performance + calibration)
  - What we can improve in the next run (upgraded detector, improved techniques)
- Will refer mainly to ATLAS, with a few comparisons to CMS.

We don’t see b-quarks…

- A b-quark fragments typically (~87% of times) into:
    - B*, B** (excited b-hadrons)
- These decay strongly or electromagnetically ($c\tau < 10^{-16}$ s) into:
    - a b-hadron + few additional particles (which form a jet)

b-hadron types



Mesons: $B_u^+ = \bar{b}u$

$B_d^0 = \bar{b}d$

$B_s^0 = \bar{b}s$

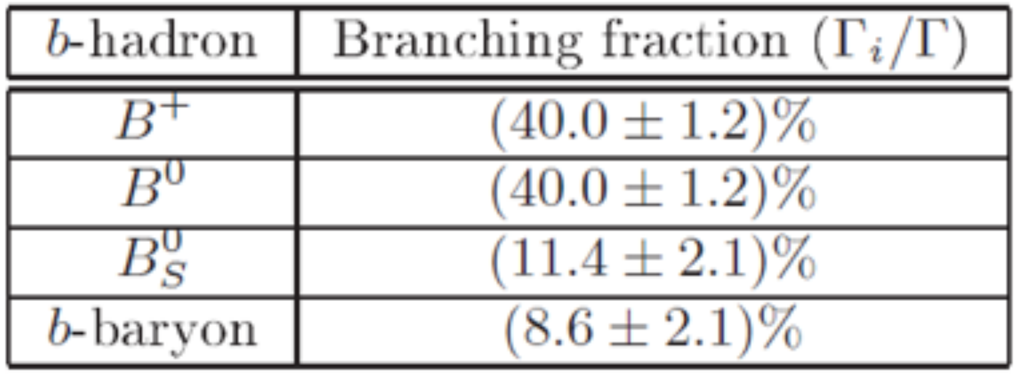
$B_c^+ = \bar{b}c$

Baryons: $\Lambda_b^0 = bud$

$\Xi_b^{0,-} = bus, bds$

$\Omega_b^- = bss$

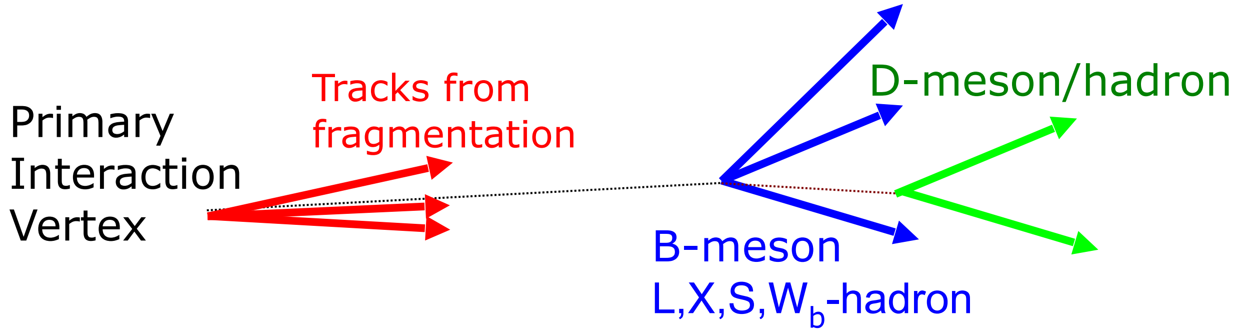
Relative production rates



b-hadron	Branching fraction (Γ_i/Γ)
B^+	$(40.0 \pm 1.2)\%$
B^0	$(40.0 \pm 1.2)\%$
B_S^0	$(11.4 \pm 2.1)\%$
b-baryon	$(8.6 \pm 2.1)\%$

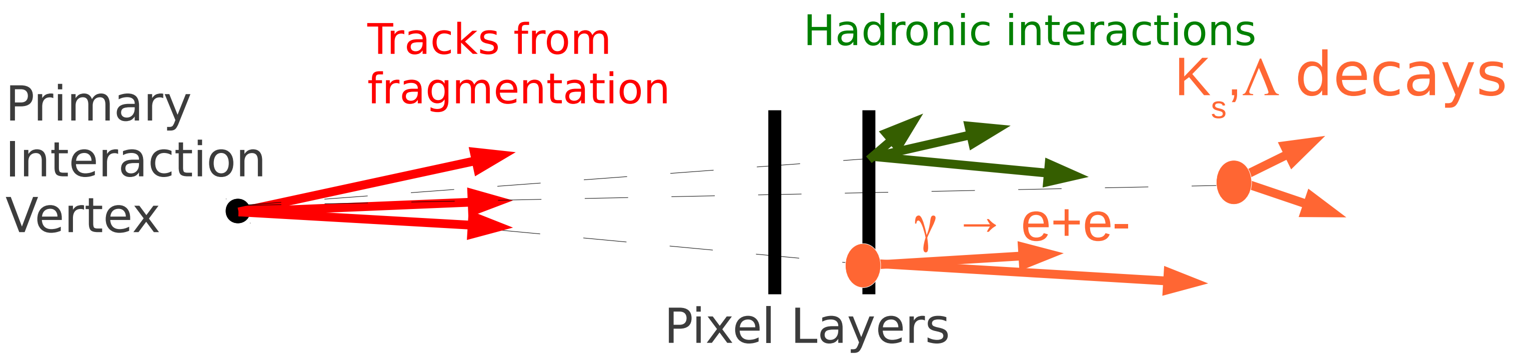
- The b-quark fragmentation function is hard: in average most of the energy of the original b-quark (~70%) goes into the b-hadron

B-hadron decays

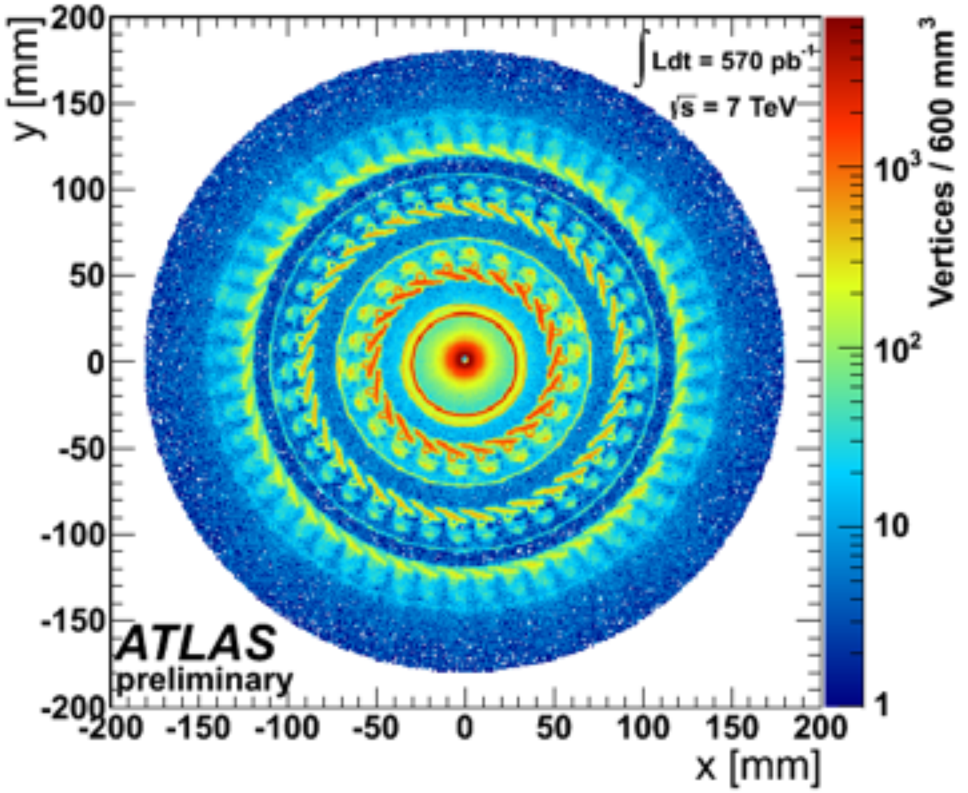


- A b-hadron undergoes a weak decay with $c\tau \sim 1.5 \times 10^{-12}$ s
- Decay properties:
  - For a b-hadron with pT ~ 30 GeV, $\beta\gamma \sim 6 \rightarrow L = \beta\gamma c\tau \sim$ ~5 mm → Measurable displaced ***secondary vertex***!
  - B-hadron mass is ~ 5 GeV
  - Since |Vcb| >> |Vub|, in most of the cases also a c-hadron is produced out of the b-hadron. $c\tau$ (c-hadron) ~ 0.4-1 x 10^{-12} s. This creates an additional ***tertiary vertex***.
  - In ~42% of the cases the b-hadron decays semi-leptonically, in ~11% directly (b → ℓ) and in ~10% indirectly (b → c → ℓ) where ℓ=e or μ.
- All these properties can be exploited to identify b-jets and separate them from u,d,s-jets (light) and gluon-jets.

Typical topology in light-jets



Hadronic interactions



- Most of the tracks really come directly from the quark fragmentation process.
- Few light jets present a real displaced vertex due to:
  - Hadronic interactions in the detector material (mostly on beam pipe and first pixel layers)
  - Photons converting into an electron-positron pair (track pair emitted collinearly)
  - Long lived particles: Ks/Λ decaying to $\pi^+\pi^-$ / p π^- (cτ(Ks) = 2.7 cm / cτ(Λ) = 7.9 cm >> cτ(B)=0.46 mm)
- Badly measured tracks (hard scatter, nuclear interactions,...) / tracks with shared hits in the first pixel layers can significantly increase the rate of fake tracks / fake vertices.

Ingredients to b-tagging

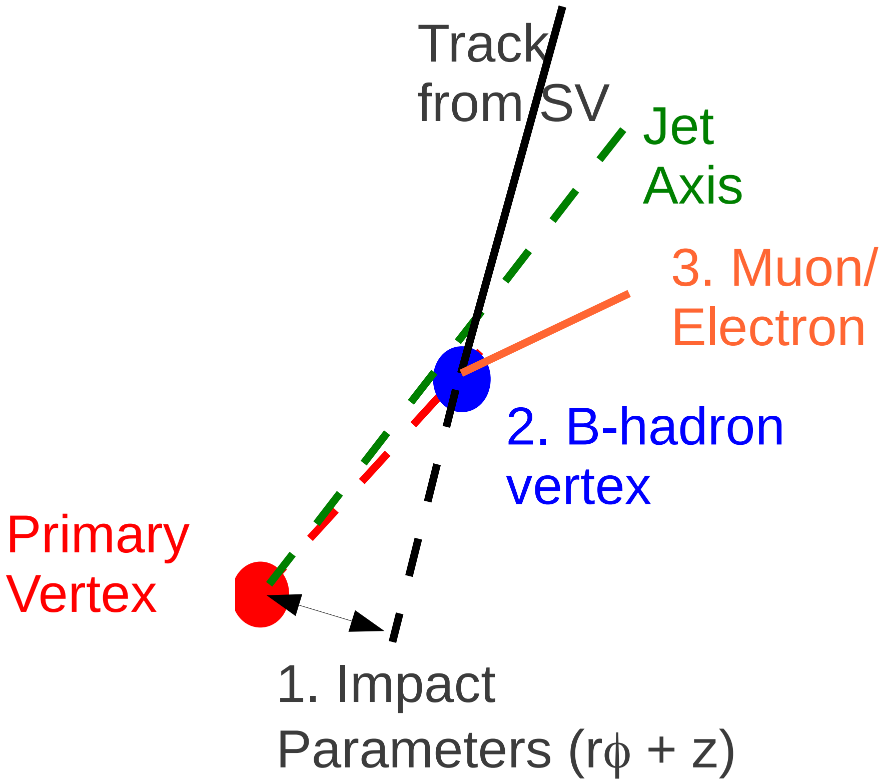
- 1. **Tracks**
  - Can only measure trajectory of charged particles
  - Tracks associated to jets based on:

$$\Delta R(\vec{p}_{jet}, \vec{p}_{trk}) < \Delta R_{cut}$$

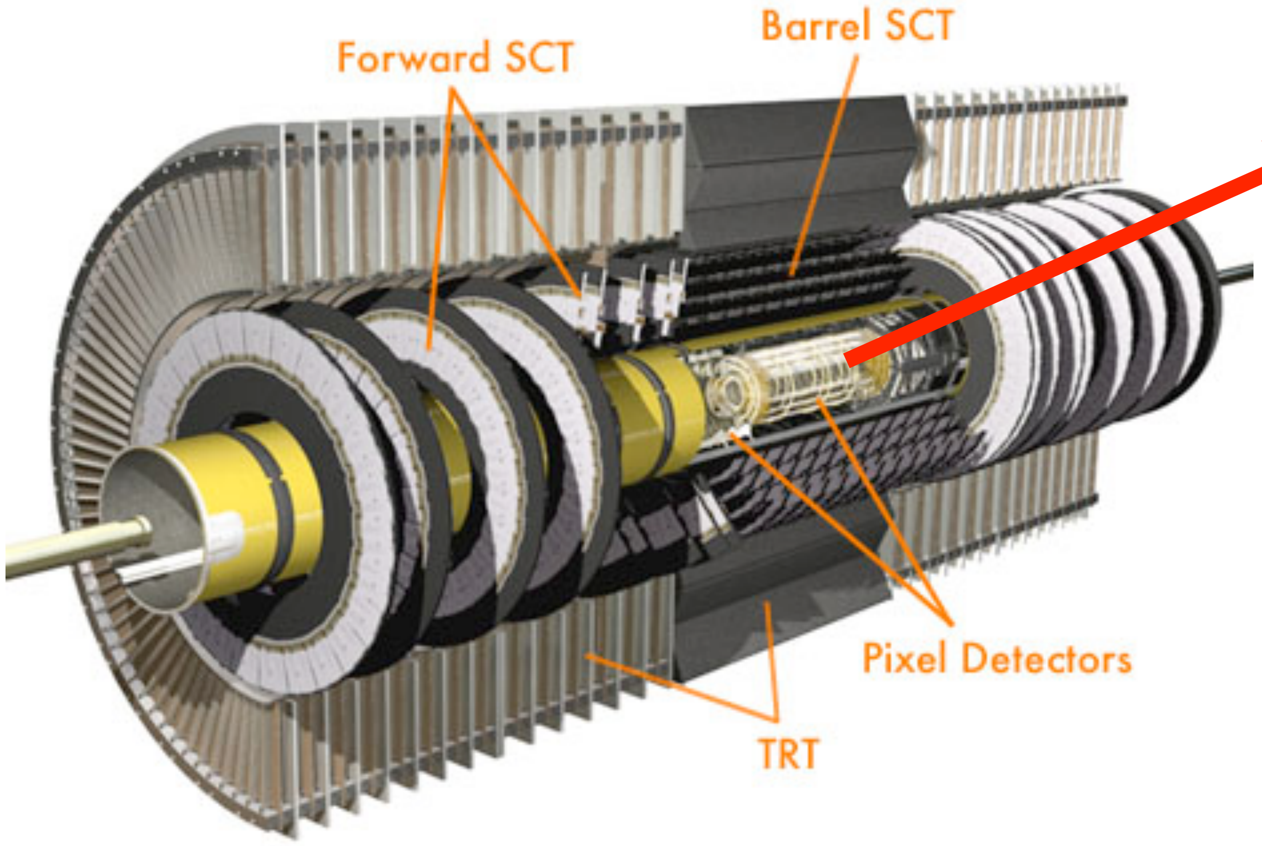
(ΔR cut pT dependent)

- 2. **Jets**
  - **Direction:** allows to assign a "lifetime sign" to tracks
  - **Transverse momentum/ rapidity:** exploit dependence of physics properties and detector resolution on jet kinematics

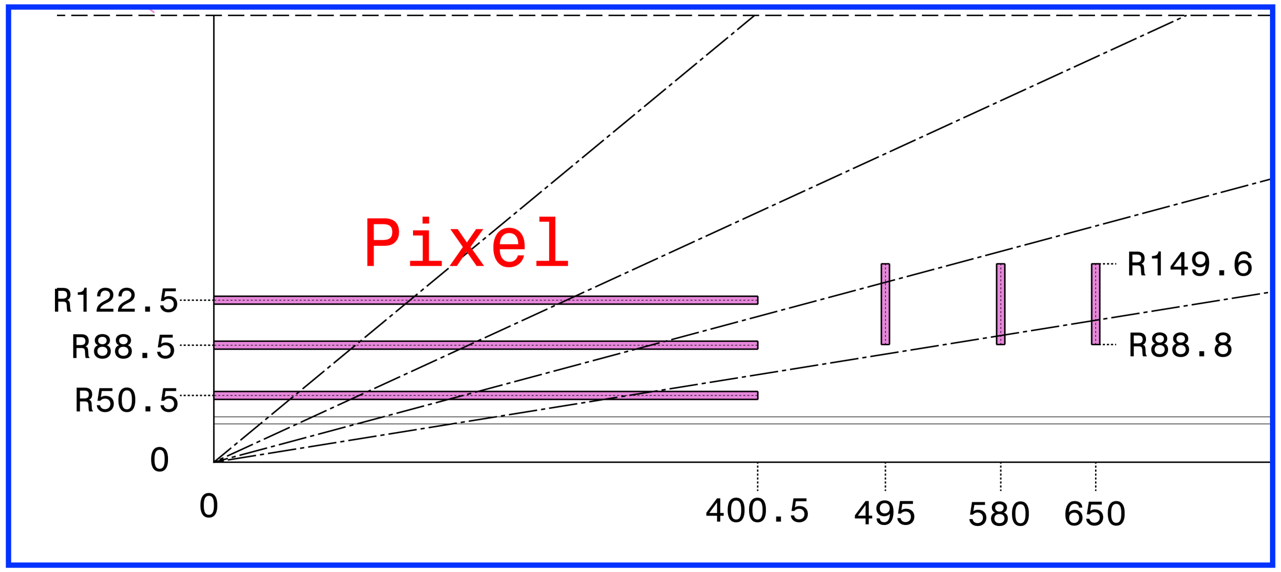
- 3. **Leptons**
  - Muons are used to identify semi-leptonic b-decays.



