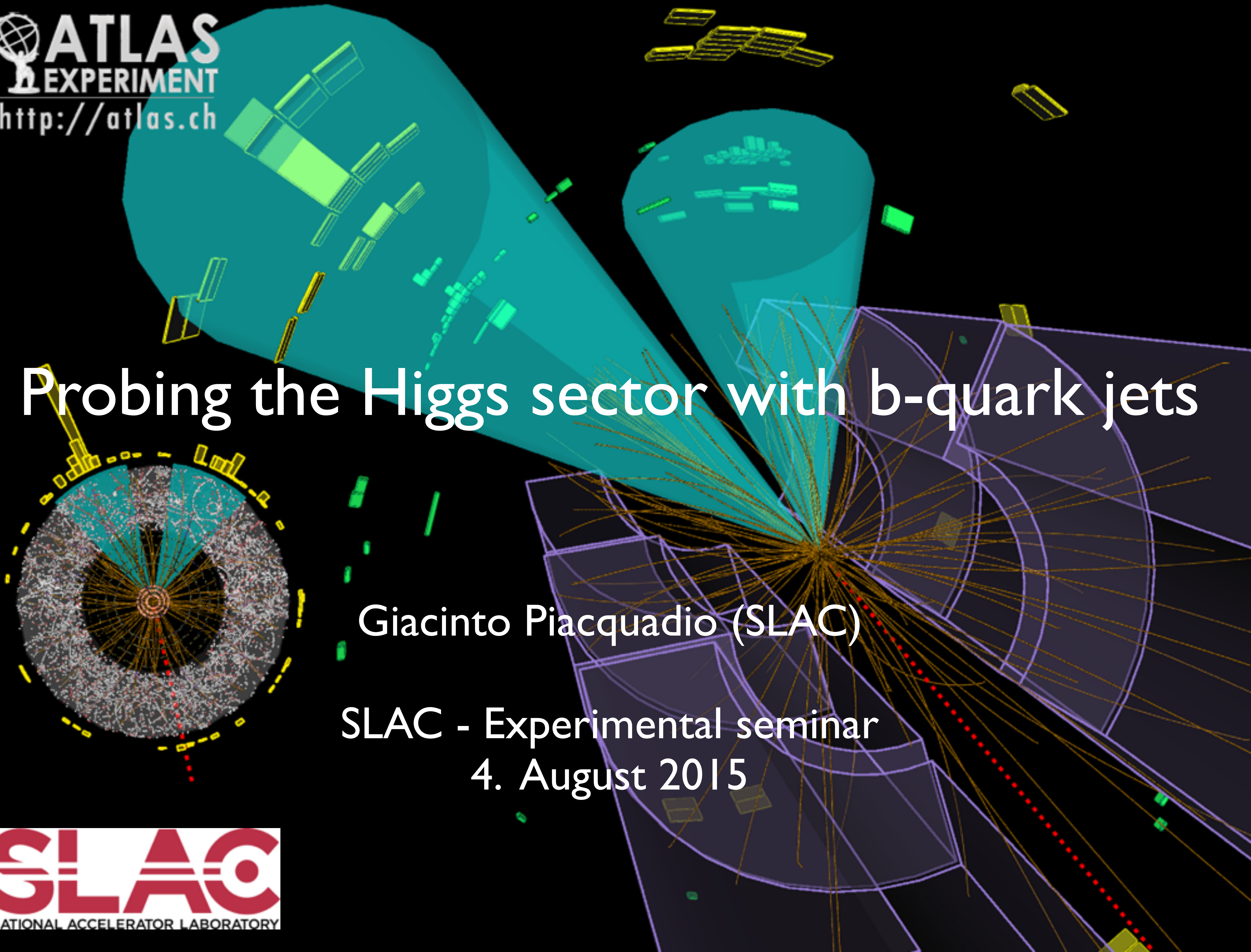
Probing the Higgs sector with b-quark jets



Giacinto Piacquadio (SLAC)

SLAC - Experimental seminar
4. August 2015

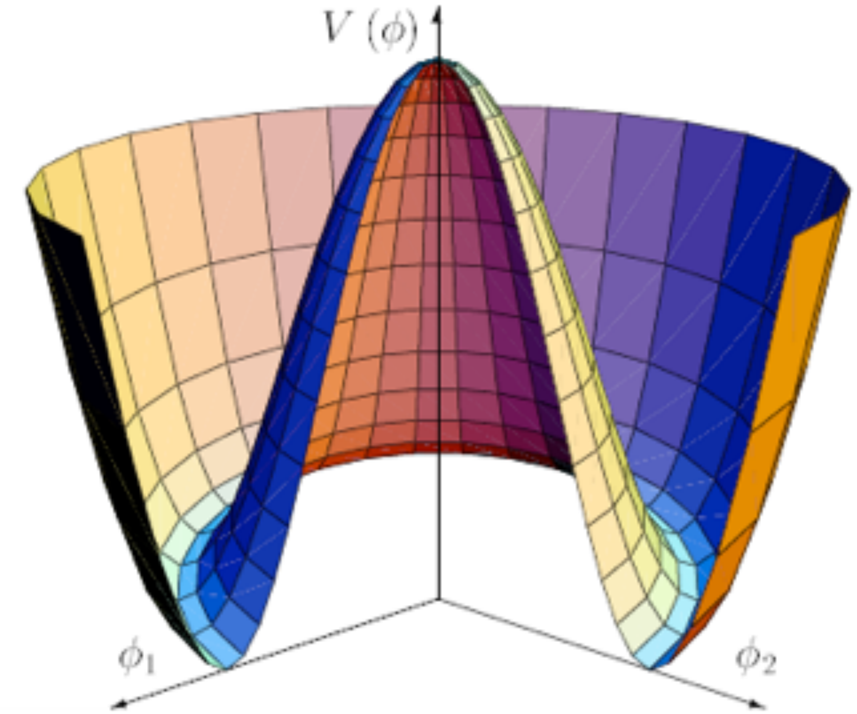
ATLAS EXPERIMENT
http://atlas.ch

SLAC NATIONAL ACCELERATOR LABORATORY

The Higgs mechanism

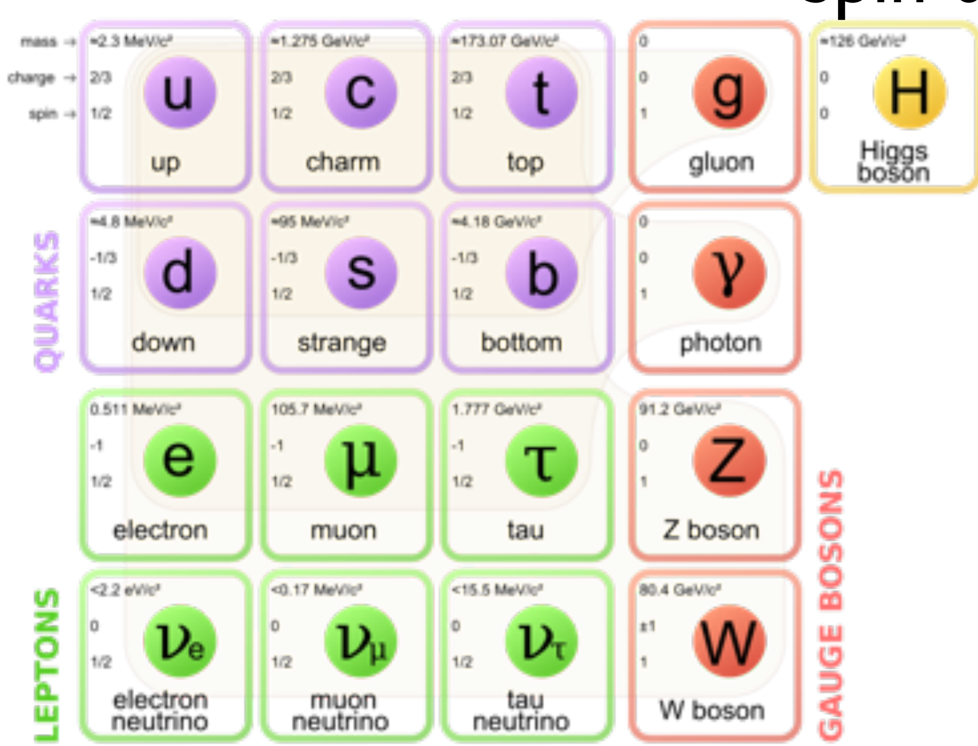
$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$
$$+ i \bar{\psi} \not{D} \psi + h.c.$$
$$+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$
$$+ |D_\mu \phi|^2 - V(\phi)$$

- Choose V(φ) such that <|φ|²>!=0
- Symmetry spontaneously broken



$$\phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

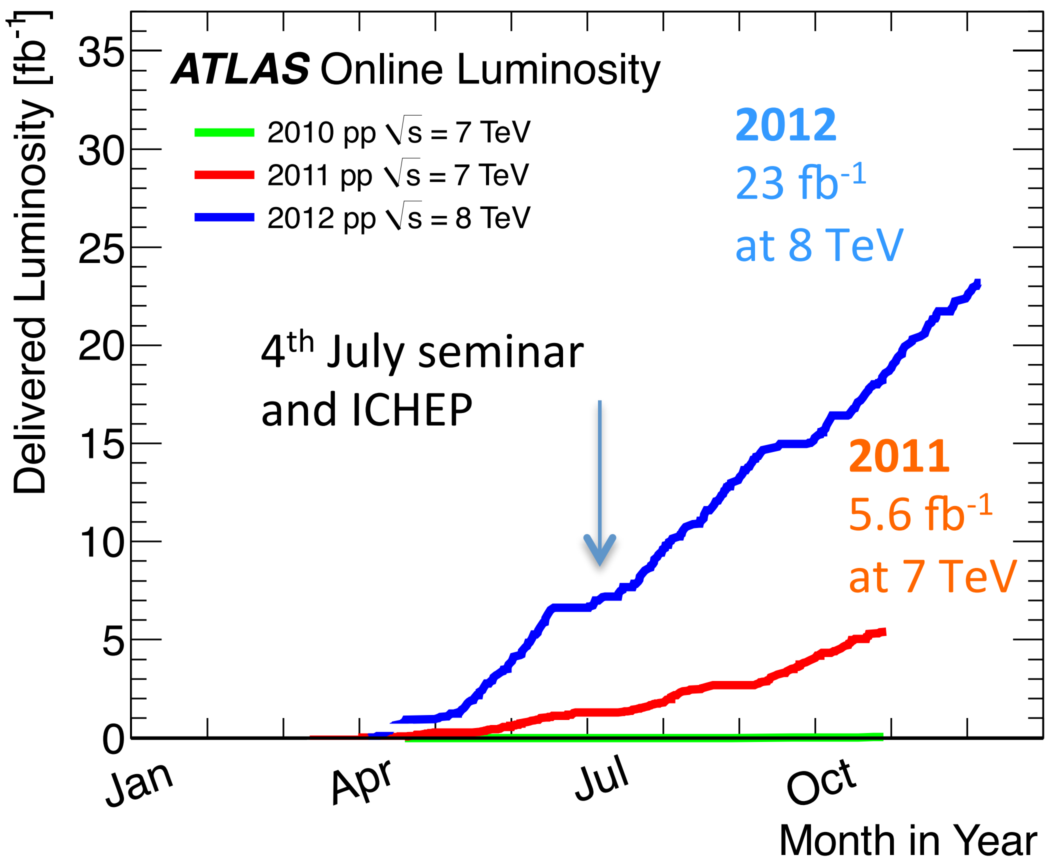
Spin 0

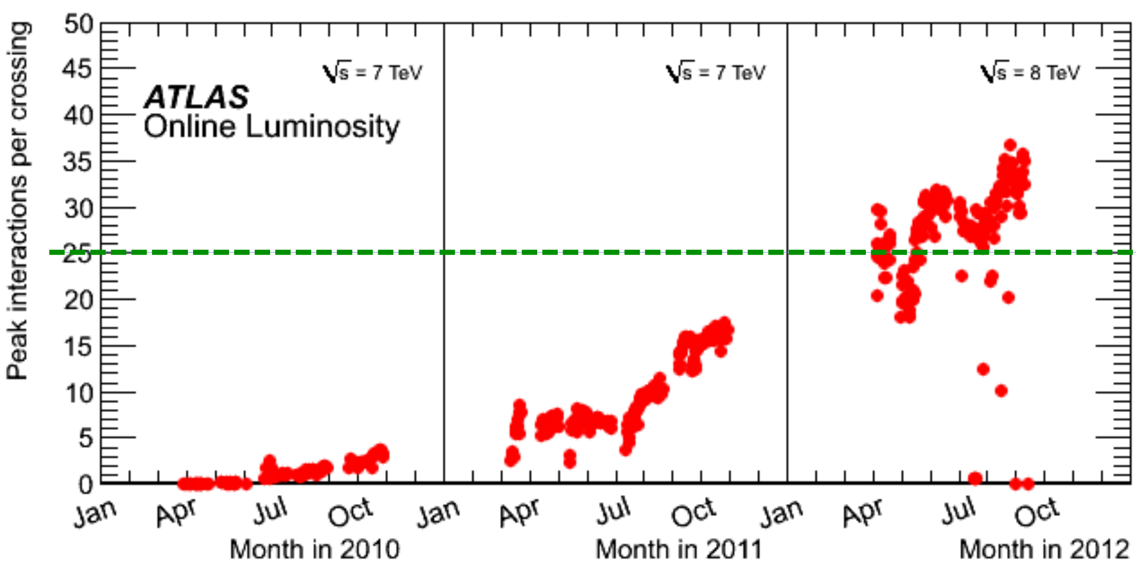


- Perturbation theory around ground state predicts existence of Higgs boson
- Once mass(H) is fixed, SM fully predictive
- Last unobserved particle of the SM until Run-I of the LHC (2011-2012)