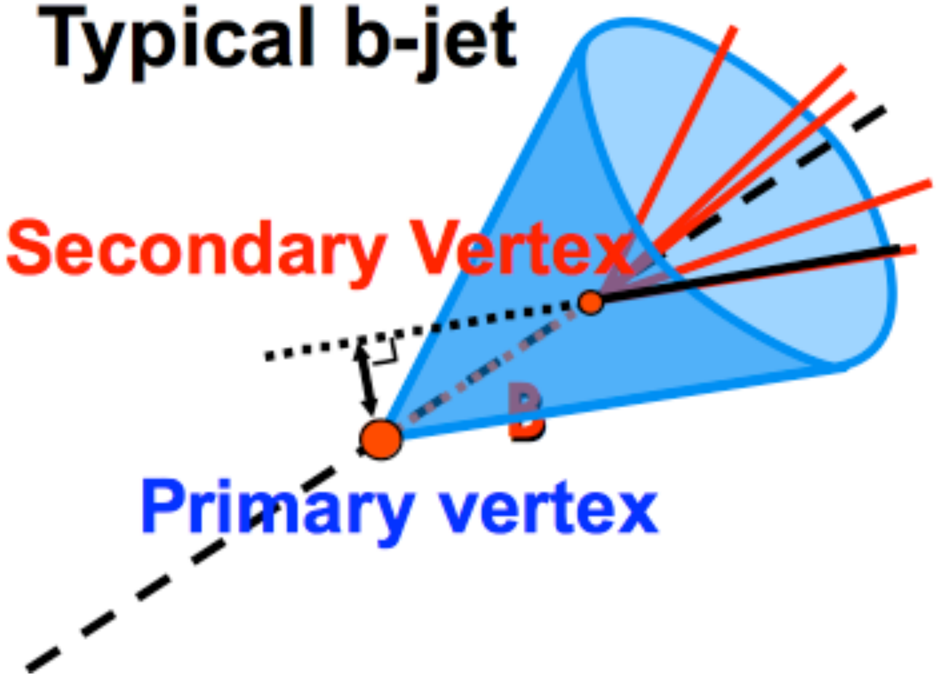
Tracking detector



PIXEL detector
Layers: 3 barrel, 3 end-caps
Pixel size: 50 μm (Rϕ) – 400 μm (z/R)
Resolution: ~10 μm (Rϕ) – ~115 μm (z/R)
~80M channels (ToT information)



Typical b-jet



- Impact parameter resolution of tracks determined by first layers of pixel detector
- Crucial to distinguish displaced tracks from b-hadron decays ($c\tau \sim 0.5$mm) from tracks from fragmentation (compatible with the primary vertex).

Impact parameter resolution

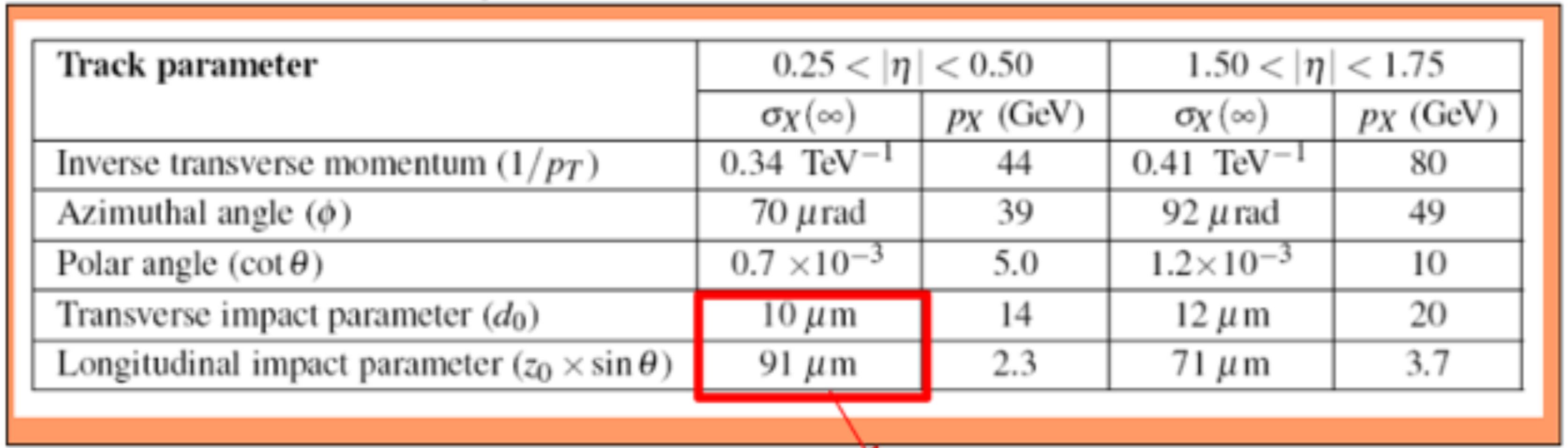
- Can be parameterized as:

$$\sigma_X(p_T) = \sigma_X(\infty)(1 \oplus p_X / p_T)$$

Intrinsic resolution at high p_T

Value of p_T where intrinsic resolution equals multiple scattering

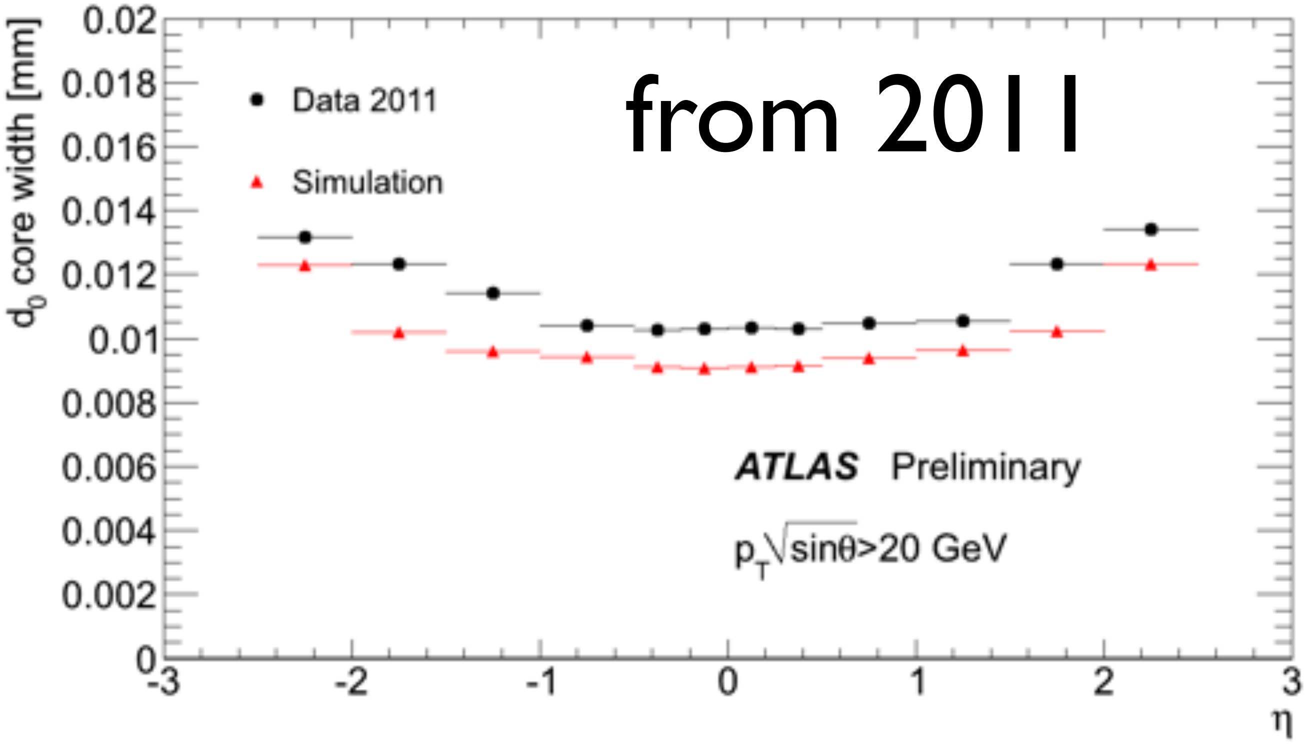
Nominal track parameter resolutions:



Track parameter	$0.25 < \lvert\eta\rvert < 0.50$		$1.50 < \lvert\eta\rvert < 1.75$	
	$\sigma_X(\infty)$	p_X (GeV)	$\sigma_X(\infty)$	p_X (GeV)
Inverse transverse momentum ($1/p_T$)	0.34 TeV^{-1}	44	0.41 TeV^{-1}	80
Azimuthal angle (ϕ)	70 μrad	39	92 μrad	49
Polar angle ($\cot\theta$)	0.7×10^{-3}	5.0	1.2×10^{-3}	10
Transverse impact parameter (d_0)	10 μm	14	12 μm	20
Longitudinal impact parameter ($z_0 \times \sin\theta$)	91 μm	2.3	71 μm	3.7

Directly determined by first pixel layers!

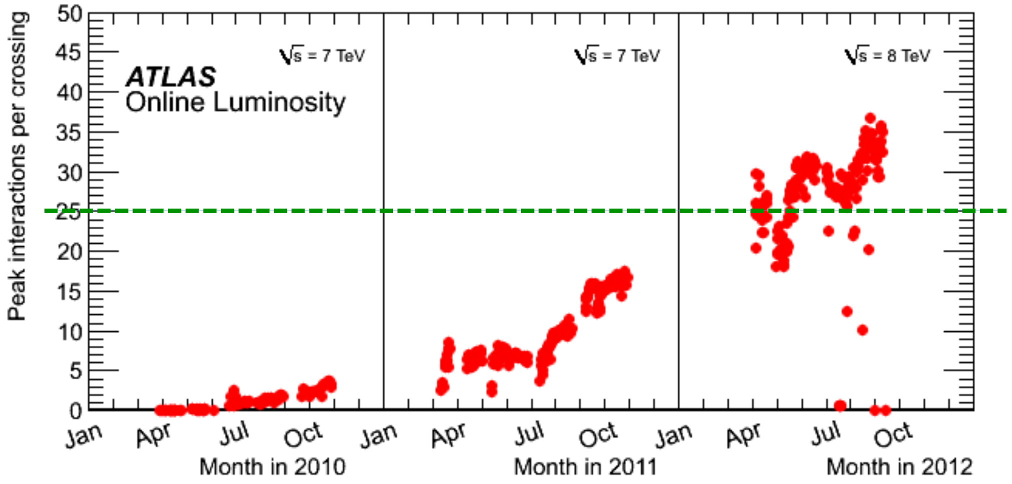
- Measured in data
- After improvements in alignment iterations ~reached nominal resolution goal (wasn't the case in 2011).



from 2011

Primary vertex reconstruction

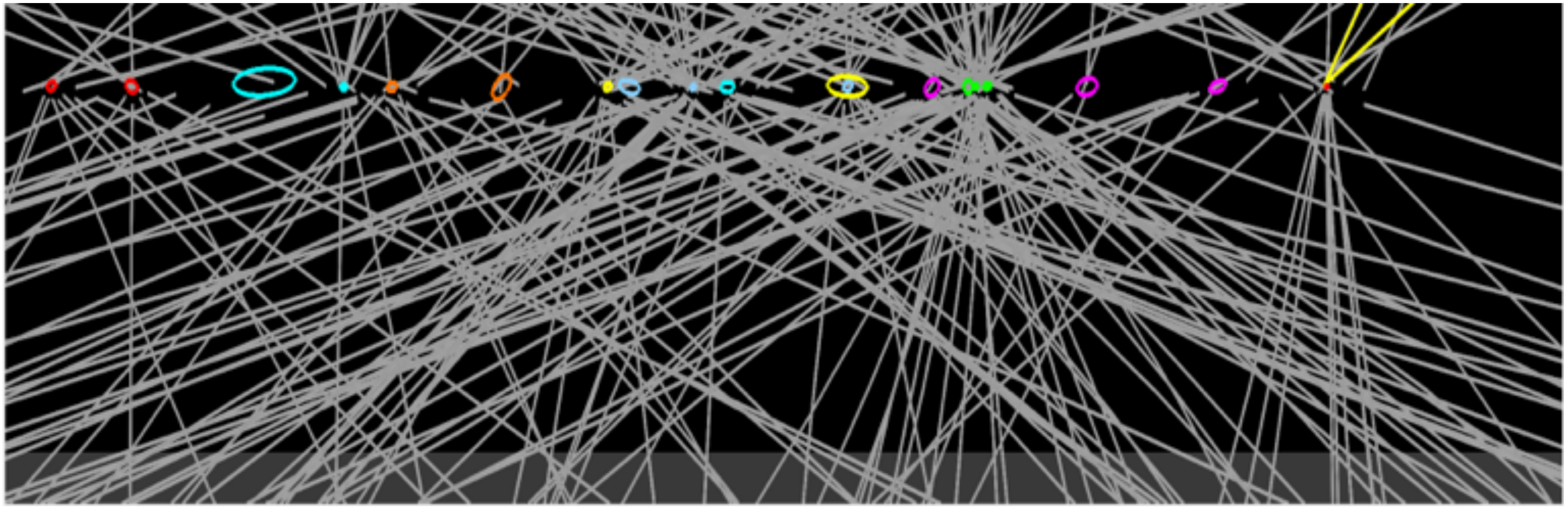
- The main challenge is the the reconstruction of multiple vertices due to pile-up.



- Present strategy: iterative vertex finder. Outliers of first vertex used to find further vertices

$$\chi^2 = \sum_{k=1}^{N} \omega_k(\chi_k^2) \sum_i \left(\frac{\vec{r}-\vec{r}_k}{\vec{\sigma}_k}\right)_i^2$$

- "Adaptive" vertex fitter used. Downweights outliers smoothly iteration after iteration.



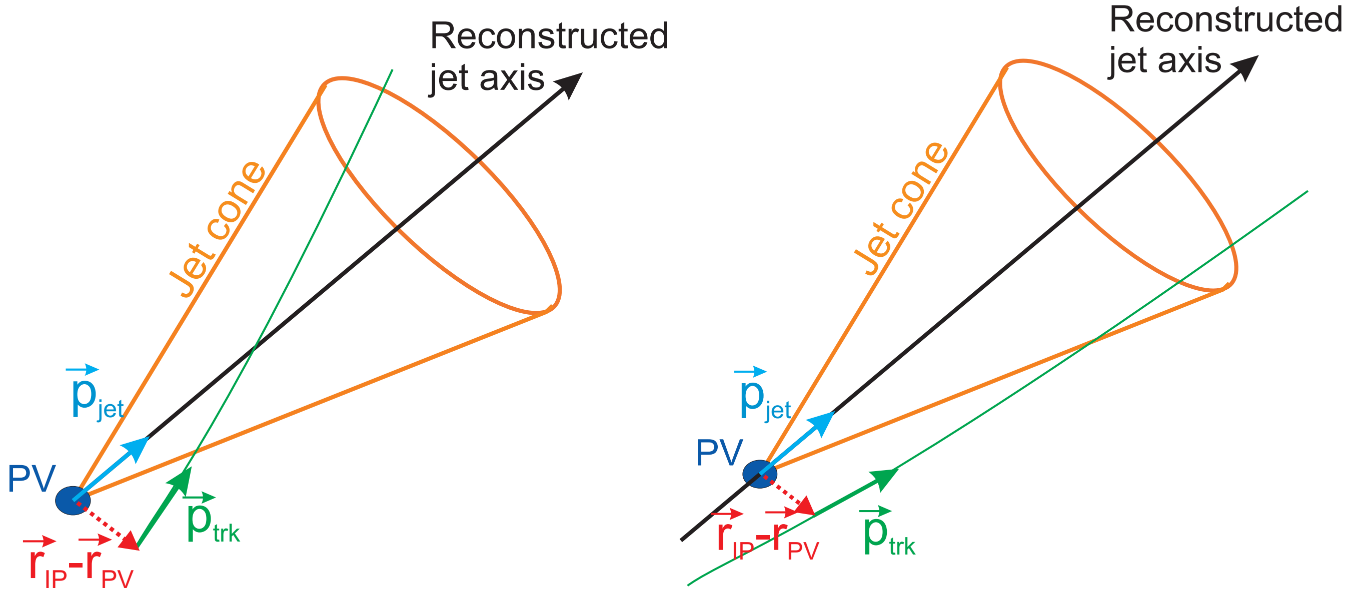
Event reconstructed in 2011 data with 20 vertices!

The PV error ellipses are magnified by 20x.