LHC Run-1

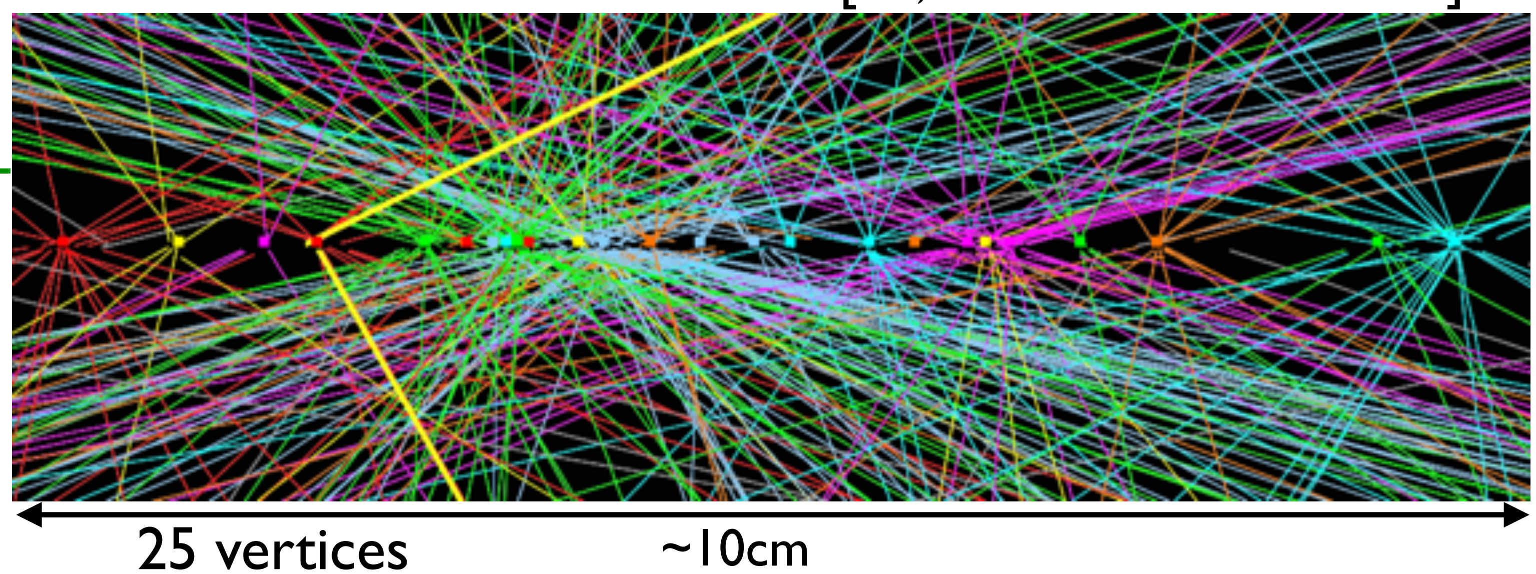
[GP et al, Eur.Phys.J.C71:1630,2011]



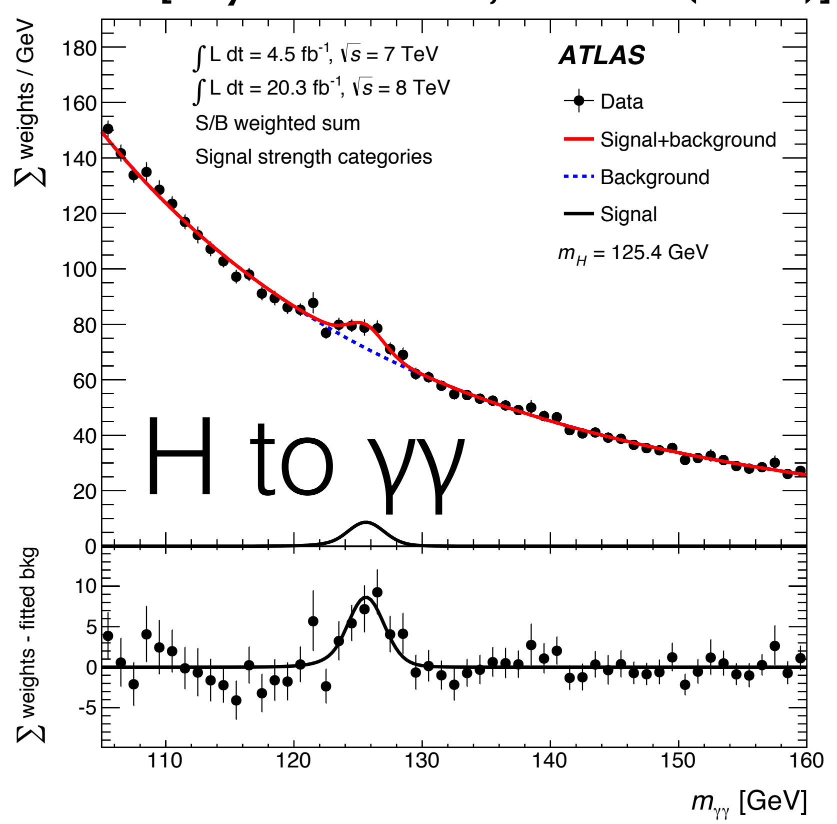


- Proton proton collisions at $\sqrt{s}$ = 7 TeV in 2011 and $\sqrt{s}$ = 8 TeV in 2012
- Two multi-purpose detectors: ATLAS and CMS
- During Run-1 ~25 inv. fb of data recorded by ATLAS.
- Peak luminosity close to design (~7×10^{33} cm^{-2} s^{-1}), but bunch spacing of 50ns pushed up pile-up by x2!
- Challenging environment
  - Up to ~30 simultaneous pile-up interactions
  - A lot of work on reconstruction algorithms to deal with it!

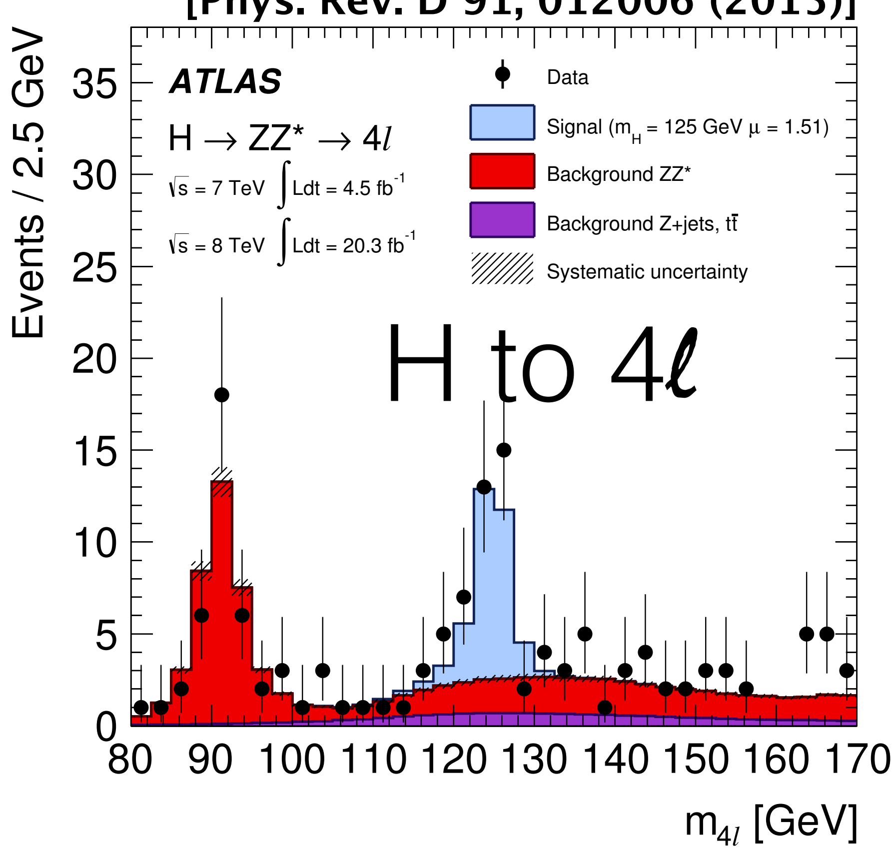
[GP, CERN-THESIS-2010-27]



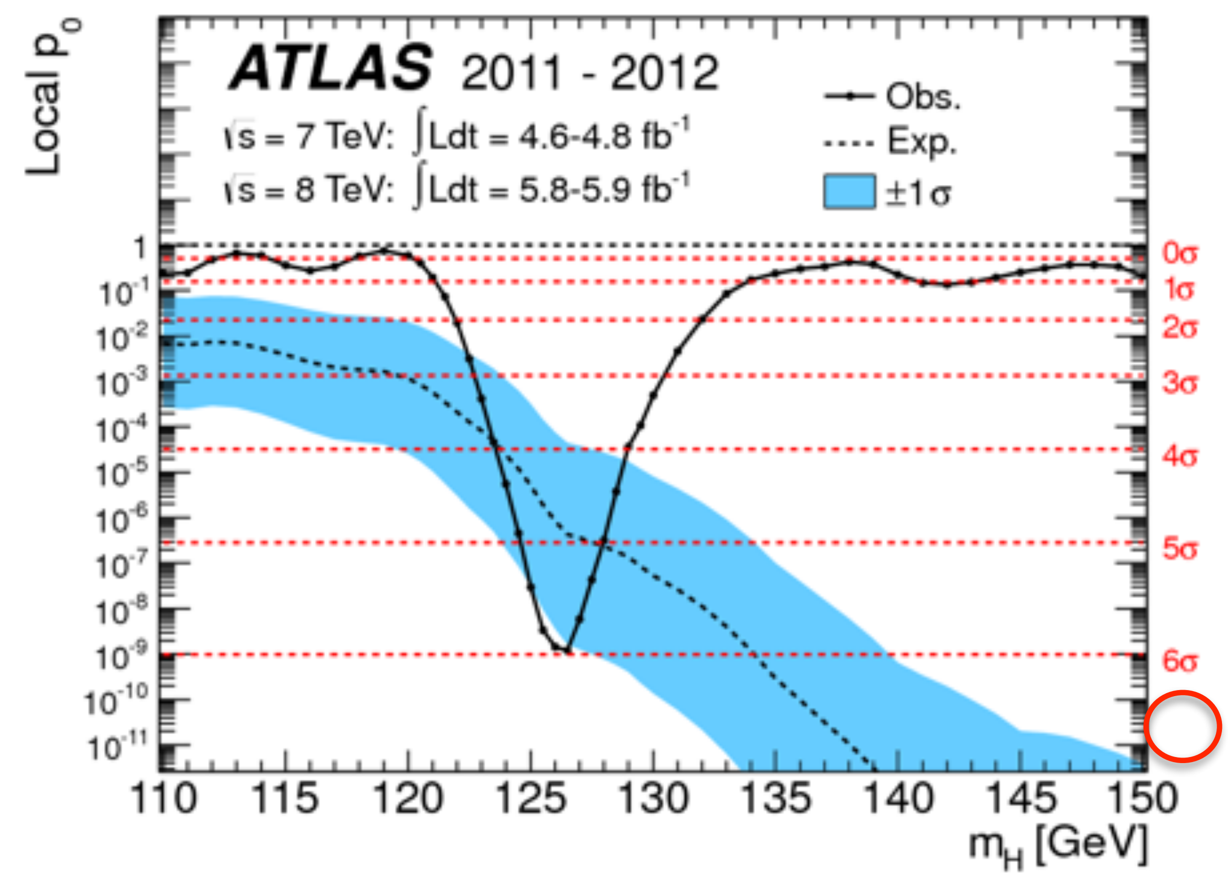
[Phys. Rev. D 90, 112015 (2014)]



[Phys. Rev. D 91, 012006 (2015)]