B-tagging algorithms

- Two main categories:
  - “Lifetime” based
    - Impact parameter based
      → exploit (in)compatibility of single tracks to PV
    - Inclusive secondary vertex based
      → determination of weak B hadron decay vertex +
      production / **decay** properties
    - PV → b- → c-hadron decay chain based
      → more detailed determination of vertex topology
  - “Lepton-ID” based
    → Exploit identification of muons from B or B → D decay

Impact parameter algorithm

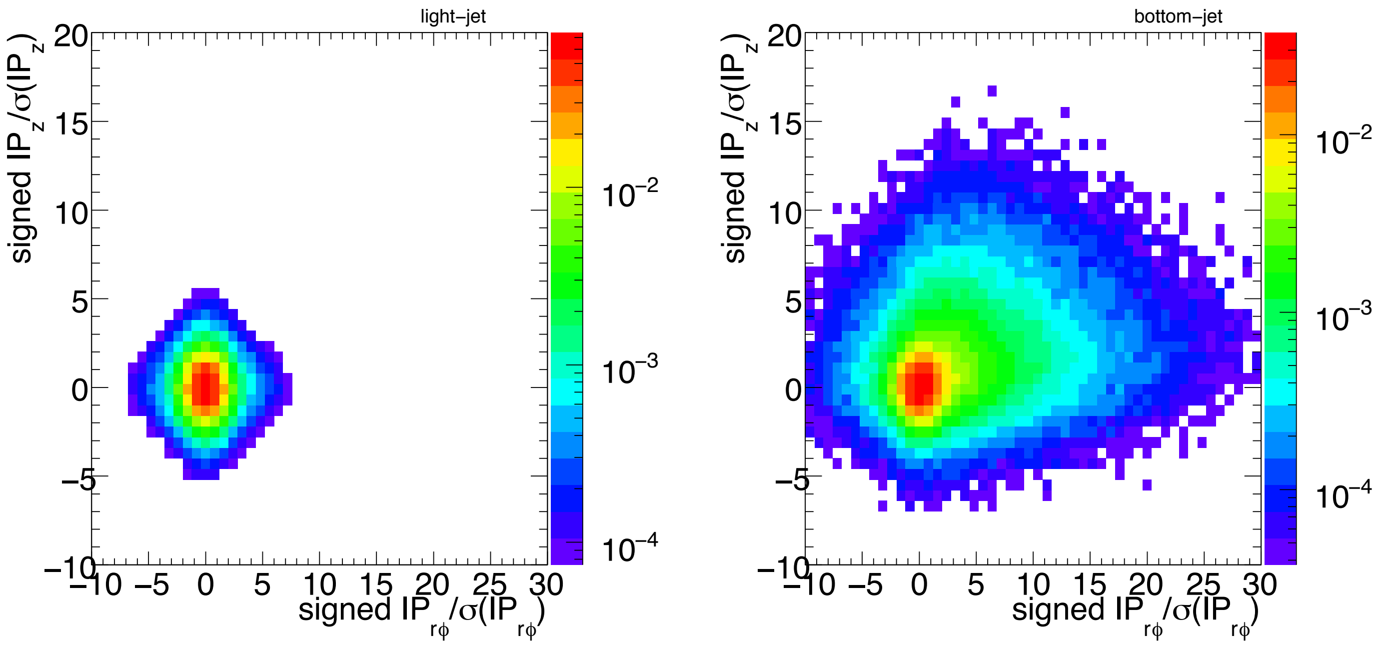


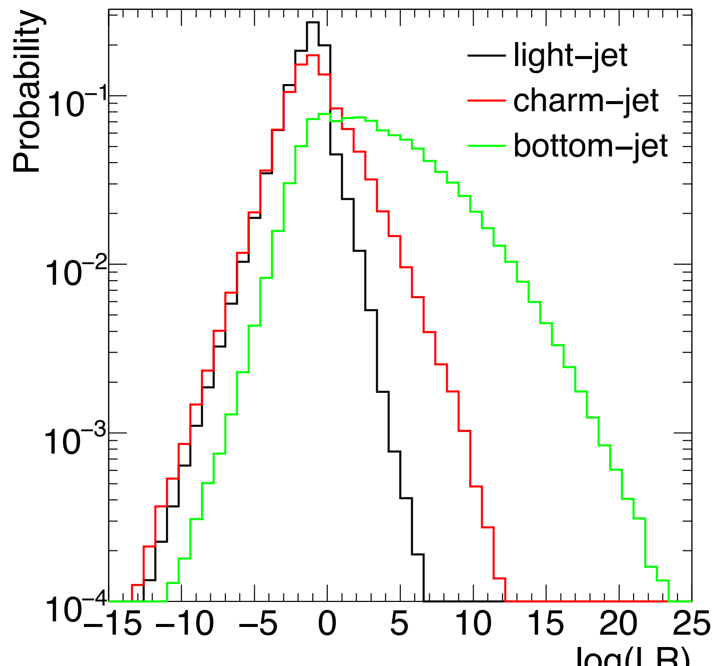
$$\mathrm{sign}_{r\phi} = \mathrm{sign}\left(\sin(\phi_{jet} - \phi_{trk}) \cdot d_{0,trk}\right)$$
$$\mathrm{sign}_{3D} = \mathrm{sign}\left([\vec{p}_{trk} \times \vec{p}_{jet}] \cdot [\vec{p}_{trk} \times \Delta\vec{r}_{IP}]\right)$$

- For each track define 2d likelihood with IP significance in rφ and z
- Assign lifetime sign to both of them
- Compute LH as:

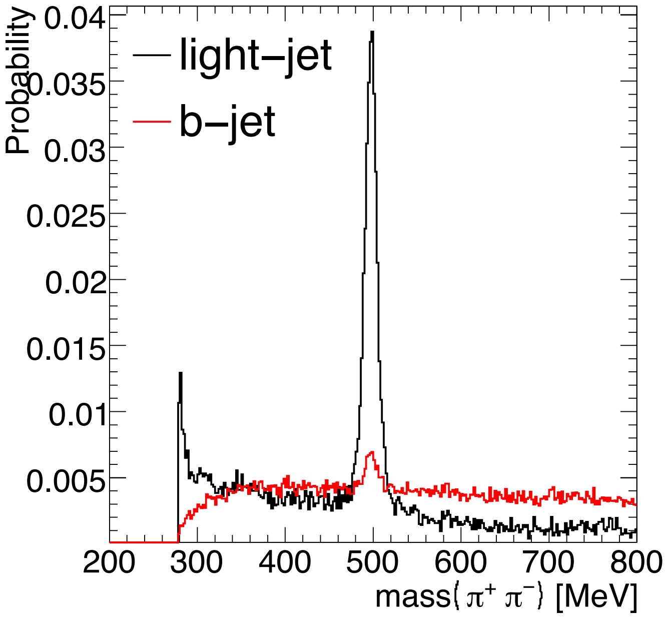
$$\mathtt{LR}(IP_1, IP_2, ..., IP_N) = \frac{\prod_{i=1}^{N} \mathrm{PDF}_b(IP_i)}{\prod_{i=1}^{N} \mathrm{PDF}_l(IP_i)}$$

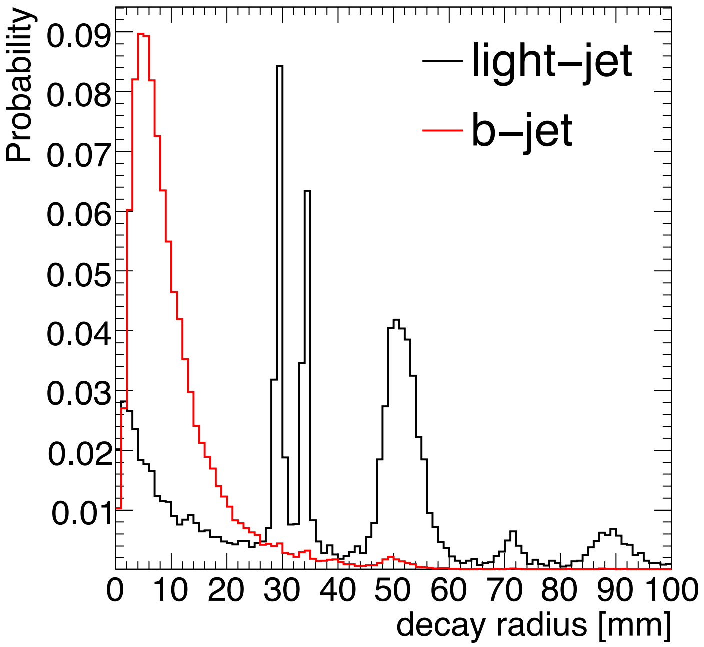
$$\mathtt{weight}(IP_1, IP_2, ..., IP_N) = \log\left(\mathtt{LR}(IP_1, IP_2, ..., IP_N)\right)$$

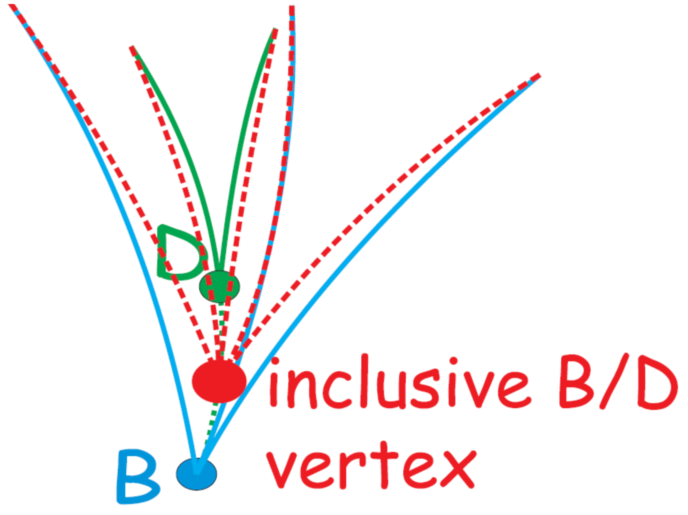




Inclusive SV algorithm

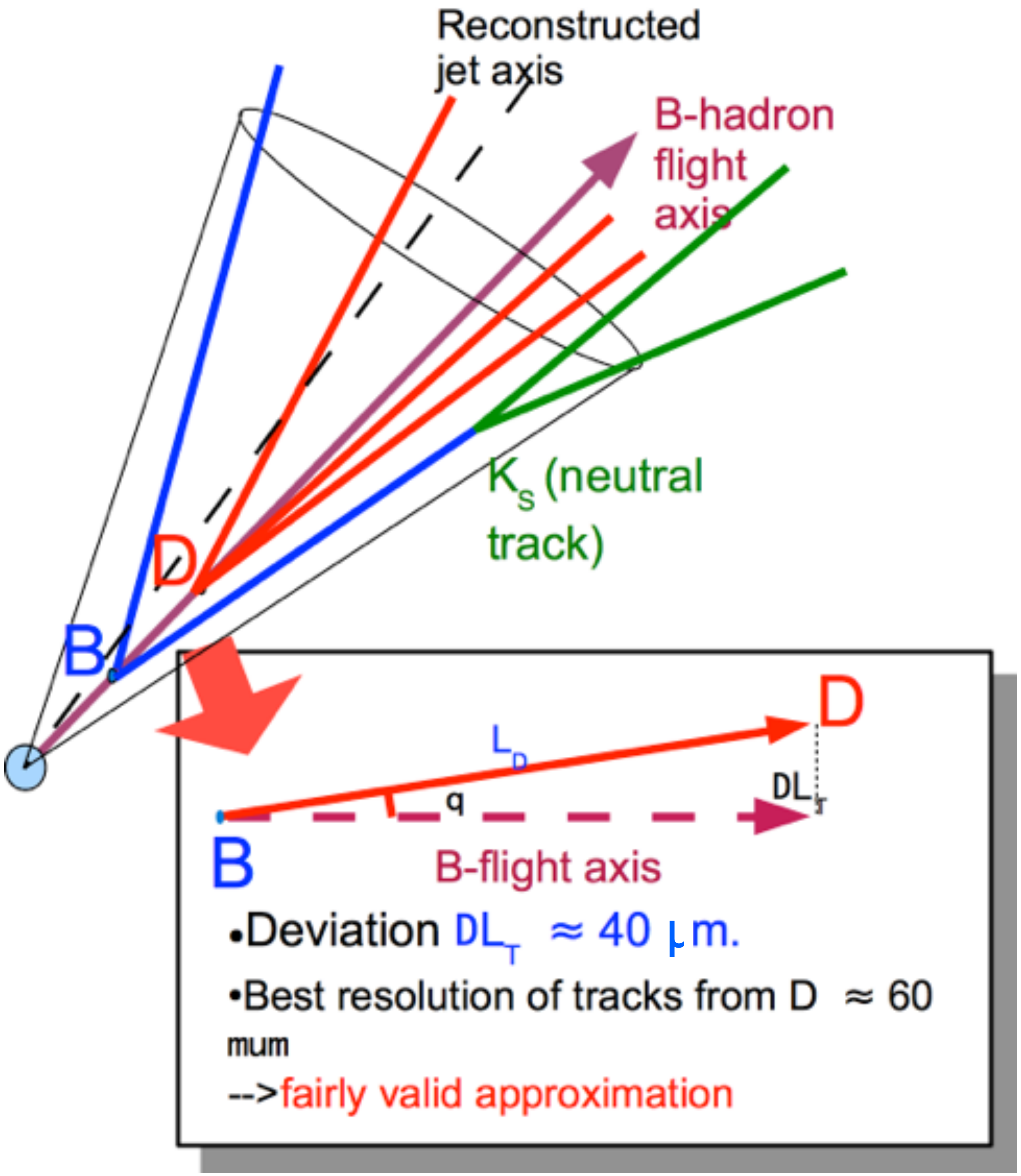






- Finding strategy:
  - Find all displaced 2-track vertices within the jet
  - Remove all vertices with di-track mass compatible with KS, Lambda decay, or photon conversion.
  - Remove all vertices in correspondence of pixel layers (likely to stem from material interactions).
- Using only tracks from any of the non-vetoed 2-track vertices, form a single inclusive secondary vertex (only require "loose" vertex with Prob(χ^2)>0.1%)
- Combine variables:
  - invariant mass at vertex
  - # of non-vetoed 2-trk vertices
  - energy fraction of tracks at vertex w.r.t. all tracks in jets
- into a 2d+1d likelihood function.

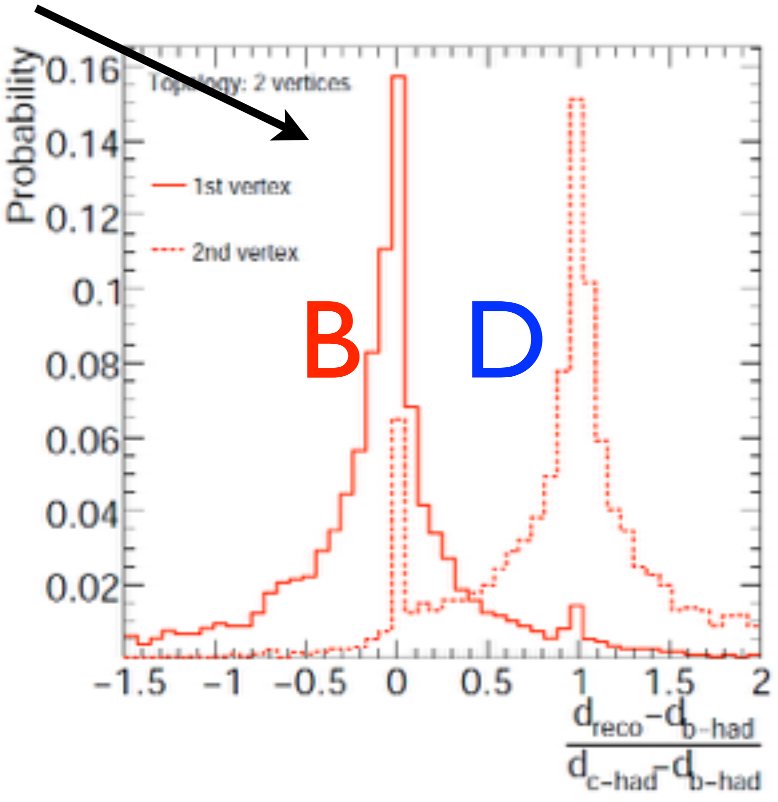
JetFitter



- Deviation $DL_T \approx 40$ μm.
- Best resolution of tracks from D ≈ 60 mum

-->fairly valid approximation

- Constraints all tracks stemming from both B/D-hadron vertices to intersect B-flight axis
- Basically a new Kalman Filter relying on the "ghost track" method first introduced in SLD [SLAC-PUB-8225 (1999)]
- **Two vertices** or 1 vertex + 1 single track reconstructed in ~6%/~14% of cases in real b-jets
- Can be used to better separate b- from c- jets

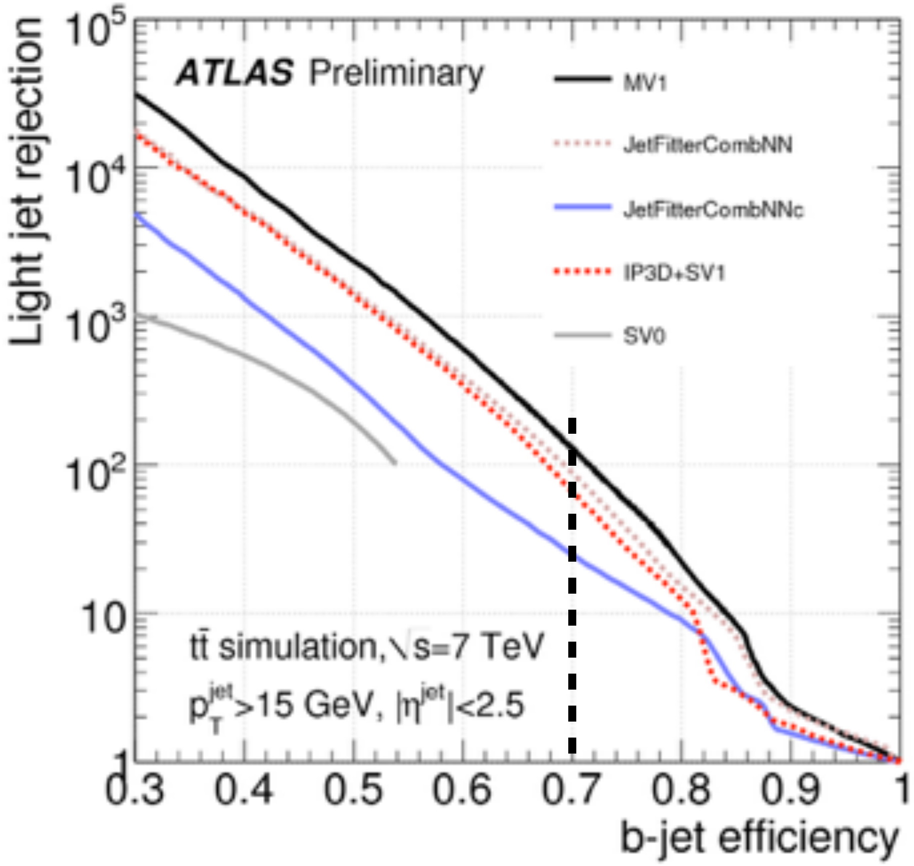


Combination of “lifetime” algorithms

weight_IP3D	LH(IP3D)
# 2-trk vertices	LH(SV1)
Energy(vtx) / Energy (tot)	
Mass	
# vertices with >1 track	NN(JetFitter)
# tracks at vertices	
# 1-track vertices	
Mass	
DeltaPhi(b-momentum, b-axis)	
DeltaEta(b-momentum, b-axis)	

Rejection = 1 / efficiency

- Combines the three discriminators into a single final Neural Network.
- Performance against light- and c-jets:



- For VH optimized b-tagging cut yields:
  - **70% b-tagging efficiency**
  - **~5 c-jet rejection**
  - **~130-150 light-jet rejection**

And in CMS?