The discovery

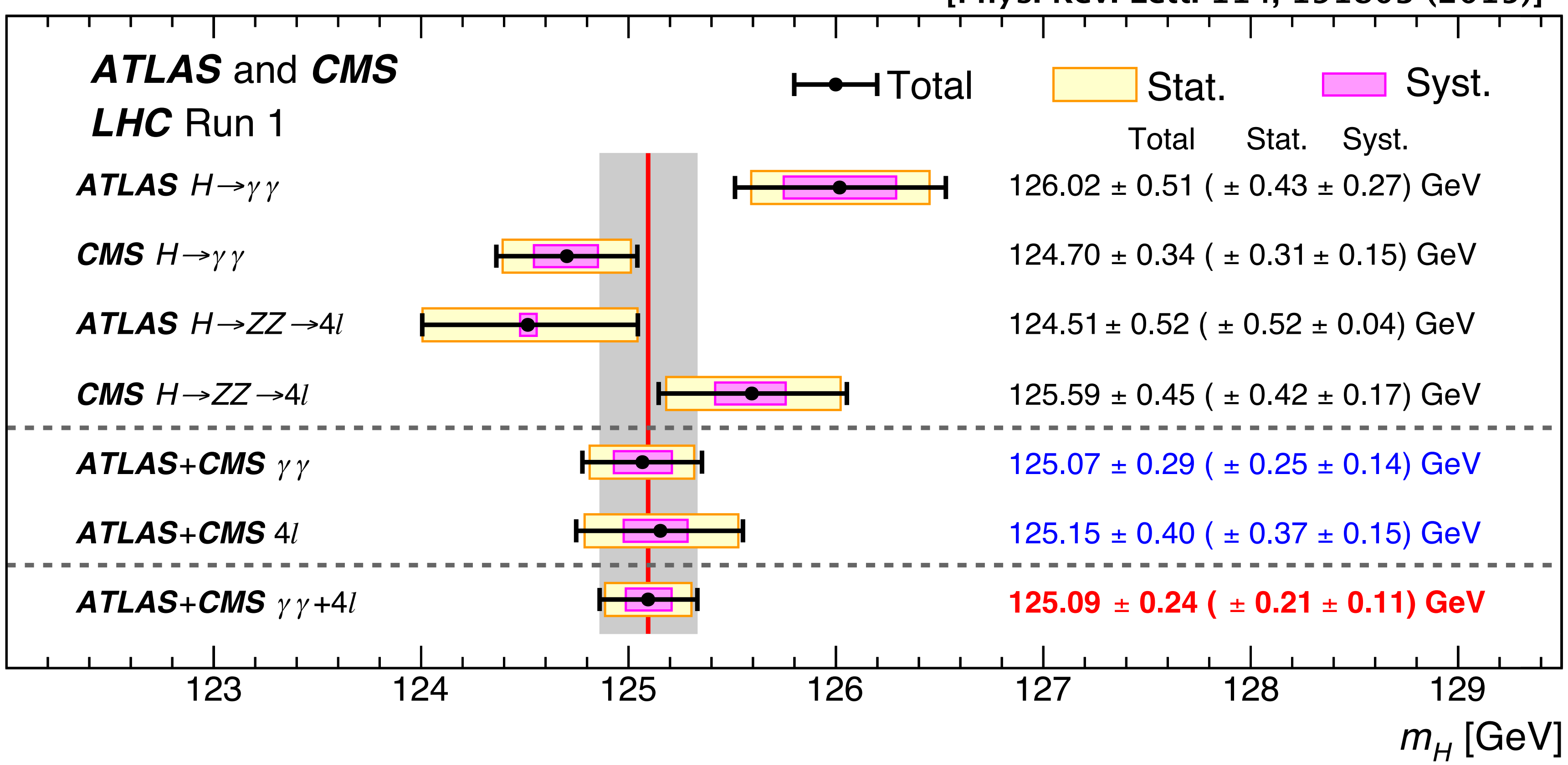


- Announced by ATLAS and CMS on 4th July 2012
- Based on Higgs boson decays to bosons (γγ, ZZ, WW)
- **But:** is this really the SM Higgs boson predicted by Brout, Englert and Higgs?

Measuring the Higgs sector

- (1) **What is the Higgs boson mass?**
  - Now measured to ~0.2% precision!

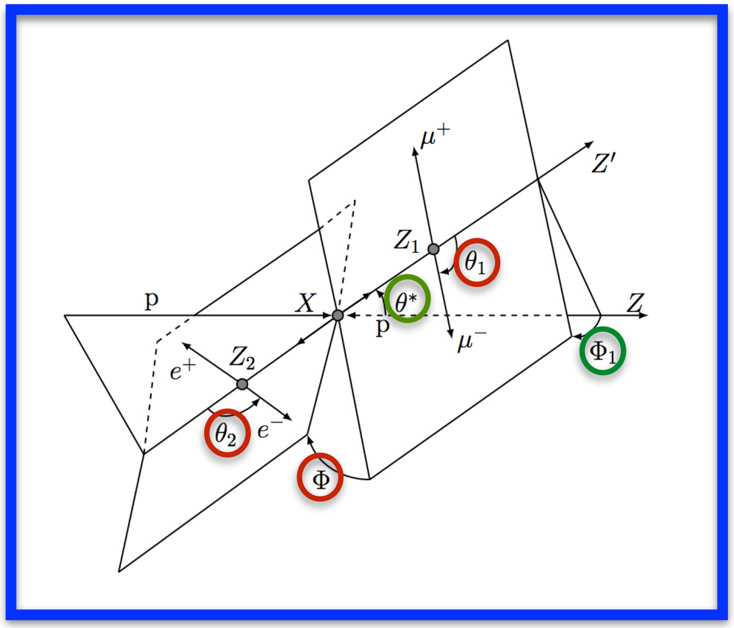
[Phys. Rev. Lett. 114, 191803 (2015)]



  - Completes parameters of SM!
  - Combination shows no sign of discrepancy between γγ and ZZ

Measuring the Higgs sector

H to ZZ* to 4ℓ



- (2) **What is the Spin/CP state?**
  - Spin 1 excluded by observation in H → γγ (Yang-Landau theorem)
  - Several spin 2 variants (e.g. graviton-like) tested
    - All excluded at >95% CL

- More tests for spin 0, probing additional couplings (BSM CP-odd or CP-even)
  - SM alternatives disfavored
- In the future these tests can be all integrated in more generic coupling fits

Spin-0 with CP mixing [Phys. Rev. Lett. 114, 191803 (2015)]

coupling to SM-Higgs

$$\mathcal{L}_0^V = \Big\{ c_\alpha \kappa_{\rm SM} \Big[\tfrac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W_{+\mu} W^{-\mu} \Big] - \tfrac{1}{4}\tfrac{1}{\Lambda} \Big[c_\alpha \kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu} \Big] - \tfrac{1}{2}\tfrac{1}{\Lambda} \Big[c_\alpha \kappa_{HWW} W^+_{\mu\nu} W^{-\mu\nu} + s_\alpha \kappa_{AWW} W^+_{\mu\nu} \tilde{W}^{-\mu\nu} \Big] \Big\} X_0$$

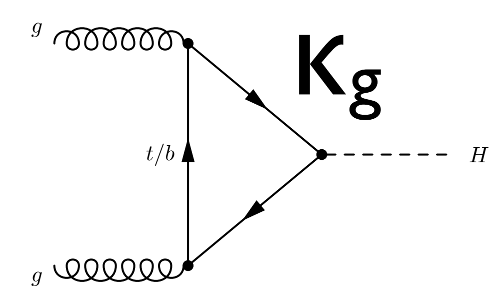
coupling to CP-even BSM-Higgs

coupling to CP-odd BSM-Higgs

Measuring the Higgs sector

- (3) **What are the Higgs boson couplings?**
  - Use LO motivated "kappa" framework (κ_X scalings)

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

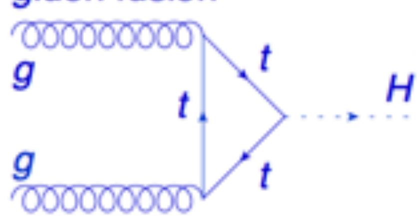
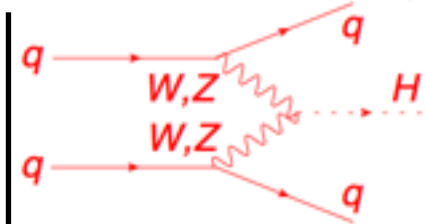
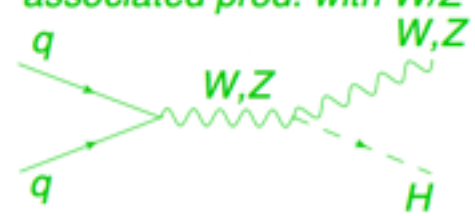
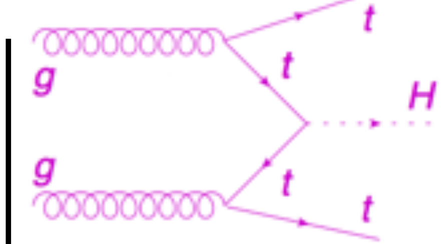
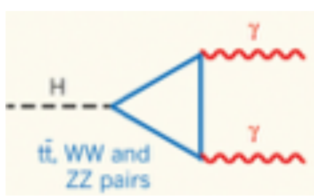
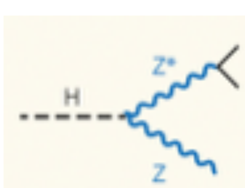
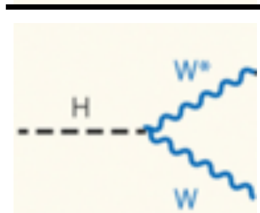
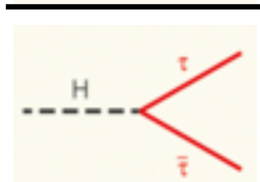
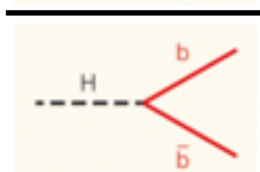


  - Each channel: $\sigma(i \to H \to f) = \dfrac{\sigma_i(\kappa_j) \cdot \Gamma_f(\kappa_j)}{\Gamma_H(\kappa_j)}$
  - i → H: production, H → f decay mode
  - Explore as many channels to simultaneously determine the kappas!

Channels investigated in ATLAS

Production

Decay

	gluon fusion	vector boson fusion (VBF)	associated prod. with W/Z	associated prod. with tt
				
	✓	✓	✓	✓
	✓	✓	✓	✓
	✓	✓	✓	✓
	✓	✓	*planned*	✓
		*in preparation*	✓	✓

$$\mu = \frac{\sigma \times \mathrm{BR}}{(\sigma \times \mathrm{BR})_{\mathrm{SM}}}$$

Total Higgs decay width

$$\sigma(i \to H \to f) = \frac{\sigma_i(\kappa_j) \cdot \Gamma_f(\kappa_j)}{\Gamma_H(\kappa_j)}$$

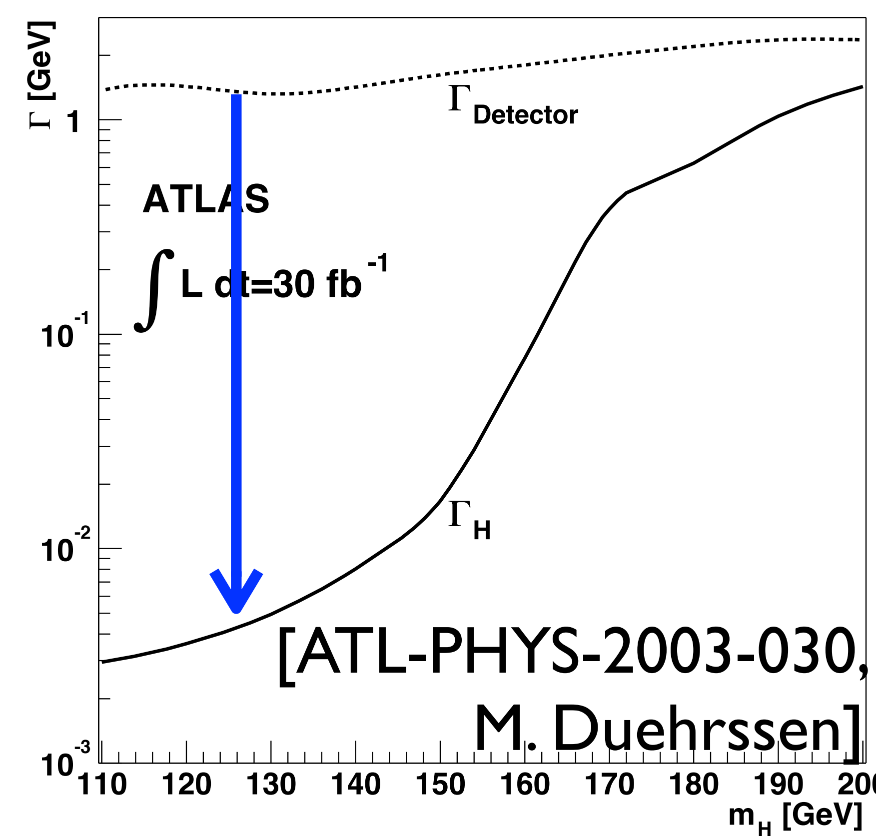
- enters as global rescaling factor.

- In most generic models, try to determine also $BR_{i.,u.}$ (invisible or undetected BR), which modifies Γ_H

$$\Gamma_H(\kappa_j, \mathrm{BR}_{\mathrm{i.,u.}}) = \frac{\kappa_H^2(\kappa_j)}{(1 - \mathrm{BR}_{\mathrm{i.,u.}})} \Gamma_H^{\mathrm{SM}}$$

- Γ_H can't be measured directly at the LHC.

- However, can measure absolute couplings if Γ_H is indirectly constrained.

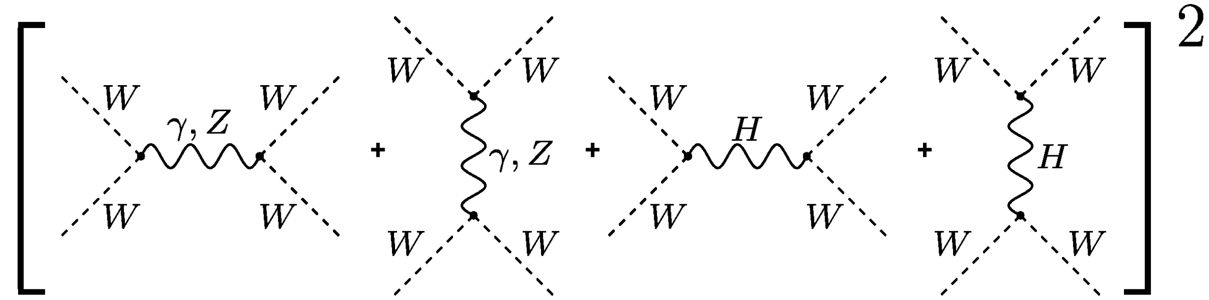


[ATL-PHYS-2003-030, M. Duehrssen]

Limits on Γ_H

Upper limit

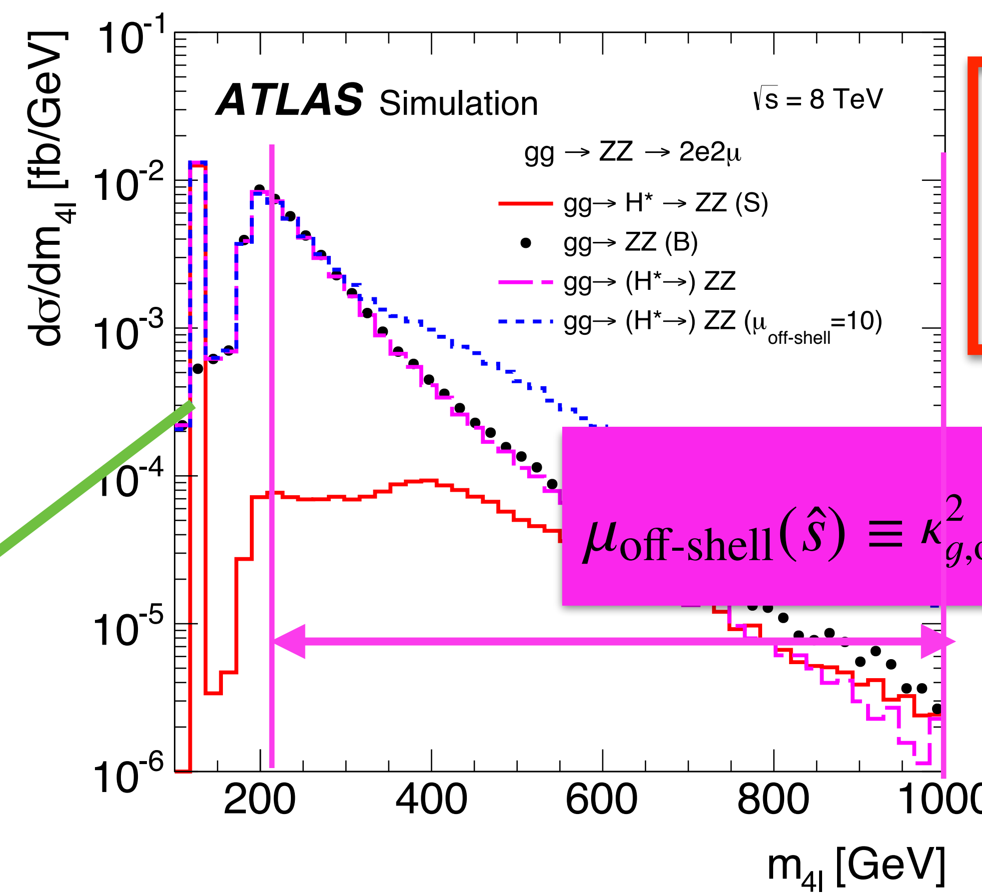
(1) unitarity of WW/ZZ scattering

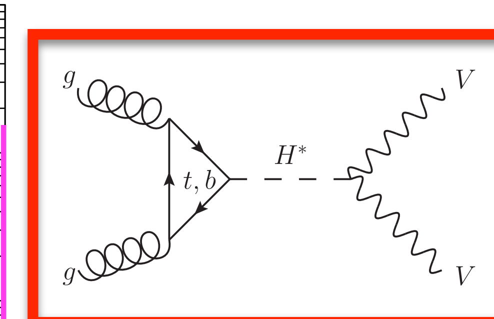


$$k_V \leq 1$$

OR

(2) use off-shell/on-shell coupling measurement





$$\mu_{\text{off-shell}}(\hat{s}) \equiv \kappa^2_{g,\text{off-shell}}(\hat{s}) \cdot \kappa^2_{V,\text{off-shell}}(\hat{s})$$

$$\mu_{\text{on-shell}} = \frac{\kappa^2_{g,\text{on-shell}} \cdot \kappa^2_{V,\text{on-shell}}}{\Gamma_H / \Gamma_H^{\text{SM}}}$$

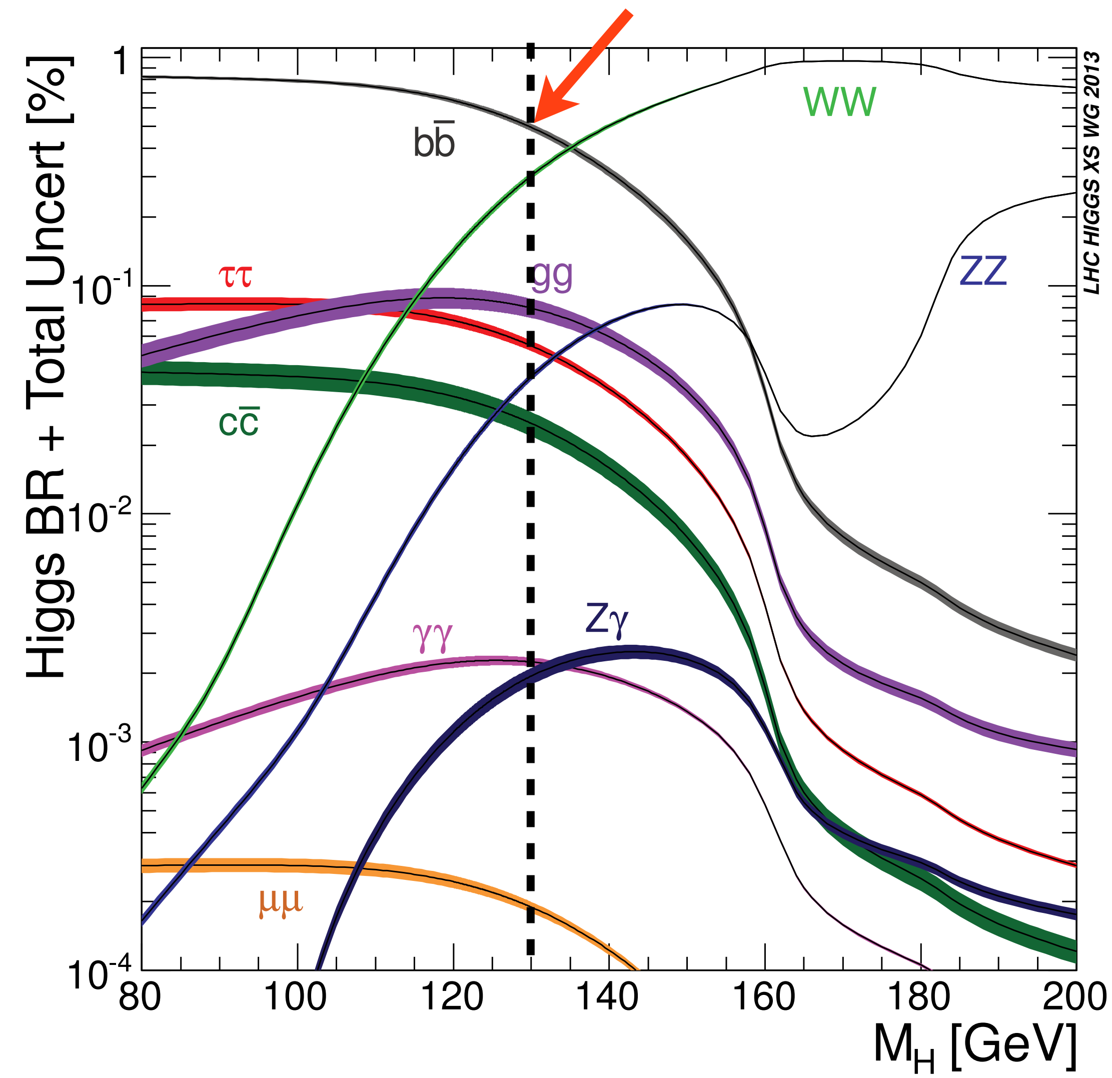
Both (1) and (2) introduce some model dependence.

Limits on Γ_H

Lower limit

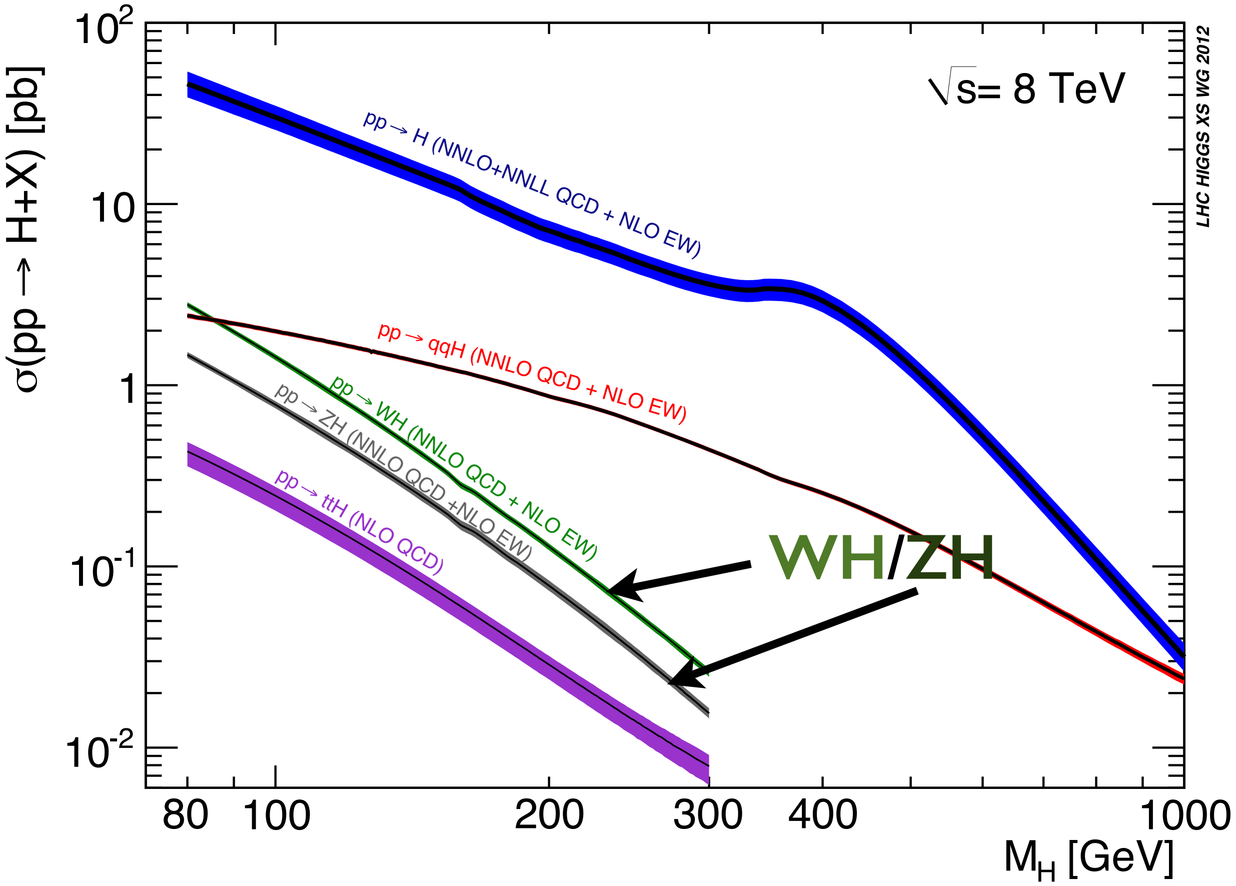
$$\Gamma_H \geq \sum_i \Gamma_{i,\mathrm{vis}}$$

- Makes it crucial to measure precisely dominant decays
- **BR(H → bb) ~ 57%**
- Uncertainty on H → bb will impact precision of all couplings



[GP et al (Higgs Cross Section WG), CERN-2013-004]

Where to look for H to bb



- Despite high BR, H to bb observation is challenging.
- **Gluon fusion mode**
  - Hopeless. Overwhelming multi-jet background.
- **Weak boson fusion**
  - Marginal sensitivity (CMS: 0.8σ in Run-1).
  - Difficult to trigger on (improved VBF trigger for Run-2)
- **Higgs-strahlung mode** (WH/ZH)
  - Exploit leptonic signature of W/Z (trigger events + suppress multi-jet backgrounds).
  - Main search channel for H to bb!
- **ttH**
  - Very challenging (jet combinatorics, high backgrounds), but interesting to measure κ_t.