- Very similar geometry of pixel detector (despite all-silicon tracker). Pixel size 100x150 µm instead of 50x400 µm.
- 3D impact parameter resolution very similar to ATLAS (momentum resolution much better in CMS, but doesn't impact b-tagging)
- Most advanced algorithm "CSV" (Combined Secondary Vertex)
  - Combination of impact parameter, "pseudo-vertex" and vertex algorithm
- Comparison of c-jet and light-jet rejection factors for 70% efficiency working point:
  - c-jets: ~5 (ATLAS) vs ~5 (CMS)
  - light-jets: ~130 (ATLAS) vs ~50 (CMS)
- Take comparison with some care (depends a bit on sample/cuts)

Where does it matter? ttH…

- Light jet rejection is for example critical in ttH, H to bb
- Below a comparison of the tt+light jet contamination in the main 1-lepton channel signa regions
- Light jet rejection is a bit less critical in VH, H to bb.

CMS analysis

	5 jets ≥4 b-tags	≥6 jets ≥4 b-tags
$t\bar{t}$H(125)	5.2 ± 1.4	8.3 ± 2.3
tt+lf	79 ± 34	71 ± 36
tt+b	29 ± 17	33 ± 20
$t\bar{t} + b\bar{b}$	38 ± 21	78 ± 47
$t\bar{t} + c\bar{c}$	32 ± 18	52 ± 31
$t\bar{t}$V	2.5 ± 0.7	5.8 ± 1.8
Single t	10.3 ± 5.3	7.3 ± 3.1
V+jets	1.9 ± 1.7	1.2 ± 1.3
Diboson	0.1 ± 0.1	0.2 ± 0.1
Total bkg	193 ± 62	249 ± 90
Data	219	260

ATLAS analysis

	5 jets, $\geq$ 4 b-tags	$\geq$ 6 jets, $\geq$ 4 b-tags
$t\bar{t}H$ (125)	$11 \pm 1 \pm 9$	$28 \pm 2 \pm 23$
$t\bar{t}+$ light	78 ± 9	78 ± 11
$t\bar{t} + c\bar{c}$	45 ± 12	75 ± 19
$t\bar{t} + b\bar{b}$	149 ± 20	300 ± 40
$t\bar{t} + V$	3.3 ± 1.0	8.9 ± 2.7
non-$t\bar{t}$	23.2 ± 2.5	18.8 ± 2.2
Total	309 ± 11	507 ± 27
Data	283	516

Rejecting c-jets

- Historically, most effort invested in light-jet rejection.
- More recently, dedicated algorithms to reject c-jets.
- Explicitly train NN / BDT against c-jets.
- Take advantage of secondary vertex properties and topology from JetFitter (decay chain fit).

MV1

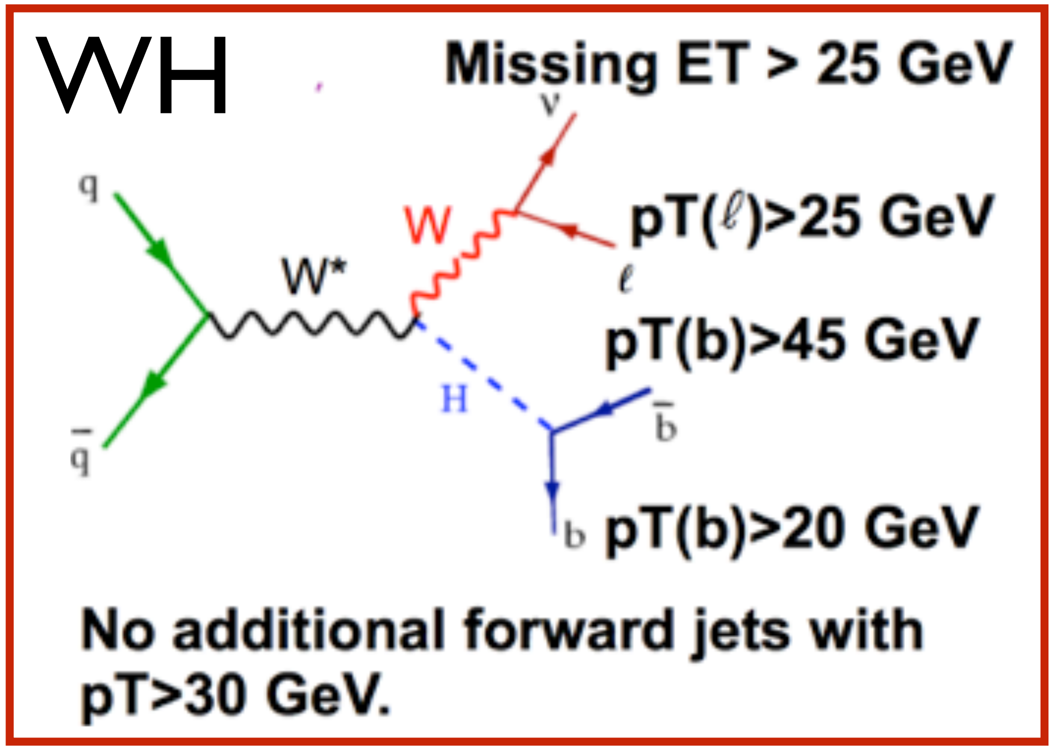
ε(B)	R(c)	R(light)
80%	~3	~27
70%	~5.0	~150
60%	~8.0	~650
50%	~14	~2500
30%	~78	~40k

MV1c

ε(B)	R(c)	R(light)
80%	~3	~29
70%	~5.3	~136
60%	~10.5	~450
50%	~26	~1400
30%	~212	~16k

Where does it matter? VH…

- In the VH, H to bb analysis, in the 1-lepton channel (WH)
- ttbar is the leading background (and will be more so at 14 TeV)



Missing ET > 25 GeV

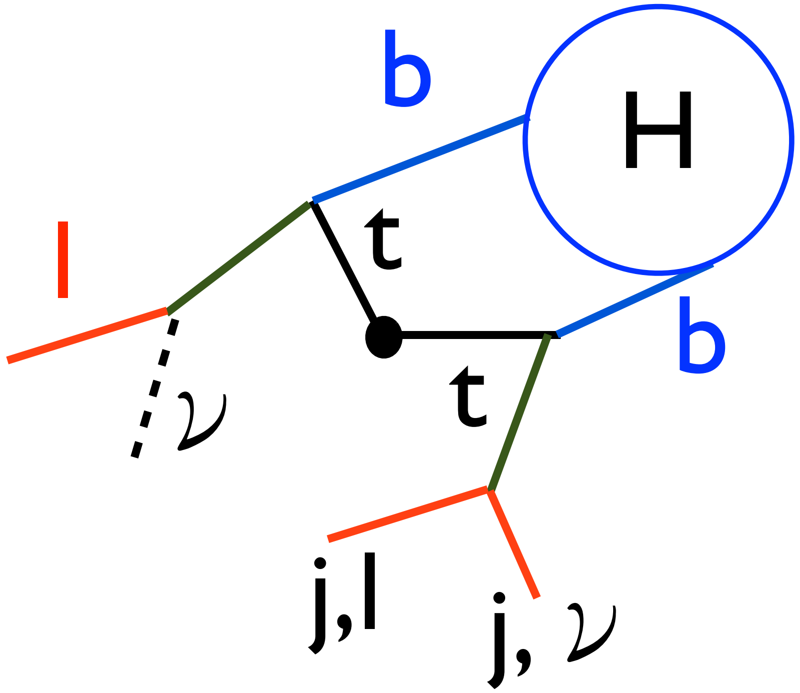
pT(ℓ)>25 GeV

pT(b)>45 GeV

pT(b)>20 GeV

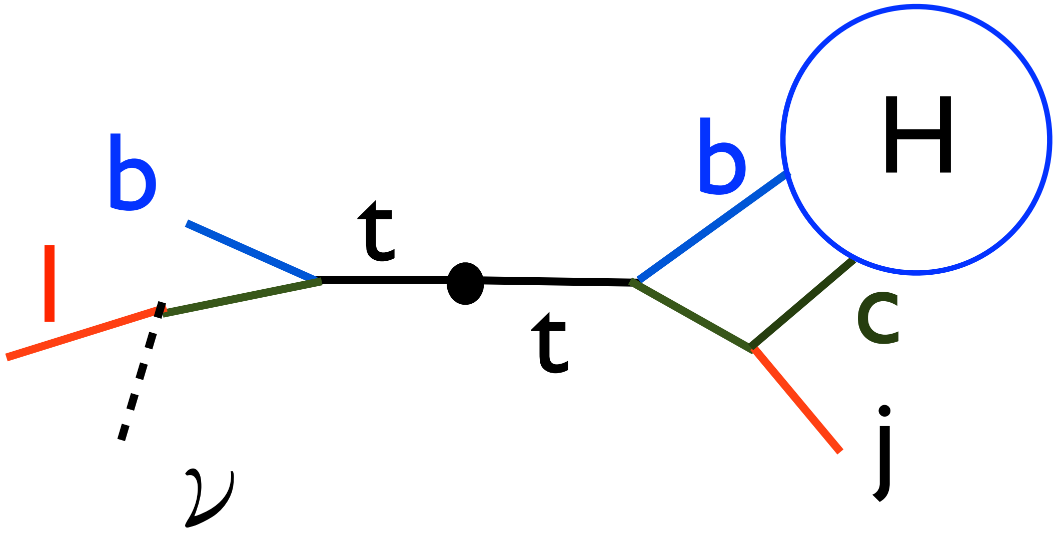
No additional forward jets with pT>30 GeV.

low pT(V)



b-tagging doesn't help!

high pT(V) - "boosted" analysis



b+c-jets: c-jet rejection crucial!

From c-jet rejection to c-tagging

- Neural Network trained against both light- and c-charm jets, with three output nodes (Pb,Pc,Pu)
- Uses combination of cuts on log(Pb/Pc) and log(Pc/Pu)
- Presently used for SUSY analysis with c-quarks in the final state
- Presently proposed working points:
    - c-tag eff: 20% → b-jet eff: 20%, light-jet eff: ~0.7%
    - c-tag eff: 95% → b-jet eff. 50%, light-jet eff: ~100%
- Algorithm being refined through the use of Deep Neural Networks
- But main problem is that in most of the discriminant variables c-jets are always between light- and b-jets.

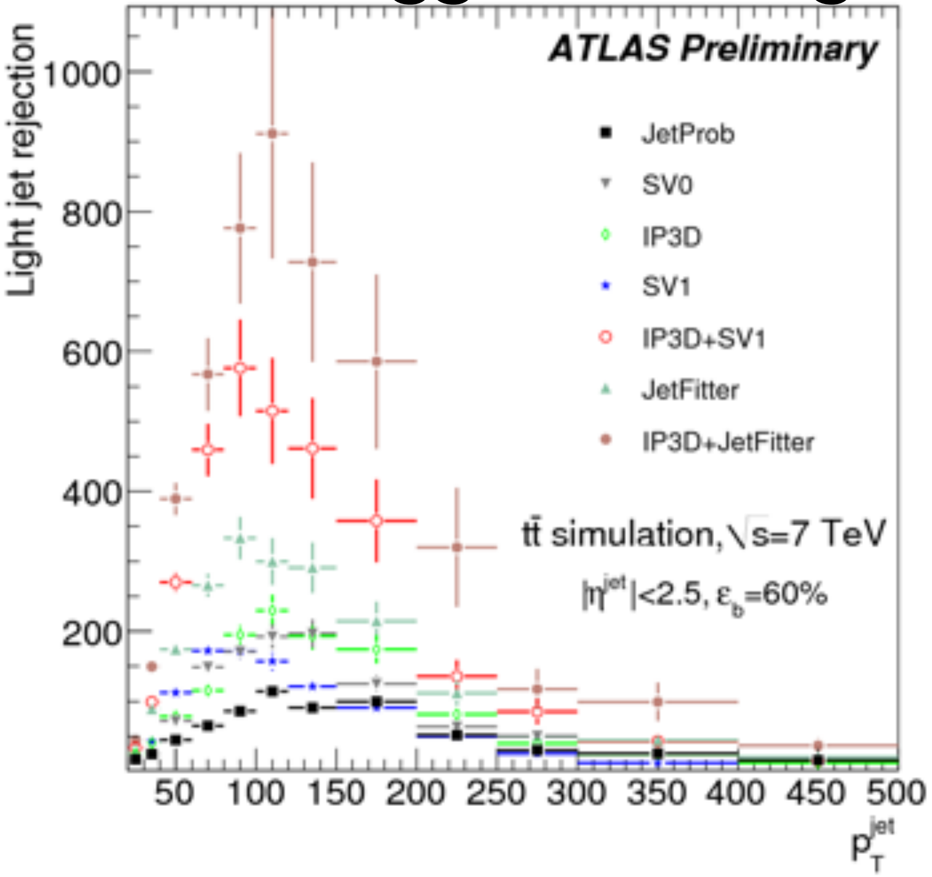
Higgs to cc ?

- Higgs to cc BR is ~2.9%, against ~57% of bb (20 times smaller)
- "C"-tagging for now is not able to reduce b-jet much more than c-jets:
  - Efficiency for c-jets significantly lower than for b-jets (ε_c^2)
  - Background from b-jets not significantly suppressed
  - Additional backgrounds from c+b and c+c (e.g. top rejection at high pT won't work anymore)
- Without really a significant improvement in b-tagging, Higgs to cc seems out of reach.

Performance calibration

- Performance is not everything
- Efficiencies/rejections need to be calibrated with data
- The calibration uncertainty can be a limiting systematics in analysis with b-jets (dominant systematics in the VH EPS 2013 analysis!)