The VH → Vbb analysis…

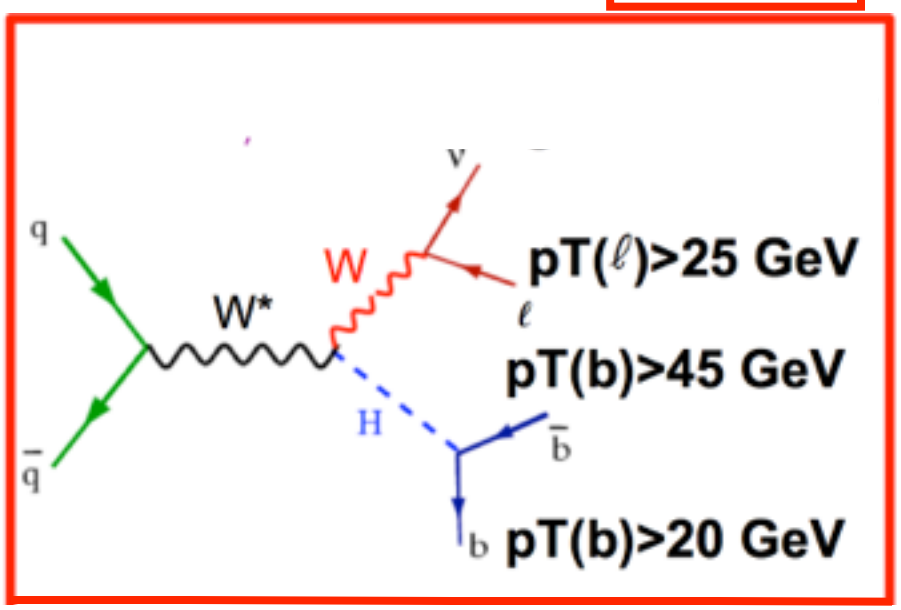
The VH analysis

V=W/Z

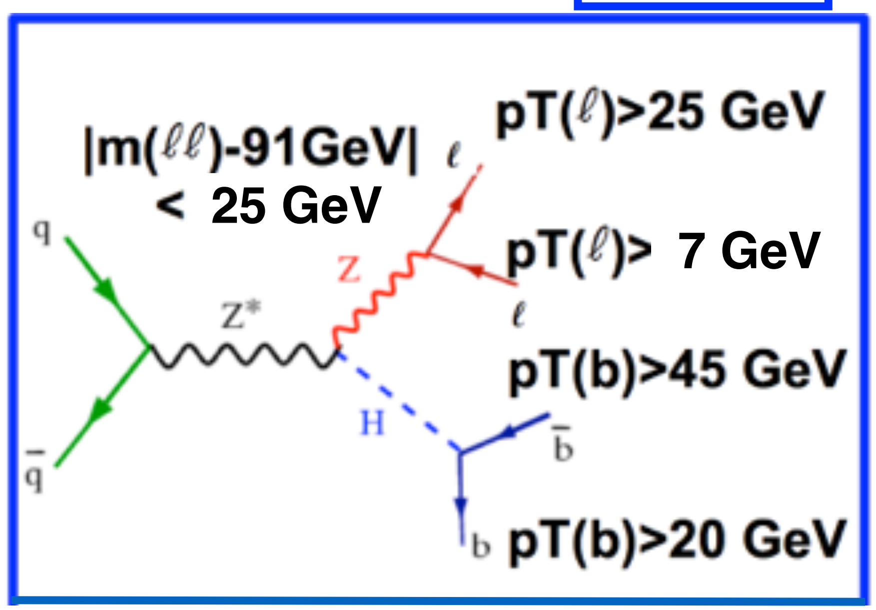
- Three leptonic signatures:
  - Missing ET $ZH \rightarrow \nu\bar{\nu}b\bar{b}$
  - 1-lepton $WH \rightarrow \ell\nu b\bar{b}$
  - 2-leptons $ZH \rightarrow \ell^+\ell^- b\bar{b}$
- Main analysis selection criteria:

- Jets reconstructed with an AntiKt4 jet algorithm.
- Leading two jets in pT used to form Higgs candidate.

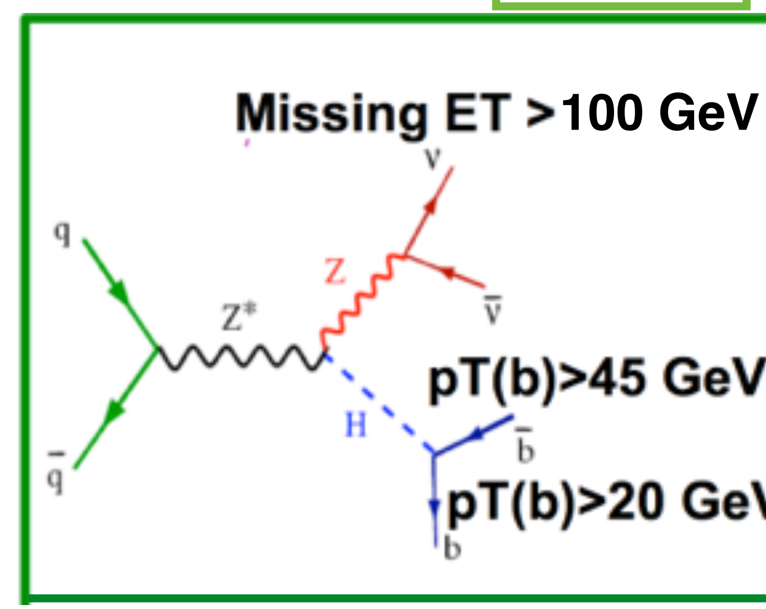
1-lepton



2-lepton

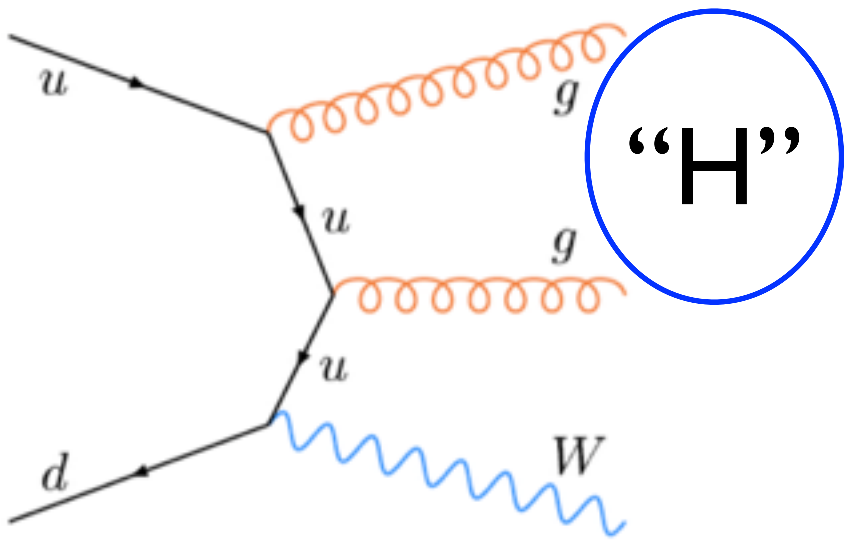


0-lepton

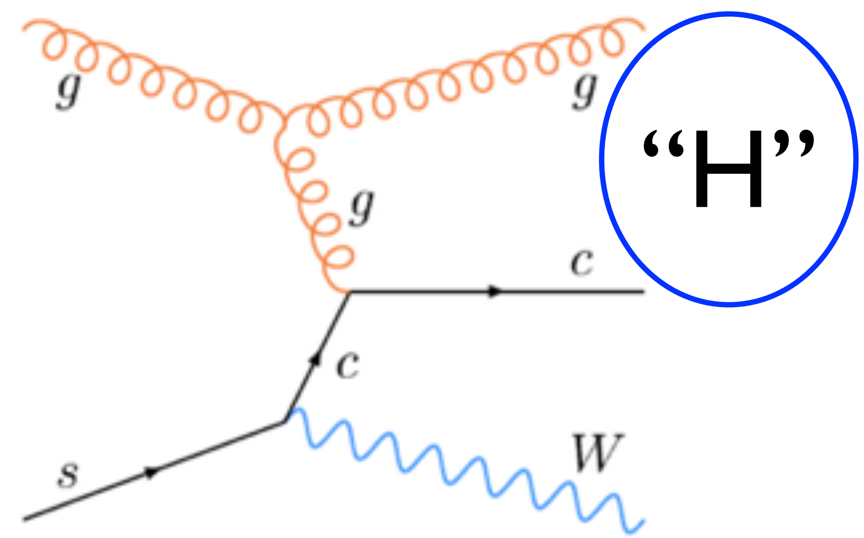


	1-lepton	2-lepton	0-lepton
σ x BR [fb]:	131	15	44
Acceptance:	~4.2%	~13.4%	~4.0%

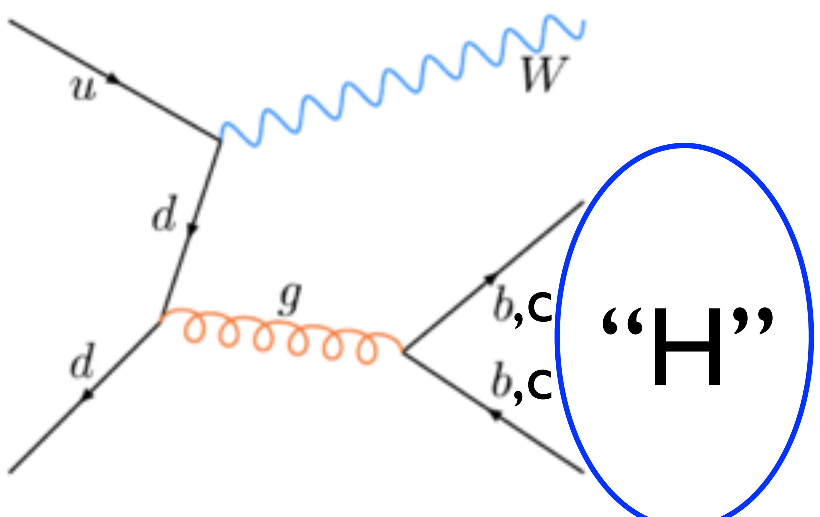
Main backgrounds



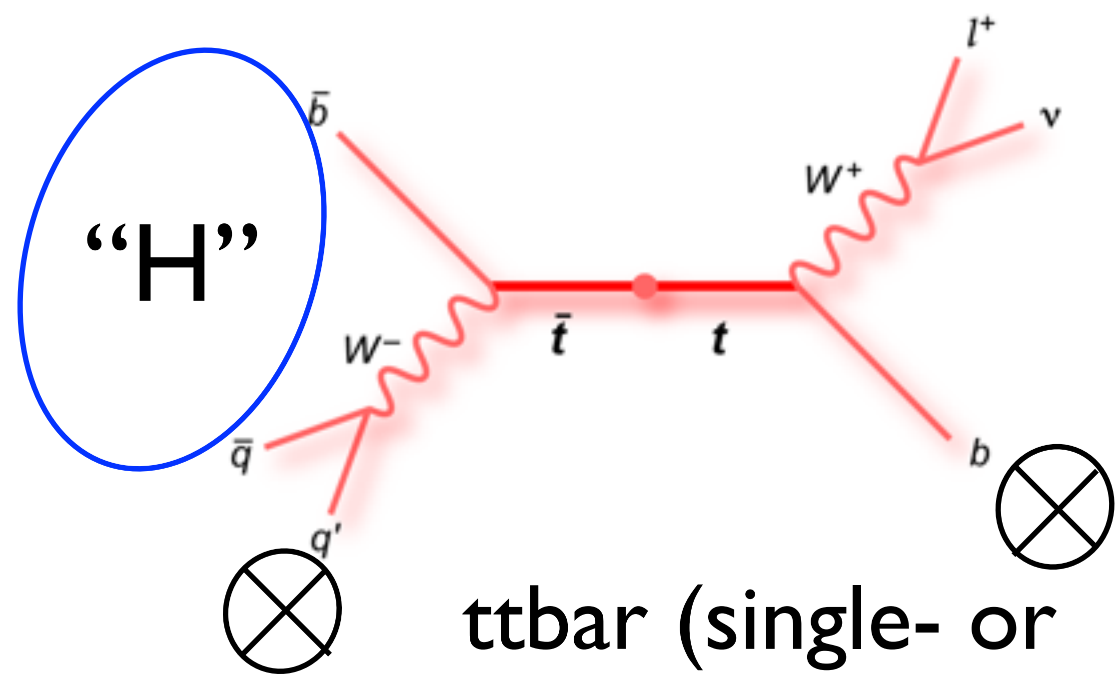
Z/W+2
"light" jets



W+c-jet

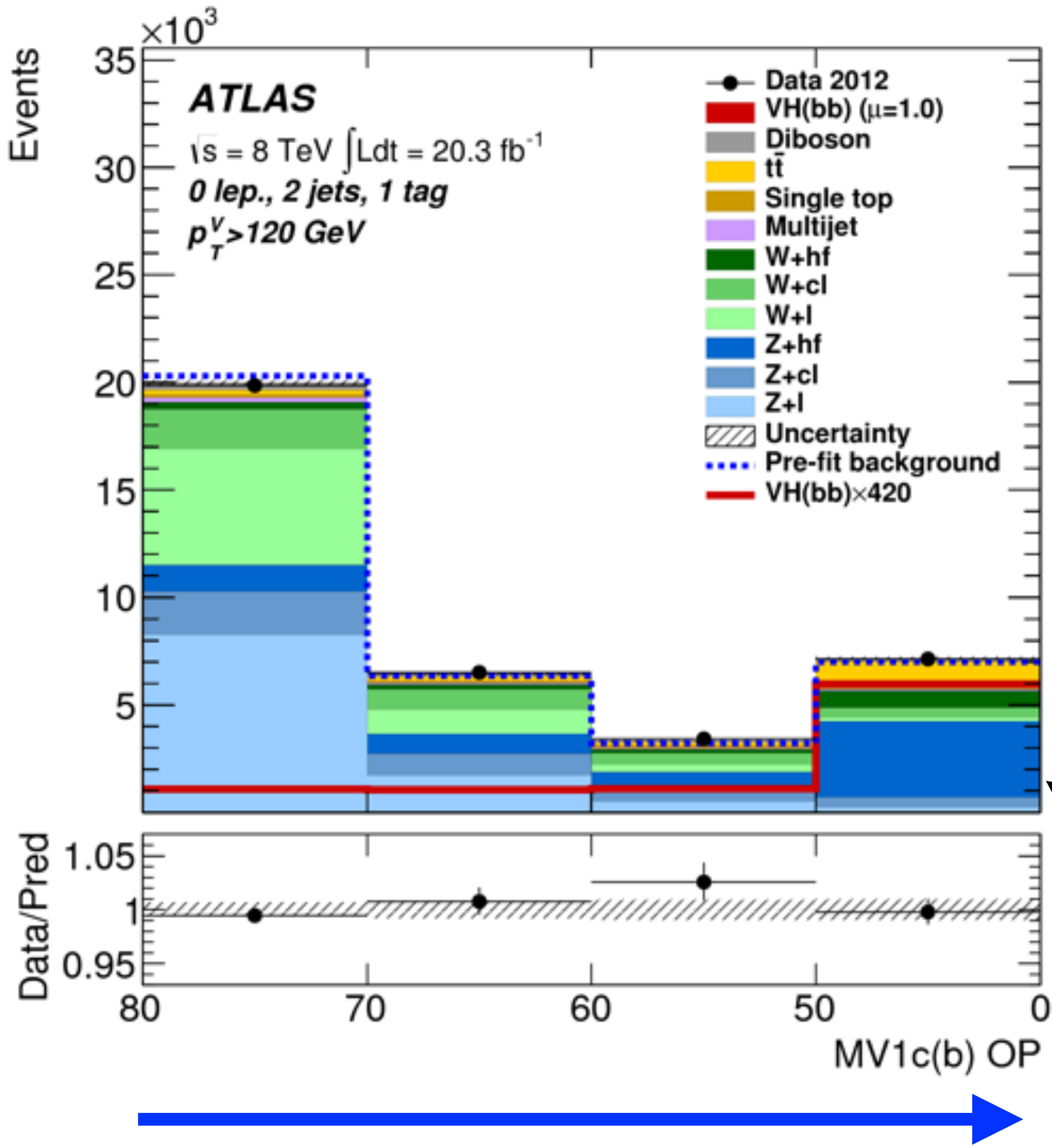


Z/W+bb/cc



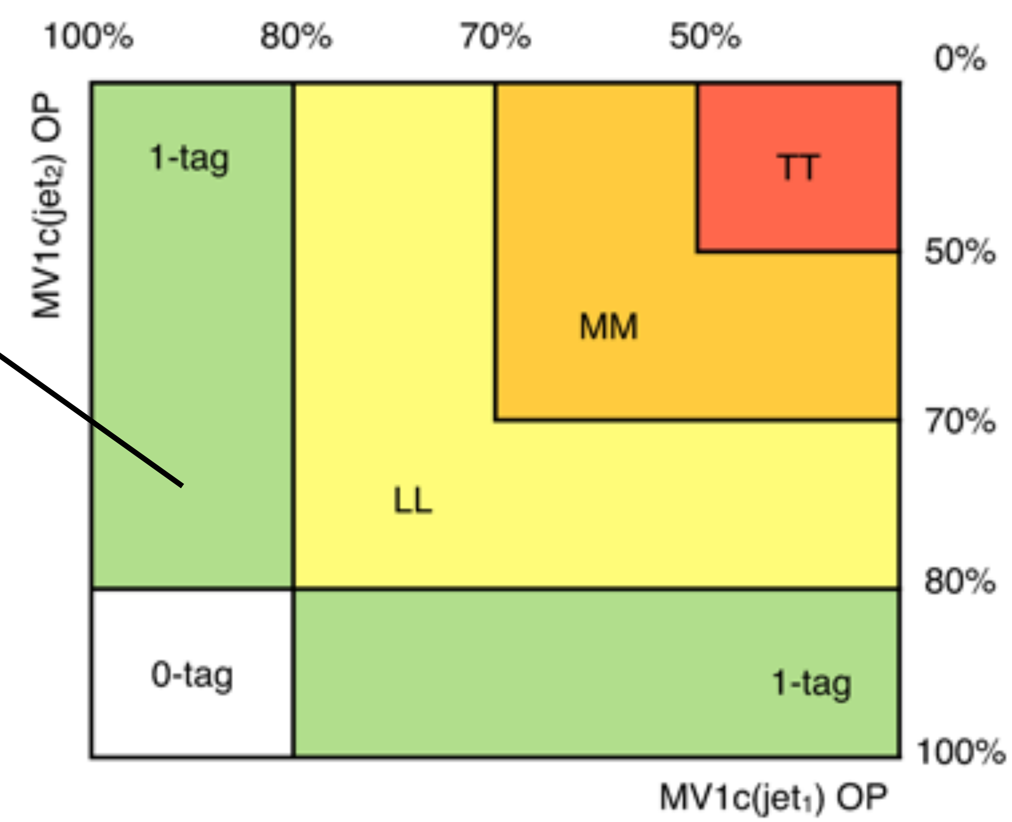
ttbar (single- or dileptonic)

Strategies for background suppression: (1) b-tagging

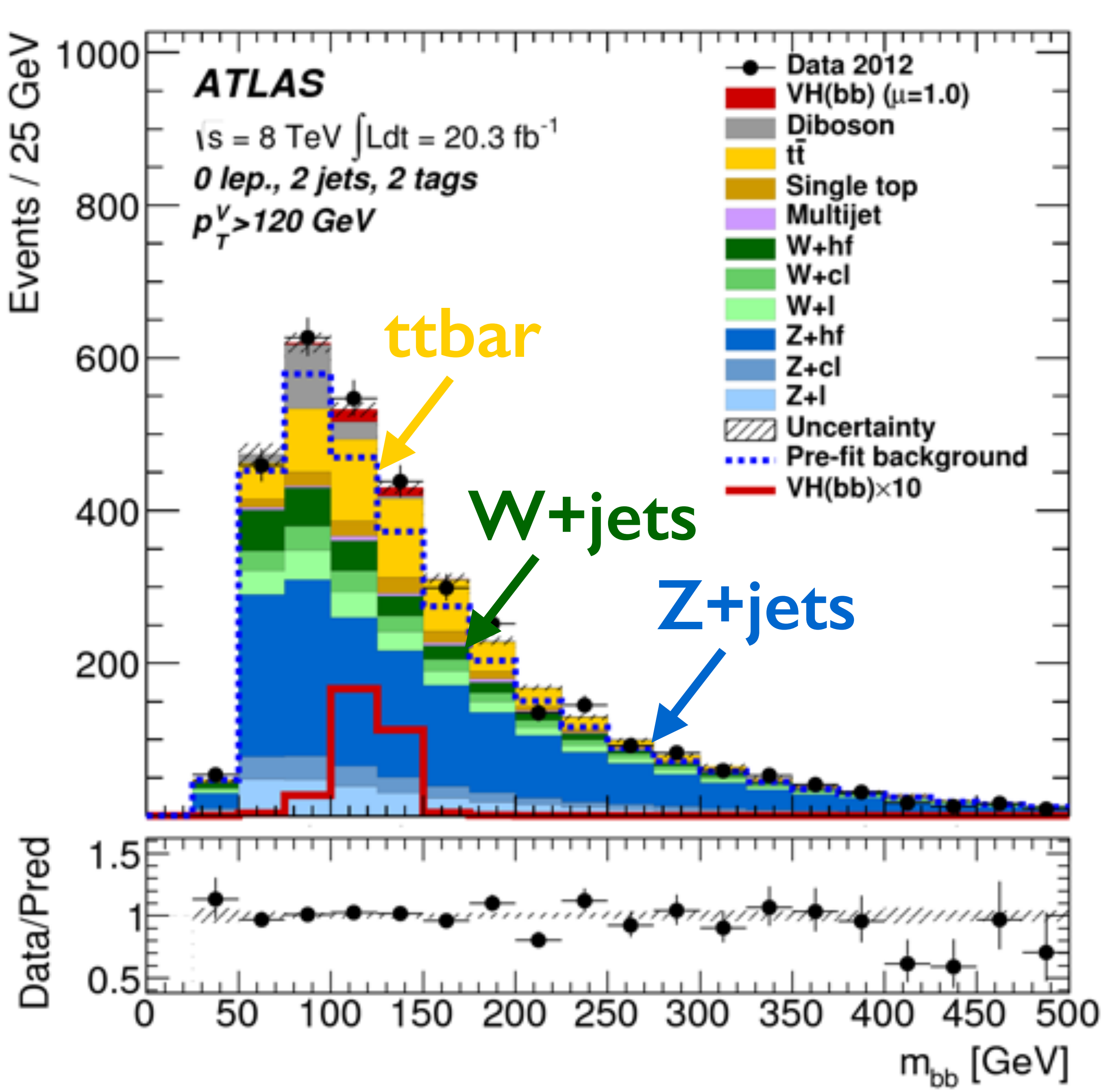


Tighter b-tagging

- Suppress non b-jet backgrounds
- Analysis sub-divided into multiple b-tagging regions, to enhance sensitivity.

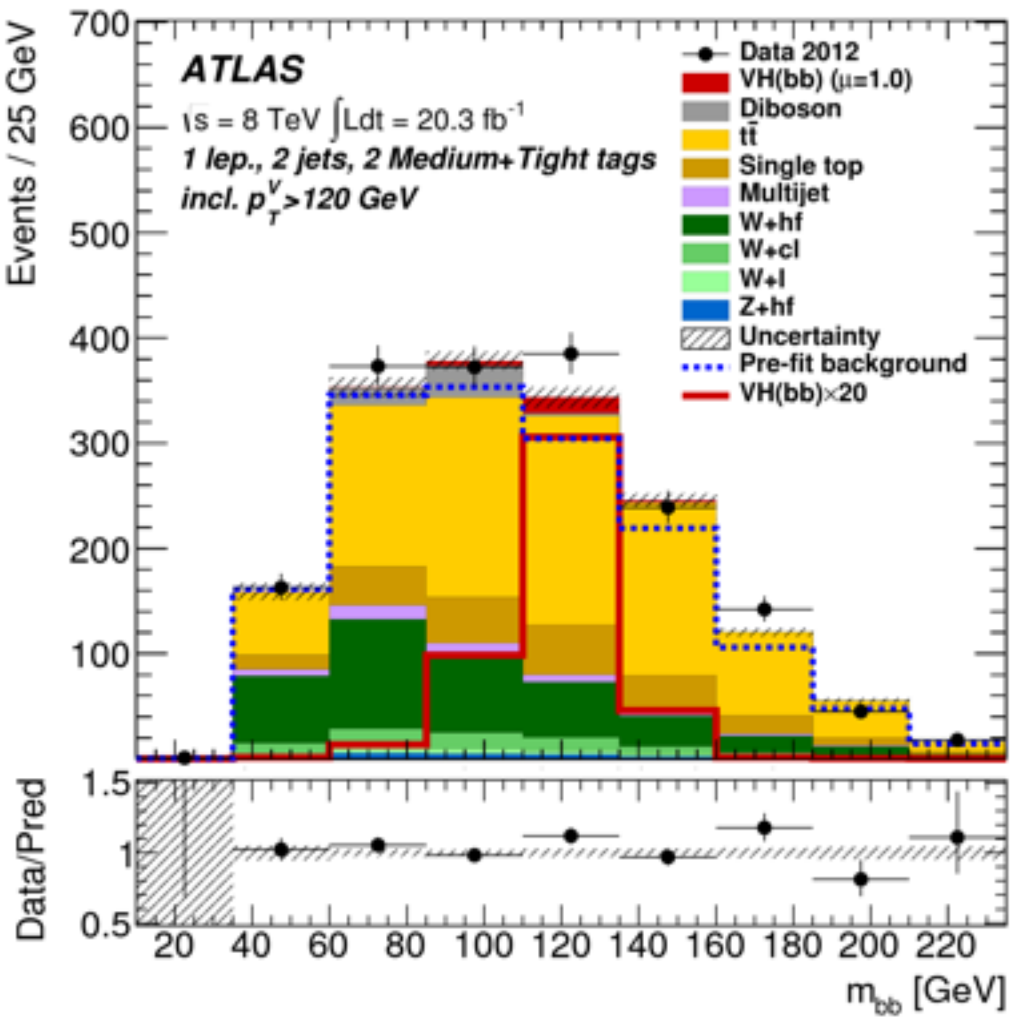


Strategies for background suppression: (2) m_{bb}

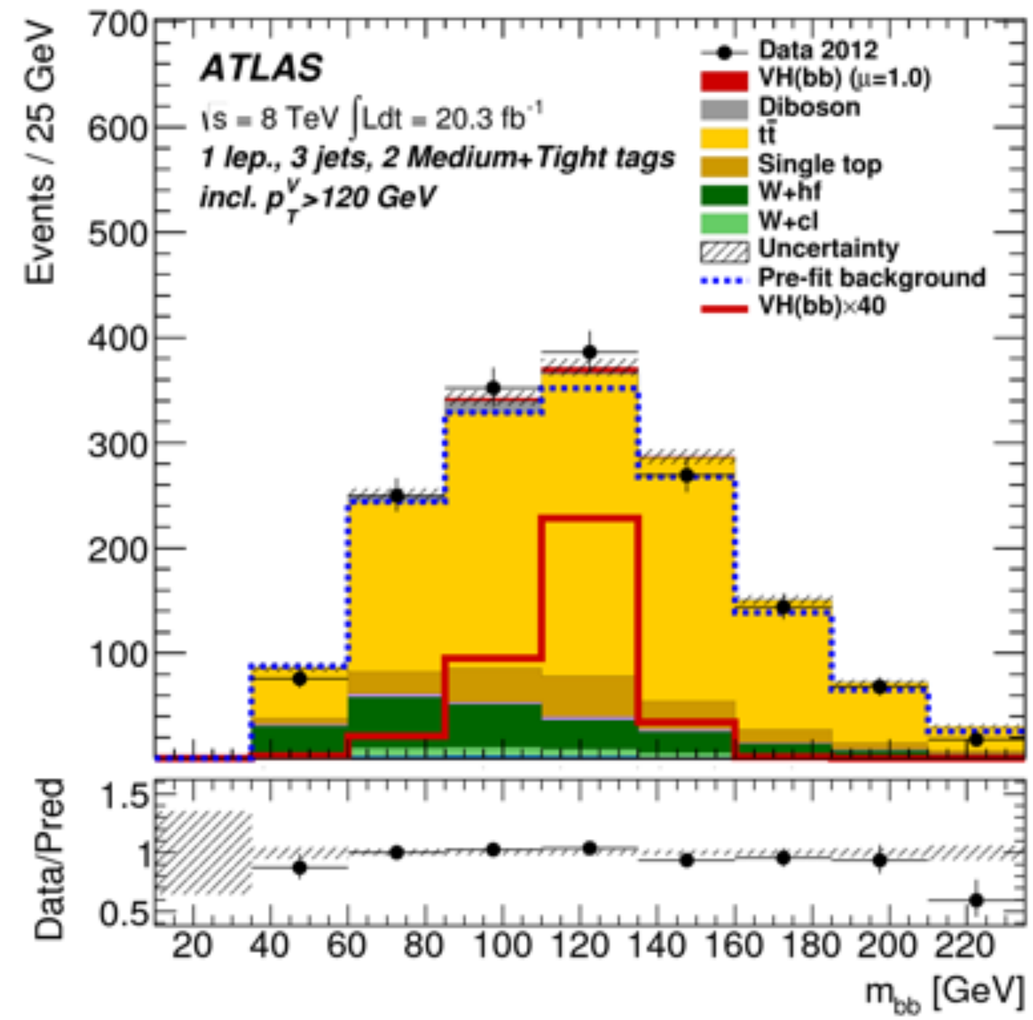


- VH signal peaks at m_{bb} ~125 GeV
- Non-resonant backgrounds from W/Z+jets, ttbar and single-top
- Resonant VZ to Vbb background at m_{bb} ~90 GeV
- Use m_{bb} side-bands for data-driven estimate of backgrounds