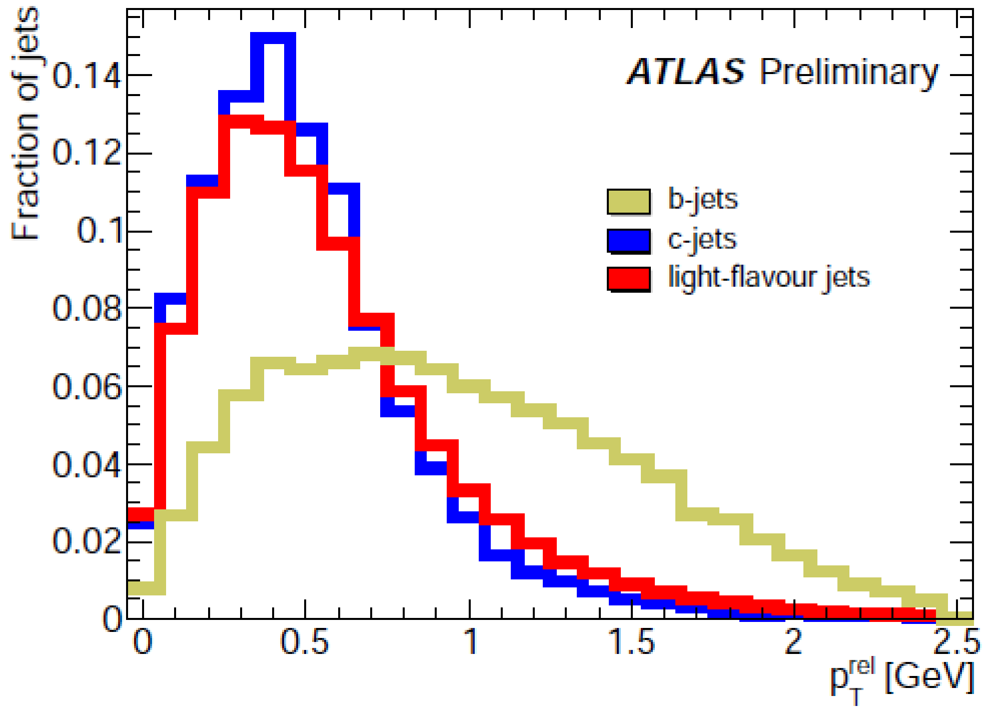
Standard tagger missing in this plot



- Both ATLAS and CMS have developed a complete set of calibration measurements, for b-, c- and light-jets
- Will briefly describe the main techniques

B-jet calibration in ATLAS

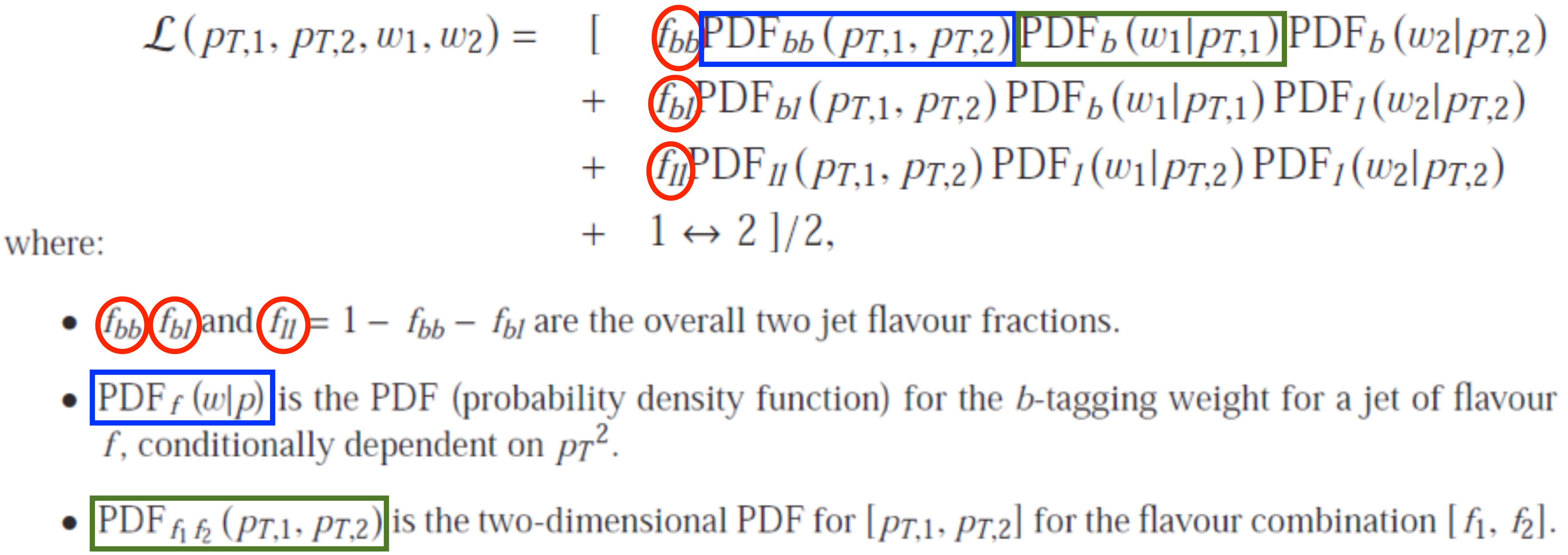
- Previously main calibration method was "pTrel", based on having two nearly independent taggers, a "muon" and a "lifetime" based one



- The dominant systematics with this method is the extrapolation of the MC-to-data Scale Factor from b-jets with B →μ+X to inclusive b-jets
  - ATLAS estimated such uncertainty to be ~4%, but no good way to rigorously justify it (+ no correlation model vs pT).
  - CMS claims this is a percent level effect and therefore negligible

B-jet calibration in ATLAS (II)

- Will present most precise of the calibrations based on ttbar events.
- Within the H to bb analysis group, we designed a new calibration method, based on applying a maximum likelihood fit to di-leptonic ttbar events with 2 jets:



$$\begin{aligned}\mathcal{L}(p_{T,1}, p_{T,2}, w_1, w_2) = \quad [\quad & \enclose{circle}{f_{bb}}\,\boxed{\mathrm{PDF}_{bb}(p_{T,1}, p_{T,2})}\,\boxed{\mathrm{PDF}_b(w_1|p_{T,1})}\,\mathrm{PDF}_b(w_2|p_{T,2}) \\ + \quad & \enclose{circle}{f_{bl}}\,\mathrm{PDF}_{bl}(p_{T,1}, p_{T,2})\,\mathrm{PDF}_b(w_1|p_{T,1})\,\mathrm{PDF}_l(w_2|p_{T,2}) \\ + \quad & \enclose{circle}{f_{ll}}\,\mathrm{PDF}_{ll}(p_{T,1}, p_{T,2})\,\mathrm{PDF}_l(w_1|p_{T,2})\,\mathrm{PDF}_l(w_2|p_{T,2}) \\ + \quad & 1 \leftrightarrow 2\,]/2,\end{aligned}$$

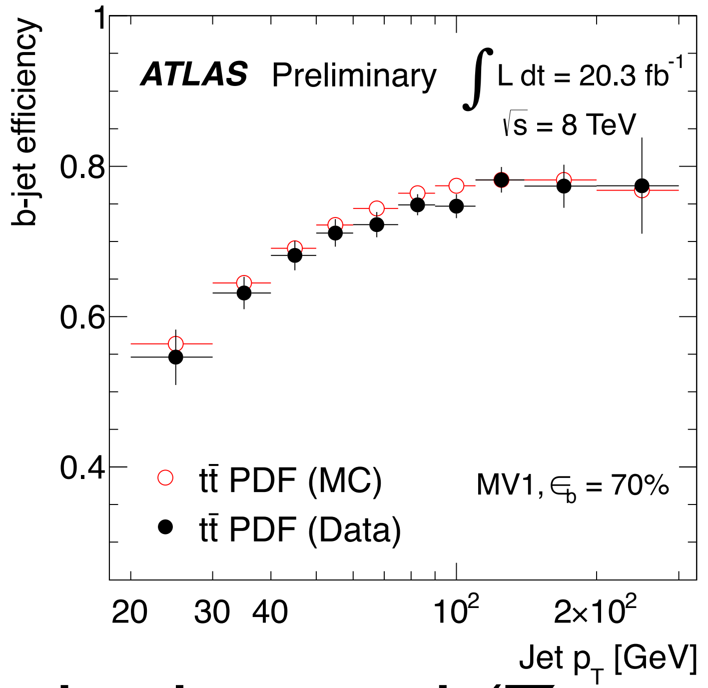
where:

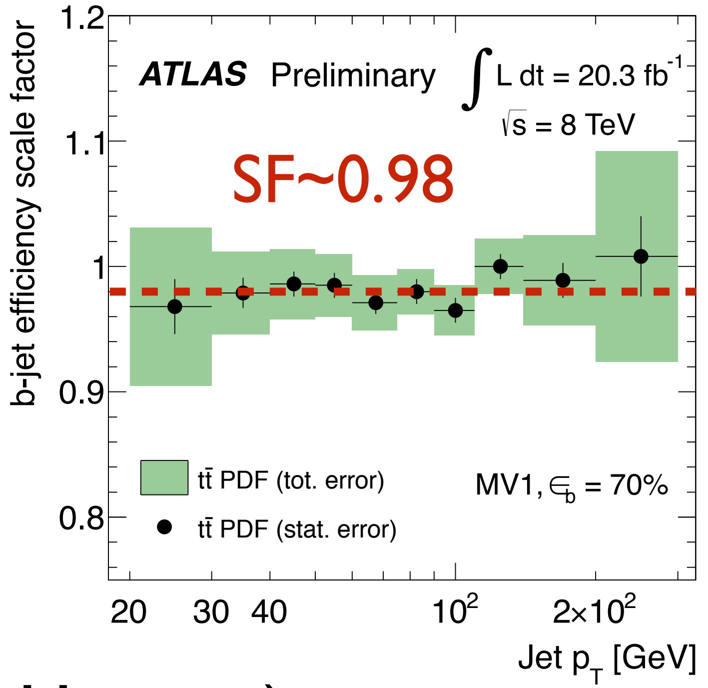
- $\enclose{circle}{f_{bb}}$, $\enclose{circle}{f_{bl}}$ and $\enclose{circle}{f_{ll}} = 1 - f_{bb} - f_{bl}$ are the overall two jet flavour fractions.
- $\boxed{\mathrm{PDF}_f(w|p)}$ is the PDF (probability density function) for the b-tagging weight for a jet of flavour f, conditionally dependent on p_T[2].
- $\boxed{\mathrm{PDF}_{f_1 f_2}(p_{T,1}, p_{T,2})}$ is the two-dimensional PDF for $[p_{T,1}, p_{T,2}]$ for the flavour combination $[f_1, f_2]$.

B-jet calibration in ATLAS (III)

- Flavor fractions and non b-jet efficiencies from MC.
- Fit extracts from data b-jet efficiency in bins of pT(jet)
- B-efficiency uncertainty reduced from ~5% to ~2% in intermediate pT region

SF = eff(data)/eff(MC)

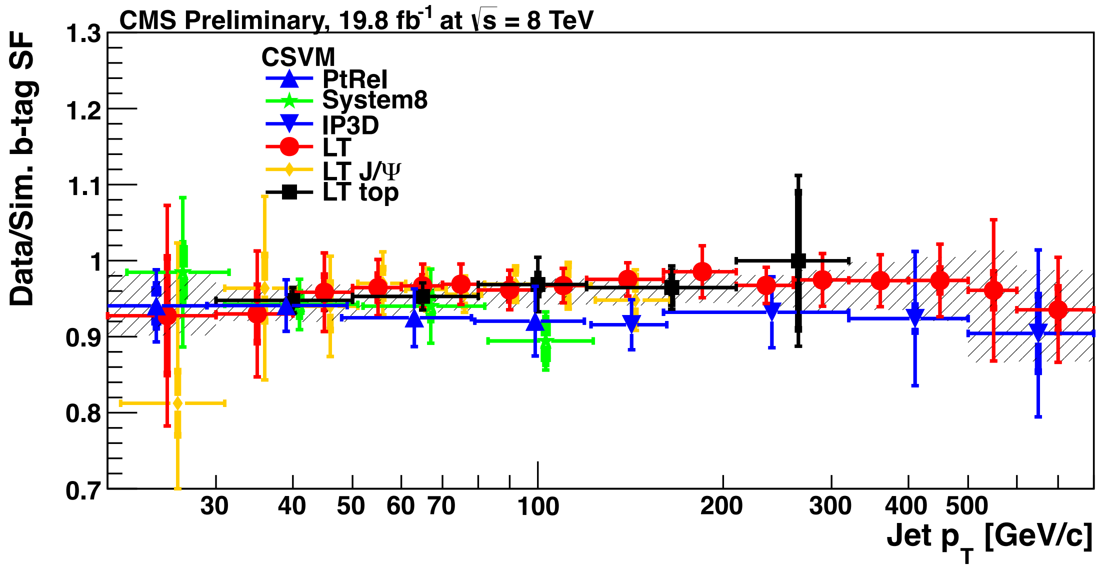




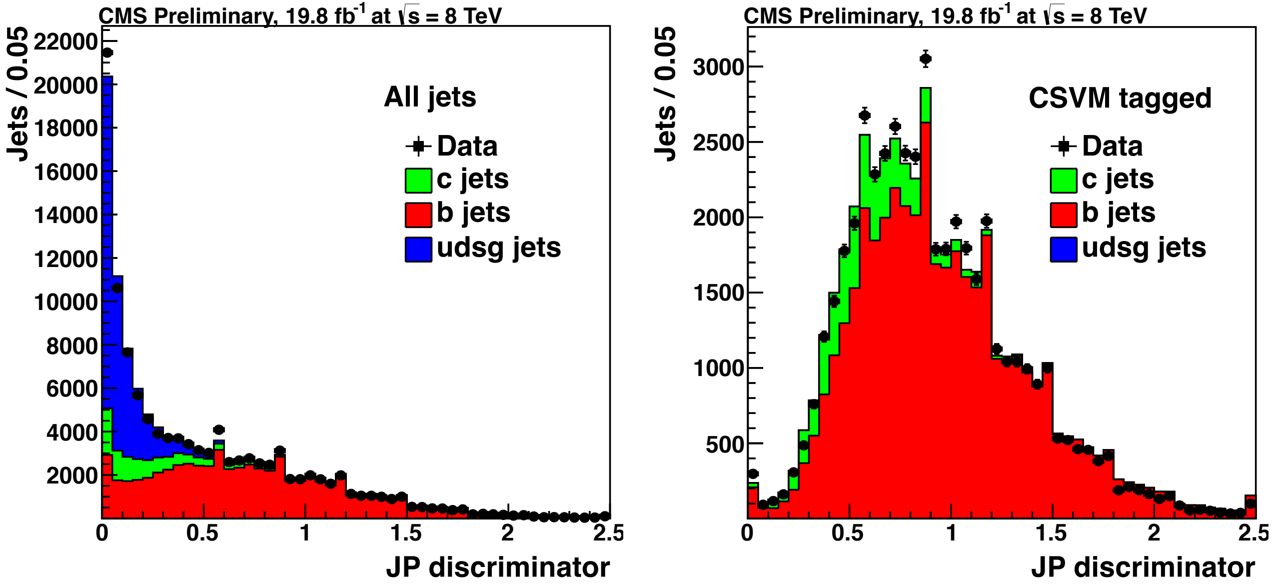
- Leading systematics:
  - Top pair modeling
  - Amount of residual non-top background (Z+jets, diboson)
  - Jet energy scale, jet energy resolution
- Uncertainty on pT dependence still significantly impacts ATLAS top mass measurement.

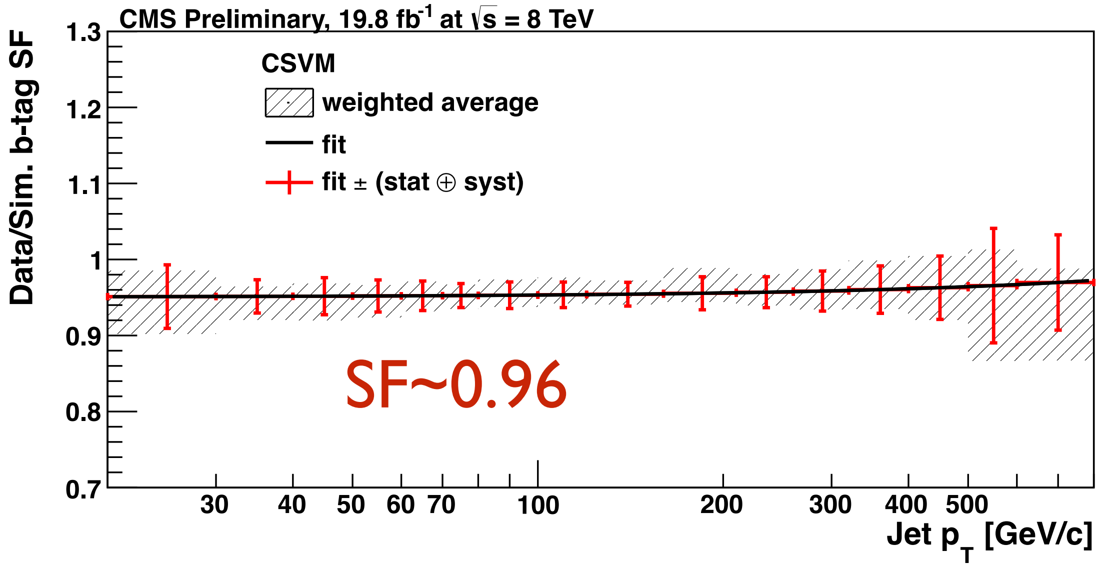
B-jet calibration in CMS

- Main calibration provided by multi-jet events:
  - Either using muon in jets
  - Or using cross-calibration of different taggers (e.g. Jet Probability (JP) based on impact parameters before/after applying a cut on the algorithm to calibrate)



before / after tagging





SF~0.96

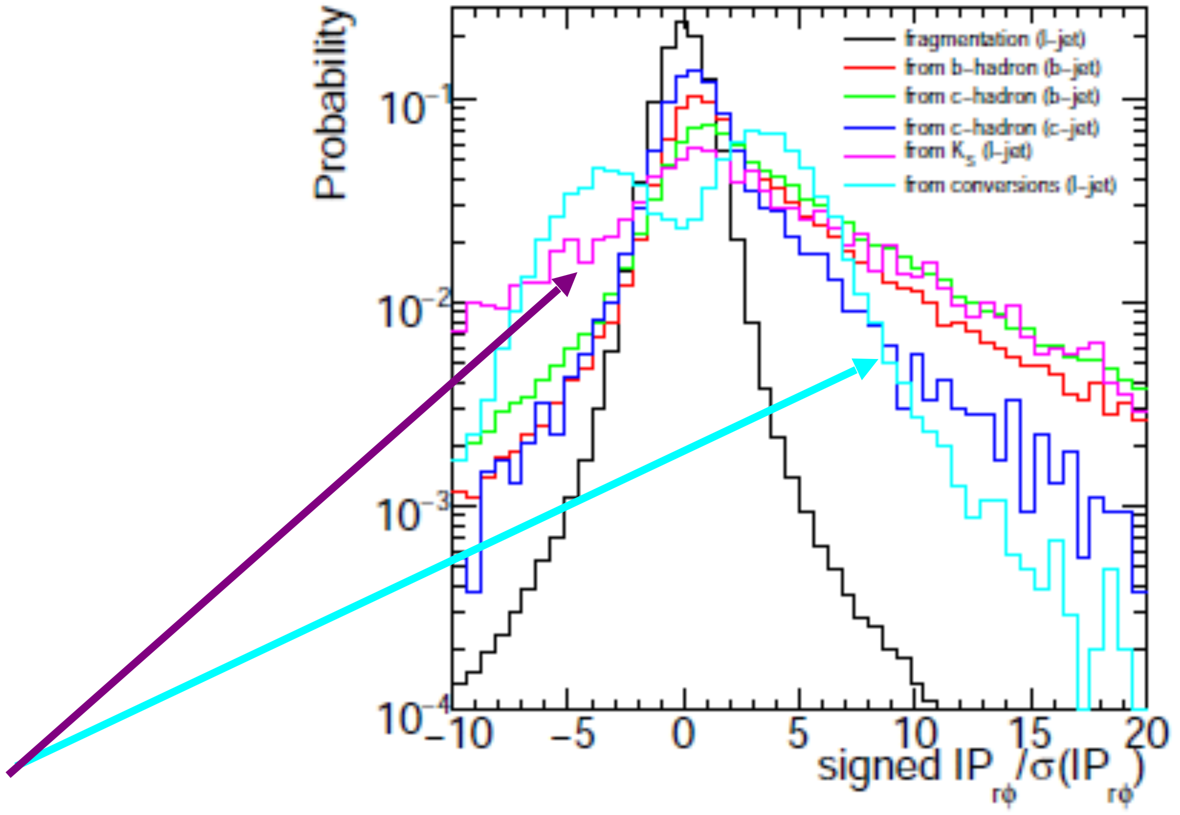
- While these methods introduce some MC dependence, they have the advantage that they allow to calibrate jets well above 200 GeV (for which ATLAS right now only uses MC extrapolation).
- At lower pT (20-200 GeV) a precision of 2-4% is obtained. Still relies mostly on multijet events, while the top based measurement has still larger uncertainties.