Strategies for background suppression: (3) jet multiplicity



2 jets

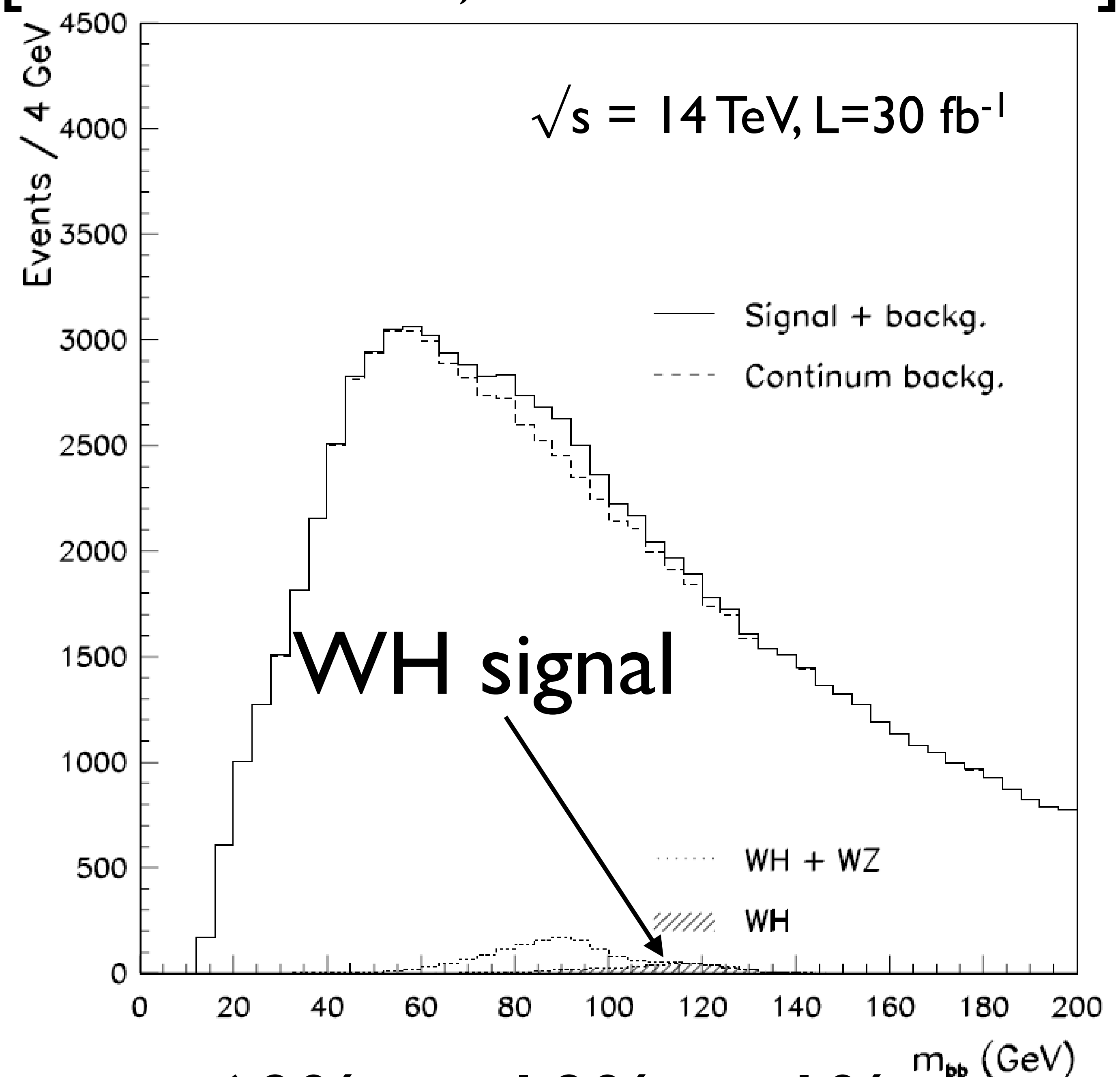


3 jets

- VH signal mostly in the 2 jet region (jet veto), ttbar background mostly in 3 jet region
- Separating them out (1) improves sensitivity (2) allows to determine ttbar background normalization from data

ATLAS expectations in 2000…

[E. Richter-Was, ATL-PHYS-2000-024]



ε_b=60%, ε_c=10%, ε_l=1%

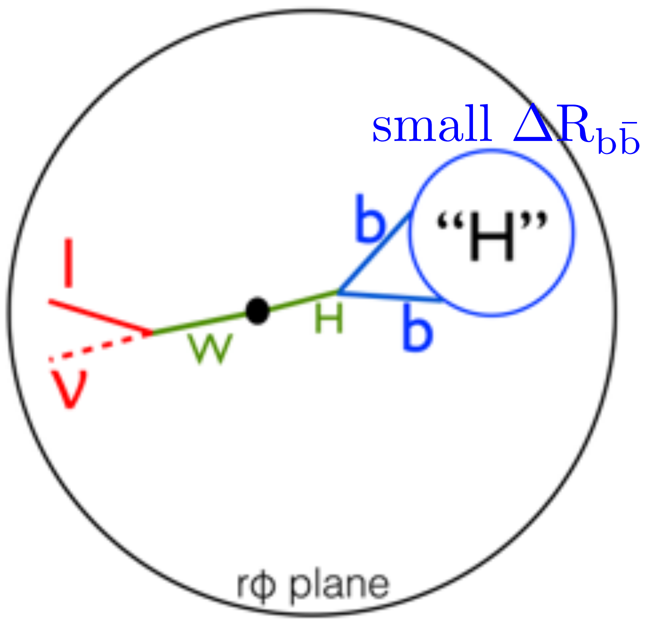
- Median expected significance: **~2σ**
- But **S/B ~ 1-2%**
- Almost hopeless!
- Many advancements since then:

1. "Boosted" regime
2. High-performance b-tagging
3. Improved m_{bb} resolution
4. Multivariate analysis techniques

1. “Boosted” regime…

The “boosted” regime

VH signal



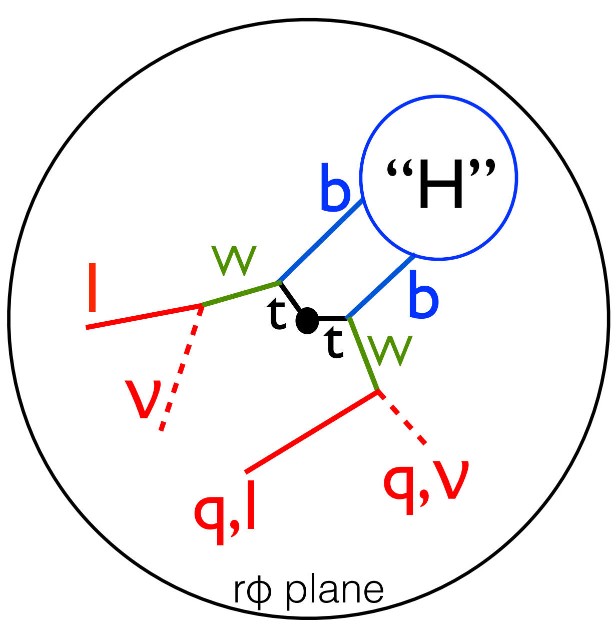
high pT(V/H)

- Require high pT(V) / pT(H)
- Small bb opening angle

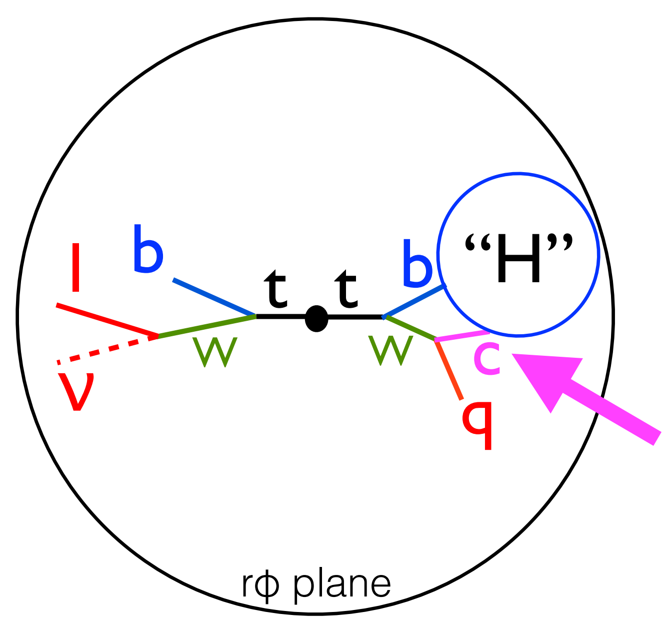
$$\Delta R(b_1, b_2) = \sqrt{\Delta\eta^2 + \Delta\phi^2} \approx \frac{2m_H}{p_T(H)}$$

  - H and V back-to-back
- Backgrounds (especially ttbar) significantly suppressed

ttbar background



low pT(V/H)



c-jet rejection crucial

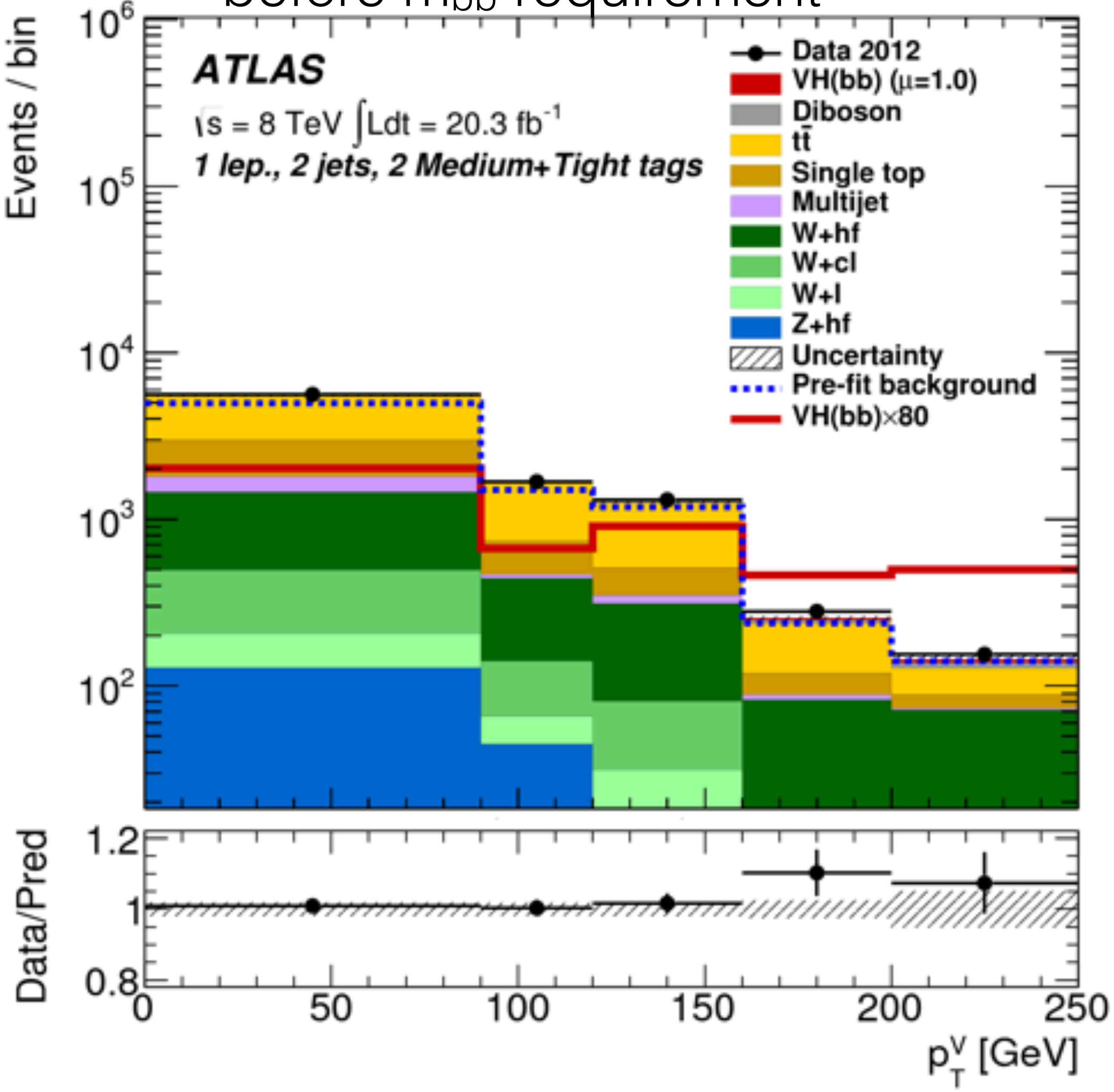
high pT(V/H)