Light-jet calibration

- Relying mainly on negative tag method
    - Hypothesis: tracks from light jets are symmetric with respect to their lifetime sign.
- Procedure: use "fake tracks or vertices" with negative lifetime sign to emulate the ones with positive sign
- However two corrections are needed to ε(neg):
    - $k_{hf} = \varepsilon_l^{\mathrm{neg}} / \varepsilon_{\mathrm{inc}}^{\mathrm{neg}}$ due to the contamination of tracks from b- and c-jets
    - $k_{ll} = \varepsilon_l / \varepsilon_l^{\mathrm{neg}}$, because of tracks in light jets which are not symmetric in lifetime sign (e.g. from conversions, Ks, Λs, …)
- Mistag rate determined as:

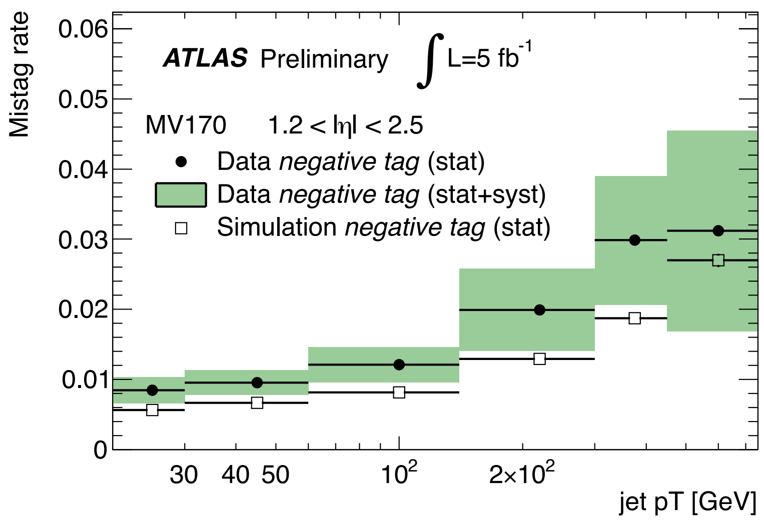
$$\varepsilon_l = \varepsilon_{\mathrm{inc}}^{\mathrm{neg}}\, k_{hf}\, k_{ll}$$

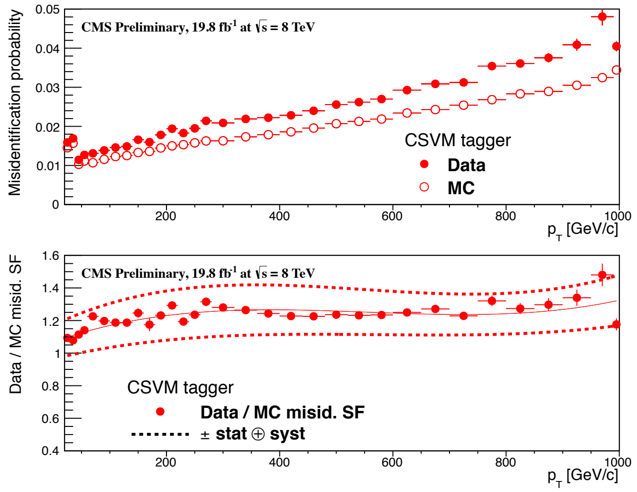
- Errors of the order of ~30%
- CMS uses ~same method, but ends up with smaller uncertainties.



ATLAS

CMS





Upgrade for Run-II

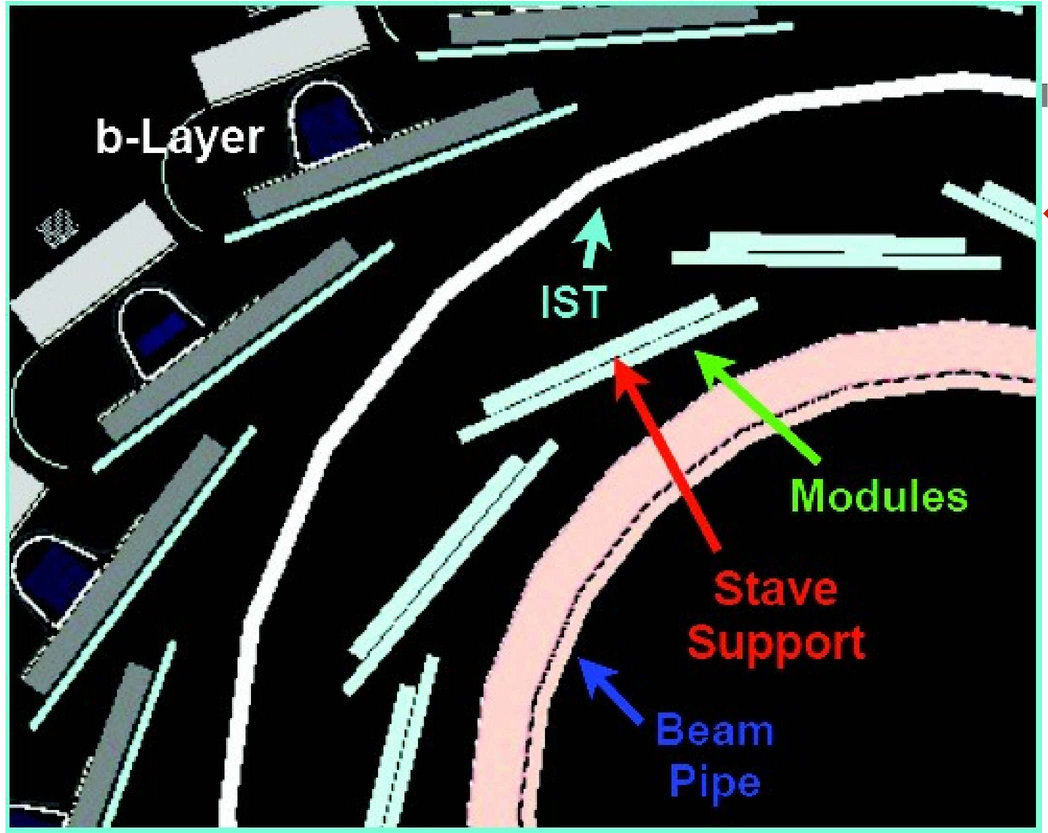
IBL:

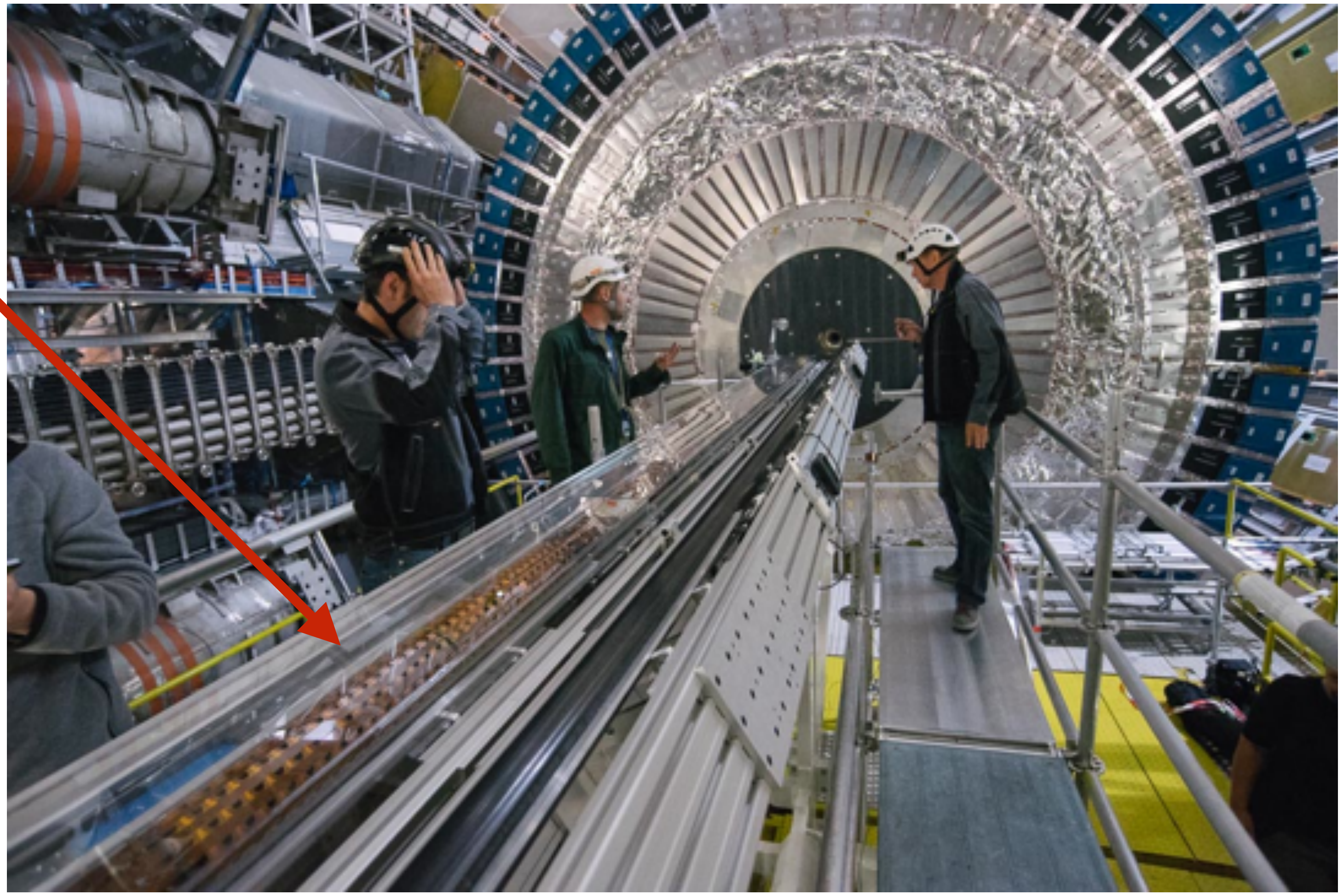
- Additional pixel layer R~3.3 cm
- Pixel size 50x250µm

ATLAS “b”-layer:

- R~5.1 cm, pixel size 50x400µm

- Insertable B Layer: new pixel layer, closer to interaction point
- It is installed on top of a new (thinner) beam pipe
- Was inserted into ATLAS on May 7th 2014.
- Planar sensors in central region, 3d sensors in forward region.

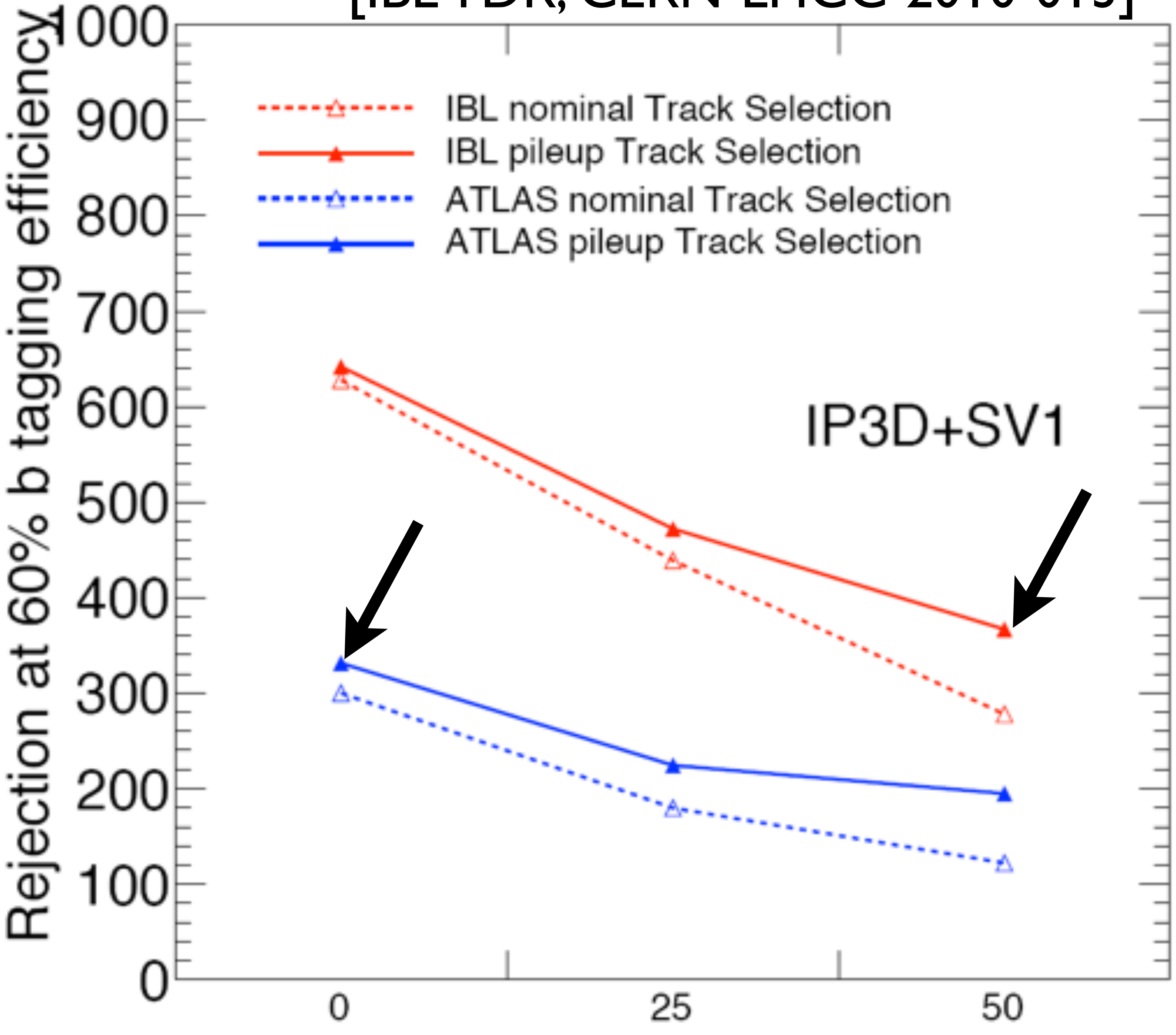




B-tagging performance with IBL

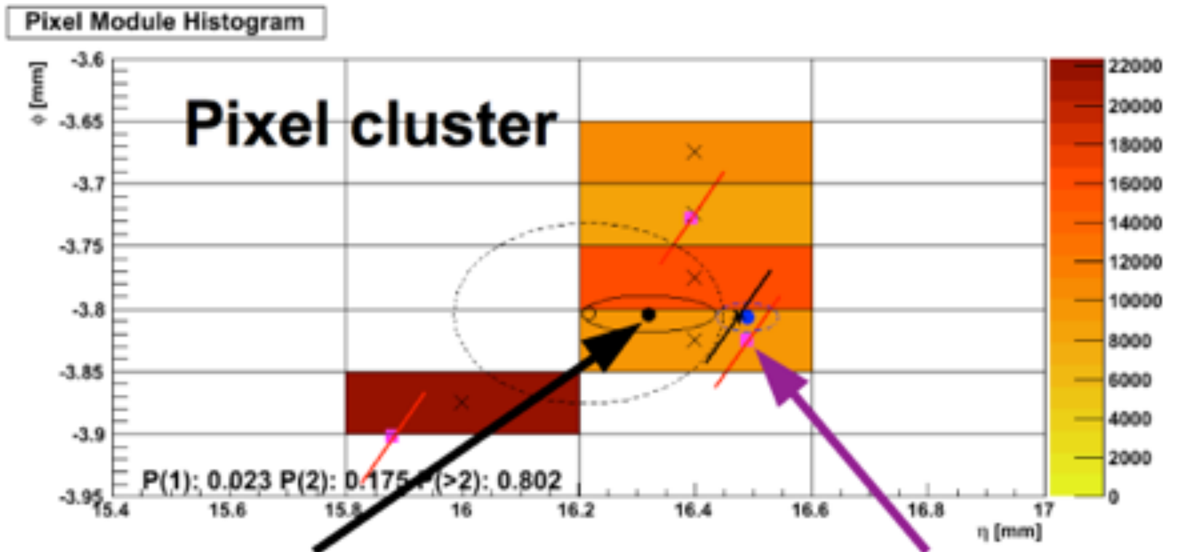
- Tracking resolution: multiple scattering term reduced by ~70%, intrinsic resolution in z improved by ~80% for |η|<0.4

[IBL TDR, CERN-LHCC-2010-013]



- B-tagging (top pair events):
  - factor 2 improvement in light-jet rejection
  - counteracts degradation due to up to ~50 additional pile-up interactions
- More detailed studies show:
  - Improvement mostly at low pT (up to x3-4).
  - Performance for pT>200 GeV nearly unchanged.

Tracking in the core of high pT jets

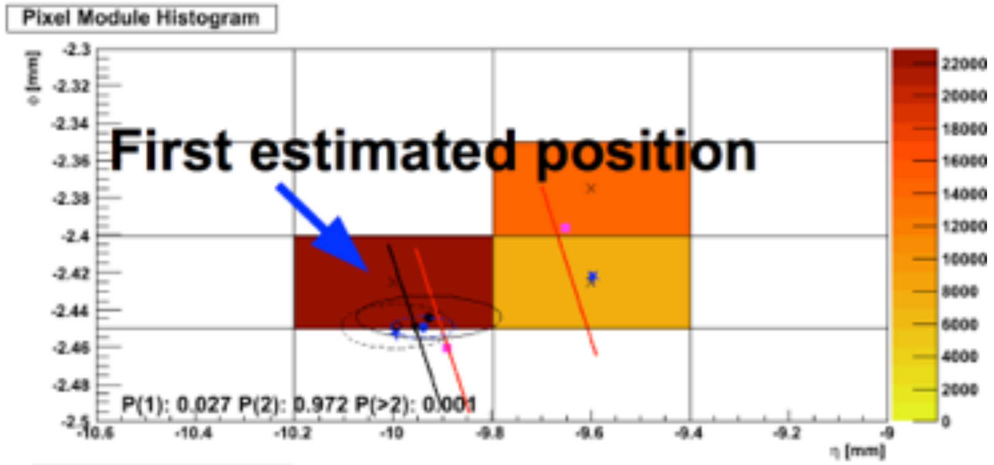


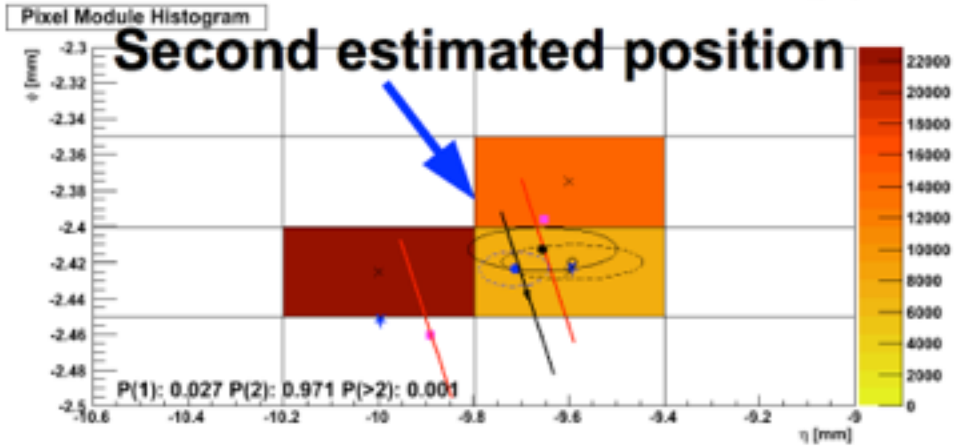
Only one (biased!) track!

True particle impact points

- Degradation due to collimated tracks in core of high pT jets: for R~3cm already relevant at pT ~ O(200 GeV)
  - relevant for VH analysis at high pT(V)

- Neural Network based clustering: allows to identify and split correctly most of the shared clusters
- Status: already commissioned with present pixel detector, now being retuned for IBL.
- Aim: be able to exploit the improved track resolution also at high pT!



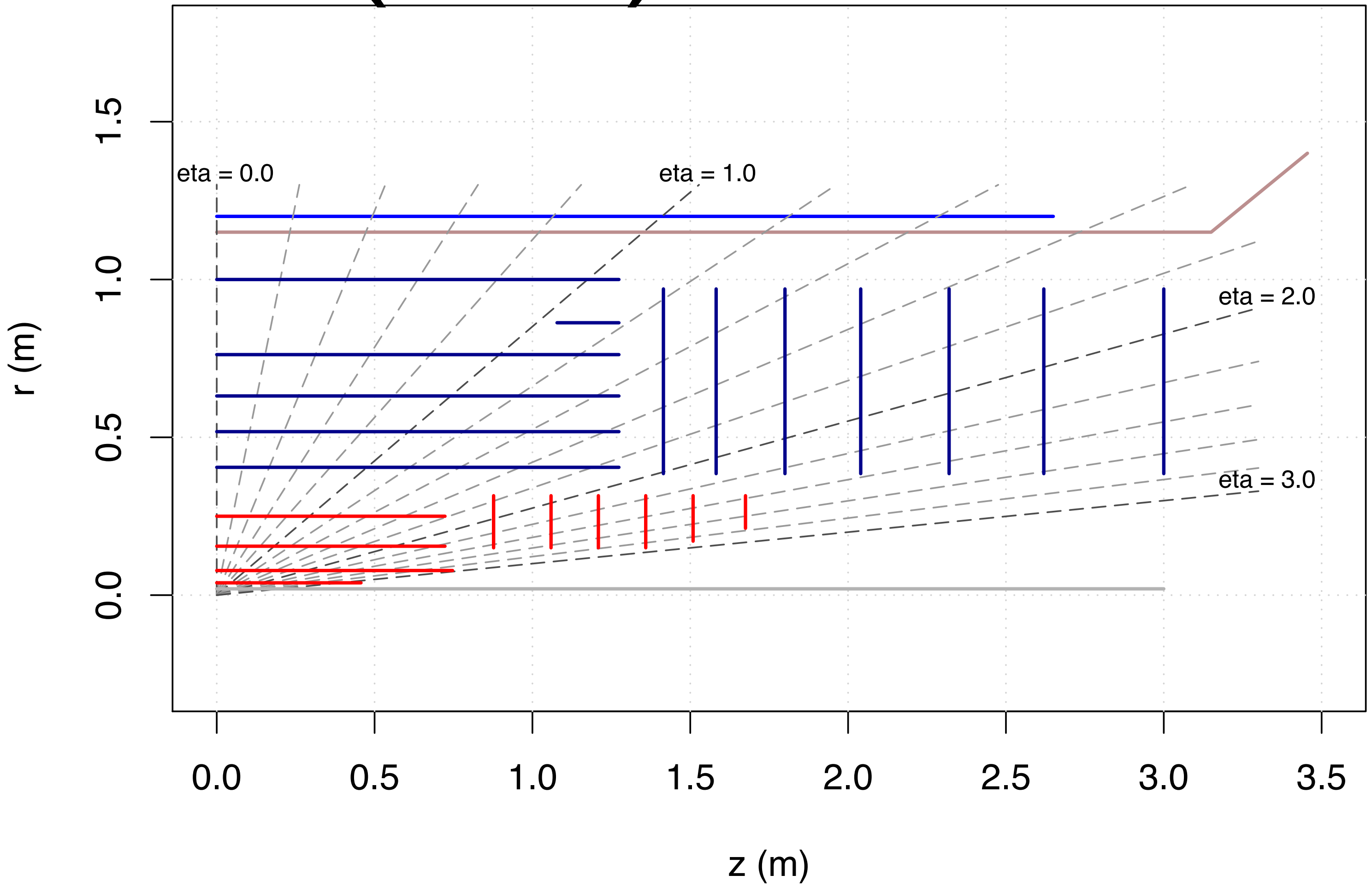


Beyond Run-II

- Phase-I Upgrade
  - Instantaneous luminosity up to ~2.2 x 10^{34} cm^{-2} s^{-1} (μ~50?) → Run from 2019 to 2012 to get ~300 fb^{-1}
- Phase-II Upgrade (High Lumi - LHC)
  - Instantaneous luminosity up to ~5 x 10^{34} cm^{-2} s^{-1}(μ~140?) → Run from 2023 to 2034 to get ~3000 fb^{-1}
- Inner Detector Upgrade
  - **CMS**: for Phase-I (ATLAS plans to live with present detector + IBL) [TDR 2012]
  - **ATLAS**: for Phase-II, all-silicon Inner Detector [LoI 2012]

Upgrade of ATLAS Inner Detector (ITK)

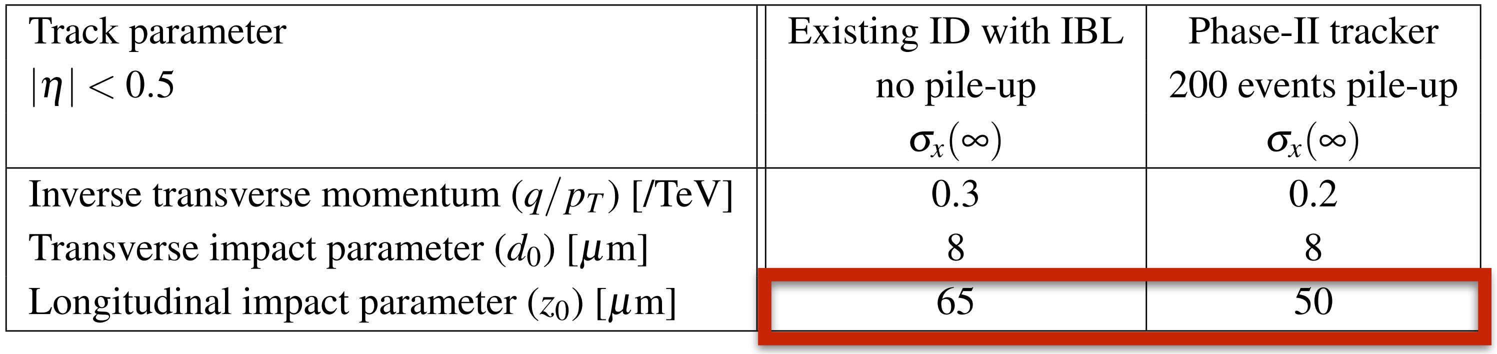
- Present pixel detector designed to survive until ~400 fb-1, IBL until ~850 fb-1
- SCT and TRT not be able to cope with High Lumi occupancy → build more granular all-silicon detector
- Barrel:
  - Presently: 3 pixel, 4 SCT, TRT
  - Proposed: 4 pixel, 3 short-strip, 2 long-strip layers
- 3 → 6 pixel discs
- Plan to use ID earlier in trigger chain (100 kHz → 200-500 kHz, challenging!)



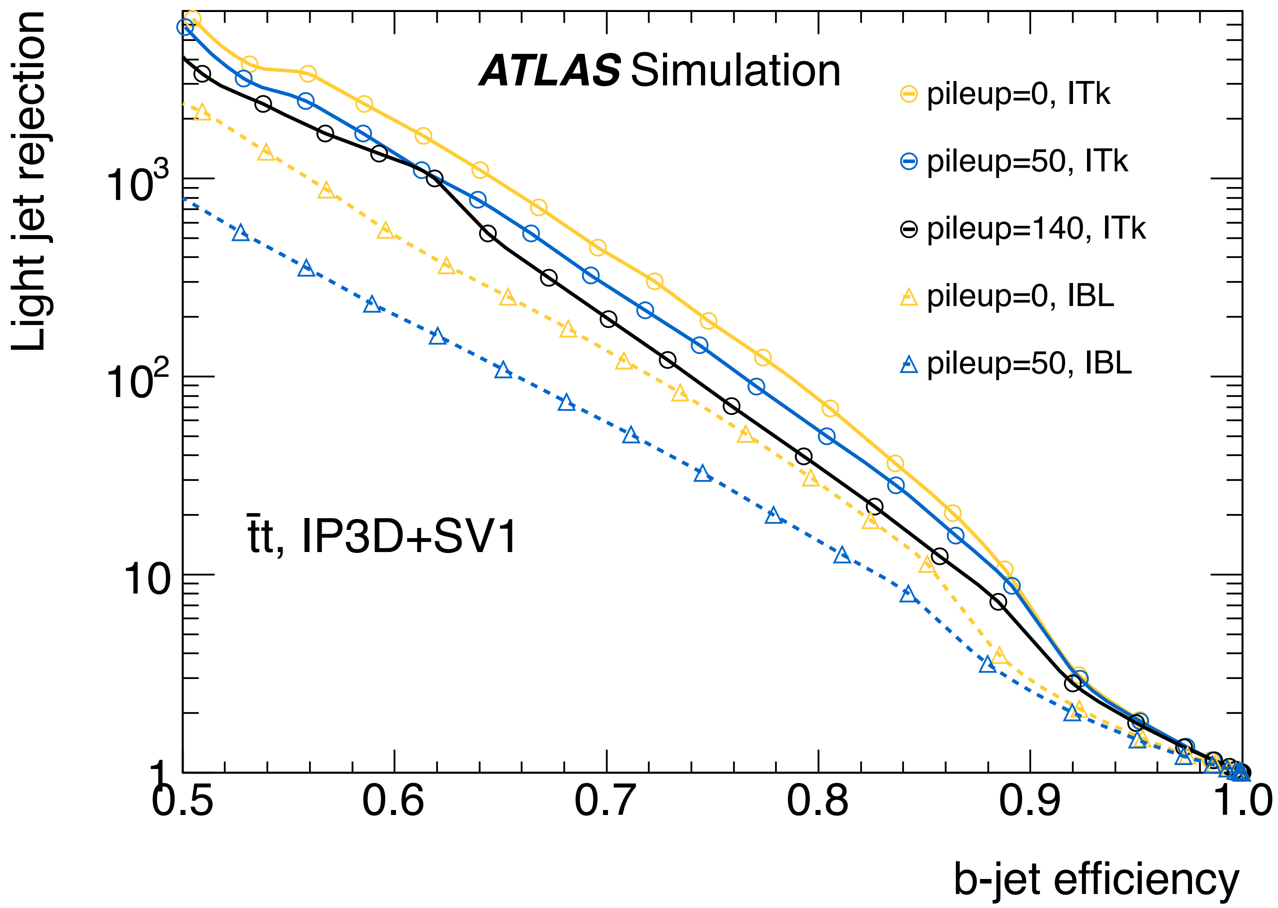
New pixel detector
- Withstand 10^{16} n_{eq} / cm^2
- 60M → 600M channels
- 25x150 µm pixels
- Planar, 3d or diamond

Projected performance

- 9 → 11 hits per track, to suppress fakes

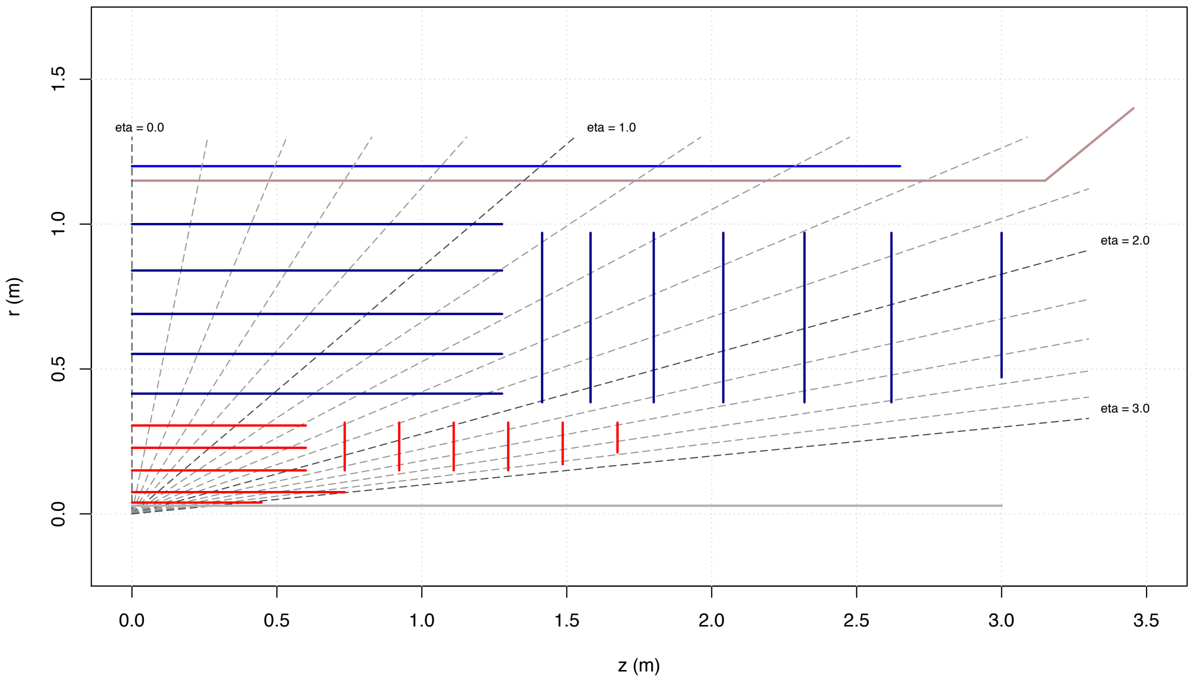


Track parameter $|\eta| < 0.5$	Existing ID with IBL no pile-up $\sigma_x(\infty)$	Phase-II tracker 200 events pile-up $\sigma_x(\infty)$
Inverse transverse momentum (q/p_T) [/TeV]	0.3	0.2
Transverse impact parameter (d_0) [μm]	8	8
Longitudinal impact parameter (z_0) [μm]	65	50

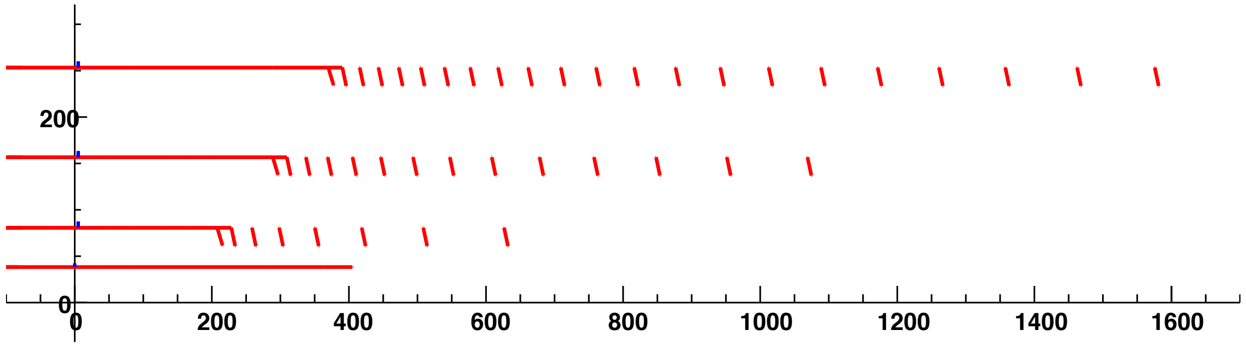


- First b-tagging studies show improvement x4 in light-jet rejection with no pile-up w.r.t. present ID
- Much less degradation due to pile-up
- Algorithms not yet optimized for pile-up

(Some) alternative layouts



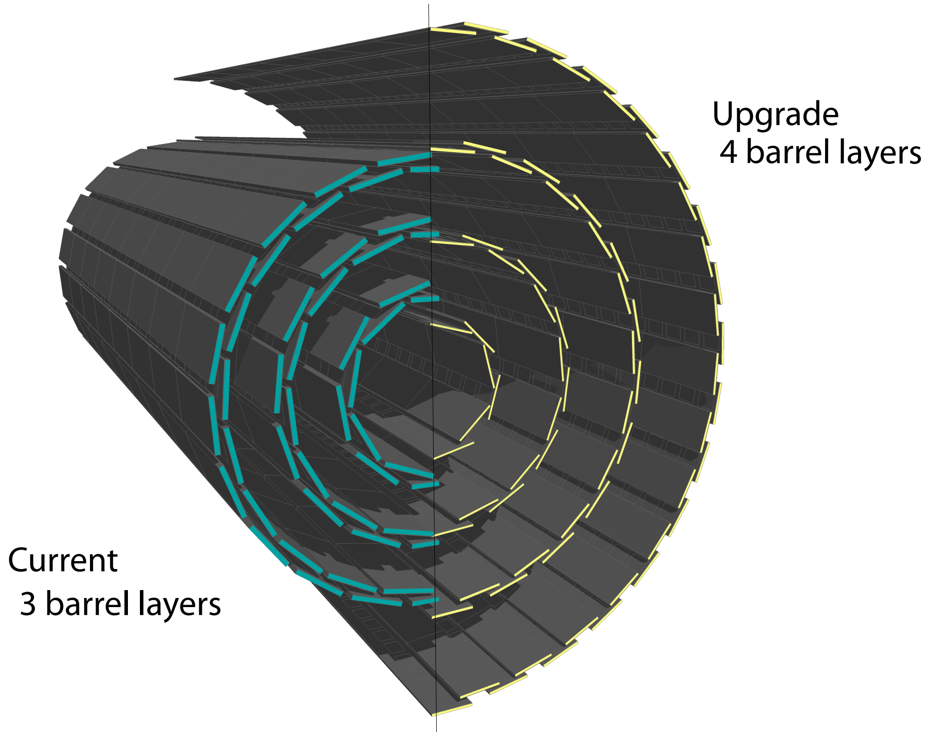
- *Five pixel barrel layers*
  - More robust pattern recognition
  - But more material

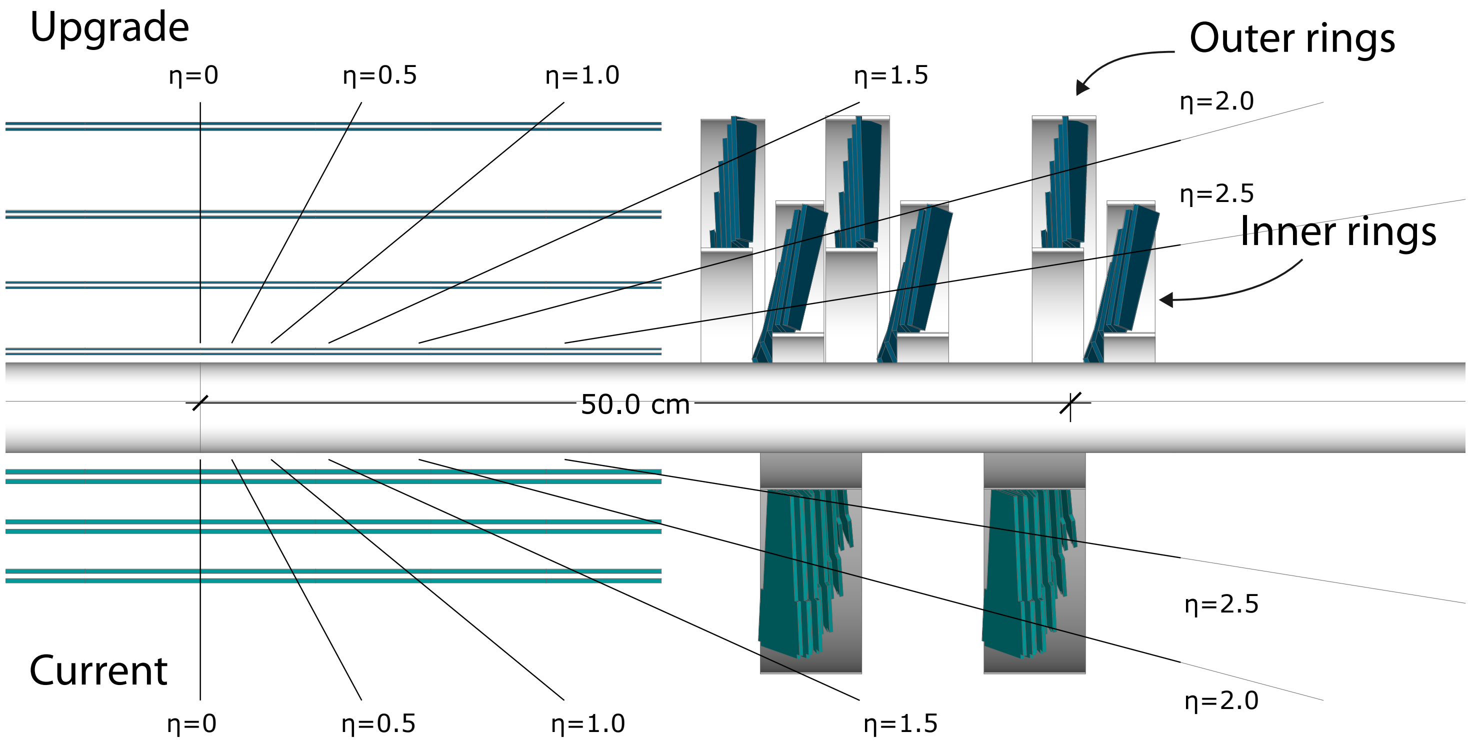


- *Alpine layout*
  - Make sensors more perpendicular to incoming particles
  - Reduces traversed material

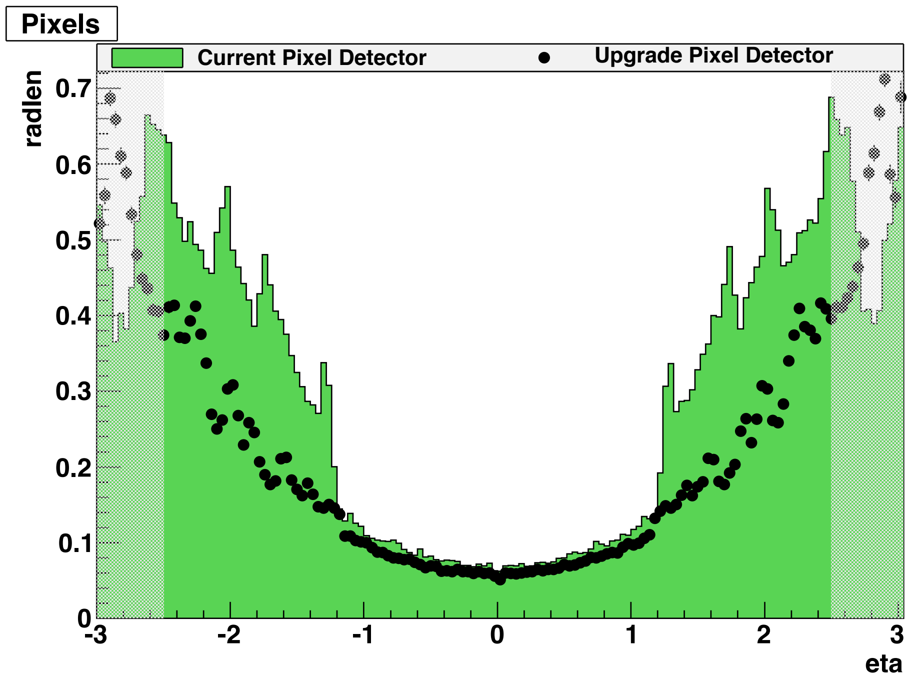
CMS upgrade for Phase-I

- Also move to 4 pixel layers in barrel (as in ATLAS after addition of IBL)
- First layer 4.4 → 3 cm
- Pixel size still 100x150 μm

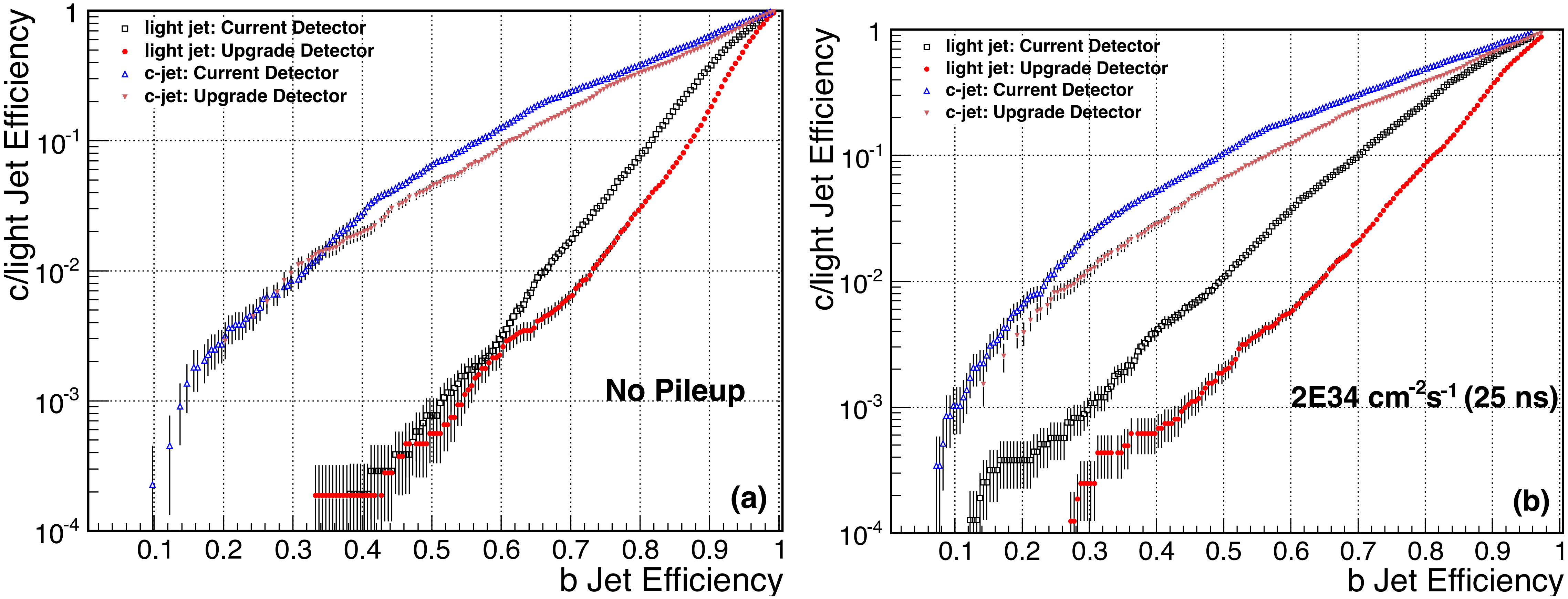




- Much less material



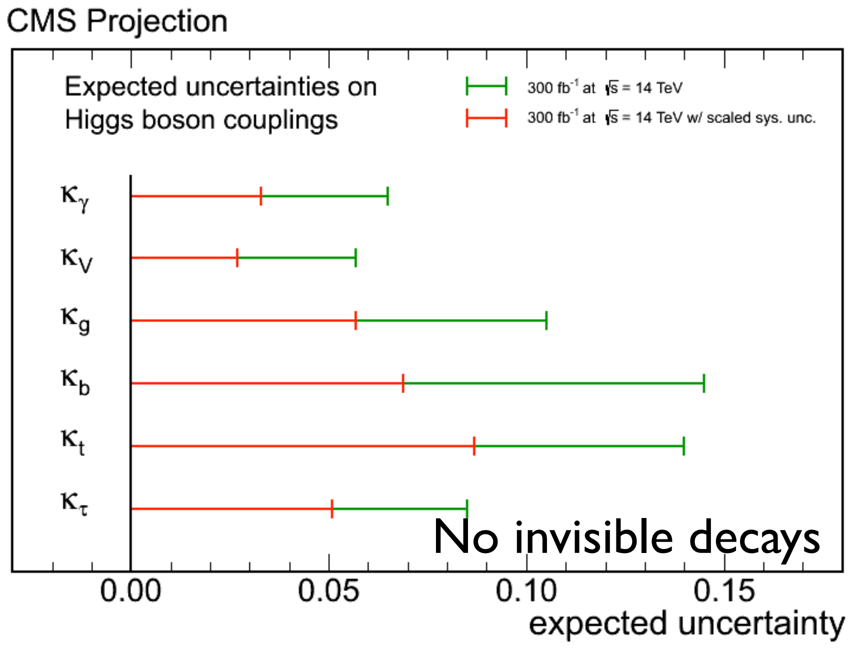
B-tagging performance



- Without pile-up 3x better light-jet rejection @ 70% efficiency
- Better with respect to the current ATLAS upgrade with IBL because of the significant decrease in material budget
- Will allow to efficiently counteract the effect of pile-up.

Prospects for Higgs couplings…

- Projections publicly available for CMS, which rely on the performance of the upgraded detector (to counteract the effect of pile-up).



No invisible decays

Scenario 2 = theory systematics / 2

Coupling	Uncertainty (%)			
	300 fb^{-1}		3000 fb^{-1}	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2
κ_γ	6.5	5.1	5.4	1.5
κ_V	5.7	2.7	4.5	1.0
κ_g	11	5.7	7.5	2.7
κ_b	15	6.9	11	2.7
κ_t	14	8.7	8.0	3.9
κ_τ	8.5	5.1	5.4	2.0

- Predictions are hard, as the main problem is controlling the backgrounds to levels of accuracy of per mille, which is VERY challenging!
  - Here the assumption is made that systematic uncertainties also scale with luminosity. So these are rather indications of the maximum ultimative precision one could reach, rather than solid predictions.
- Nevertheless it shows the incredible potential of 300 or 3000 fb^{-1} of LHC data.

Summary and outlook

- Identification of b-quark jets in LHC Run-I matched and exceeded expectations
  → Can select 70% of b-jets, with well below 1% light-jet fake rates
- Calibration for b-jets reached a precision of 2-4% over most of the pT spectrum (against ~5% of most optimistic assumptions before start of data taking)
- Rejection of c-jets has been significantly improved, but more work needed to reach decent c-tagging performance
- The insertion of IBL in ATLAS or, in the future, the tracker upgrades of ATLAS and CMS will further improve the performance, despite the more and more demanding high pile-up conditions.
- Exciting times are (still!) ahead of us!