- First proposed in the context of jet substructure

[J. Butterworth et al. (PRL 100:242001,2008), GP (CERN-THESIS-2010-07)]

pT(V) categorization

before m_{bb} requirement

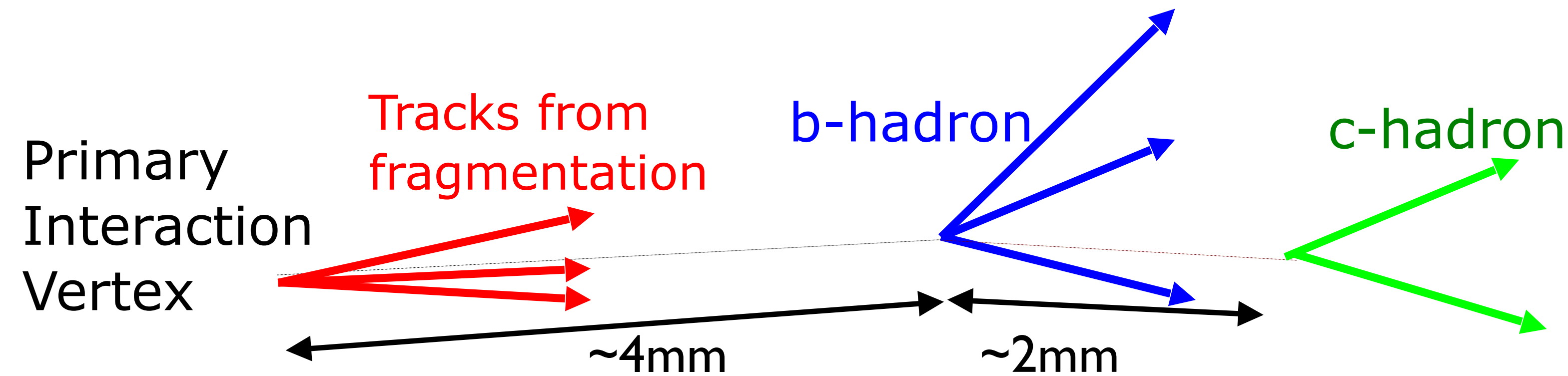


- Increase sensitivity by categorizing events in intervals of pT(V)
  - At high pT(V) require smaller ΔR(bb)
- Low pT(V) region mainly to control the background
- Significant improvement w.r.t. inclusive analysis [GP et al, Phys. Lett. B 718 (2012) 369-390]

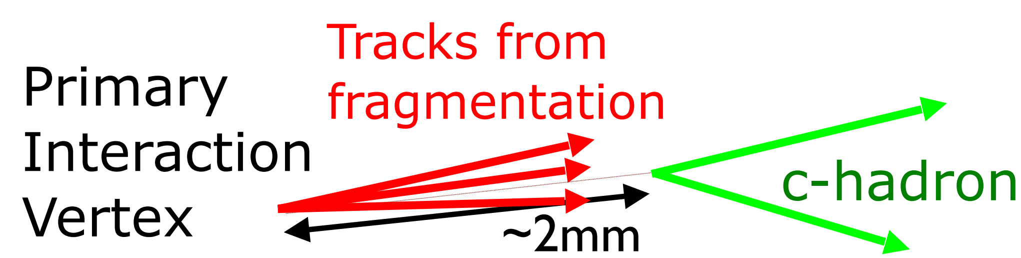
2. High-performance b-tagging…

Identifying b-quark jets

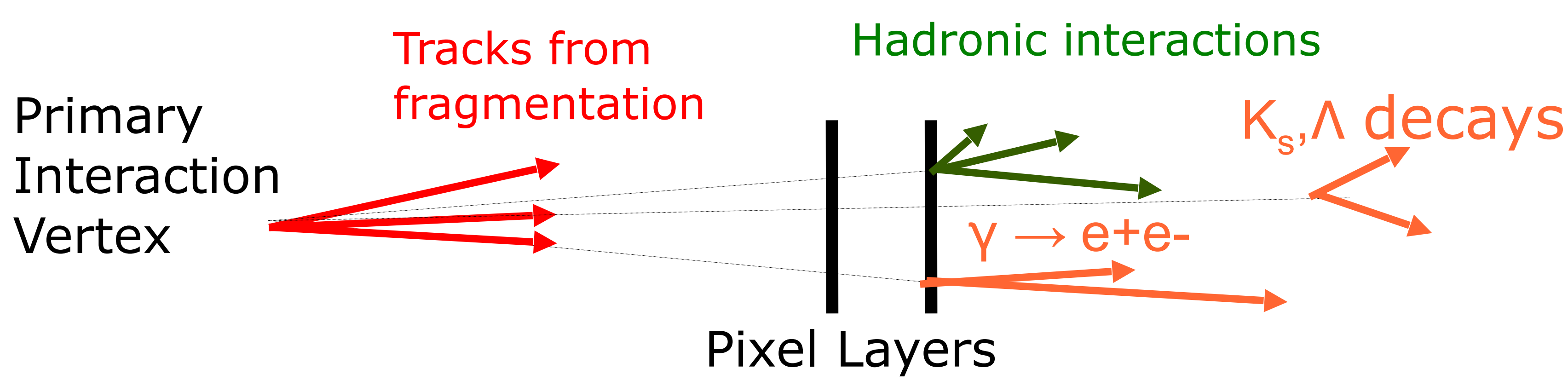
B-quark jets



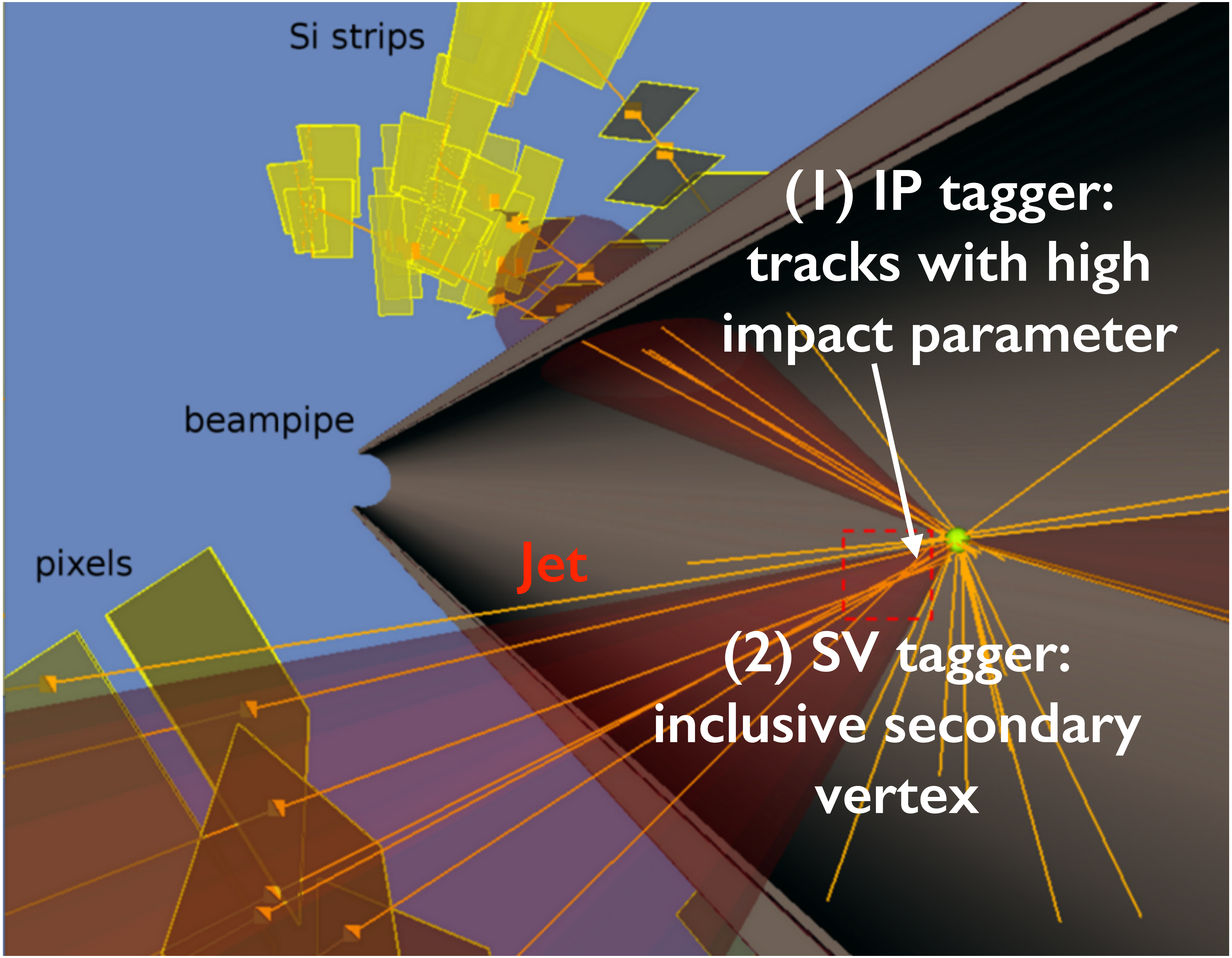
C-quark jets



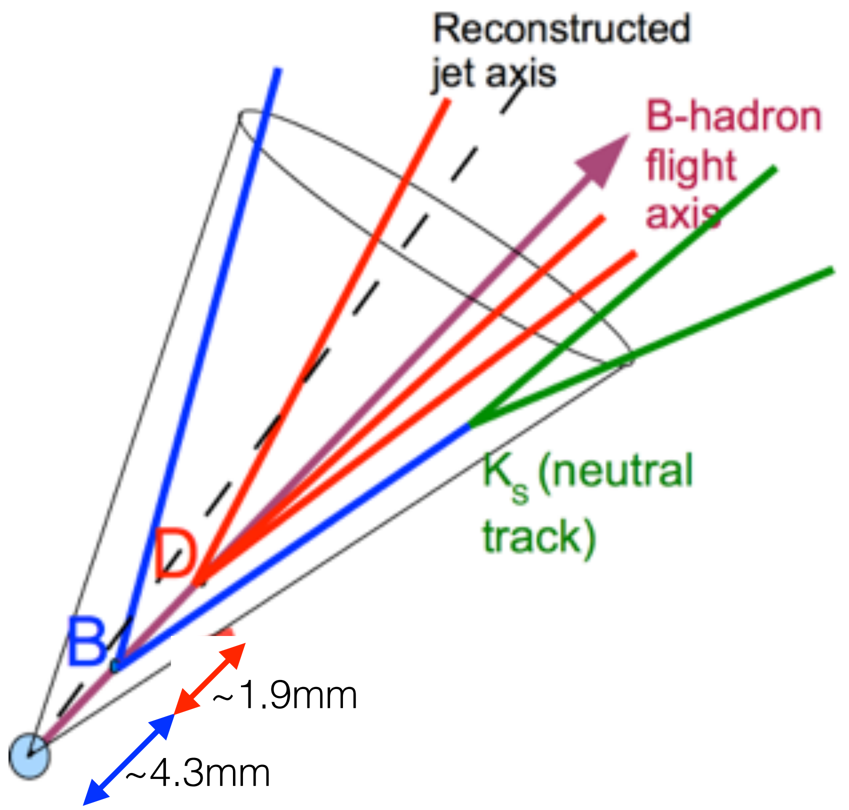
Light-flavour jets
(u,d,s-quark, gluon)

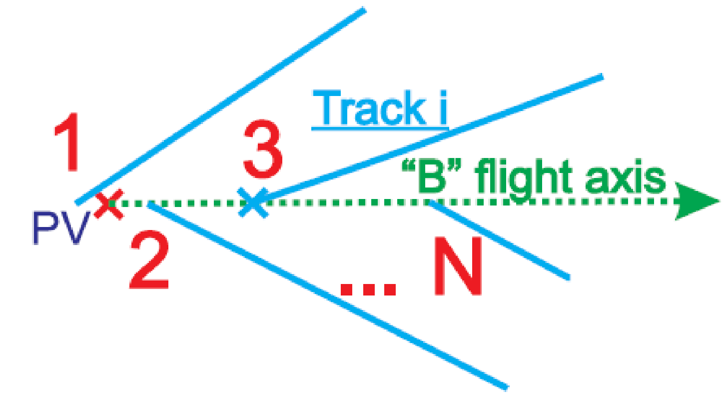


- Three algorithms: **(1)** Impact parameter based **(2)** Inclusive Secondary Vertex finder **(3)** Reconstruction of full PV → b- → c-hadron decay chain

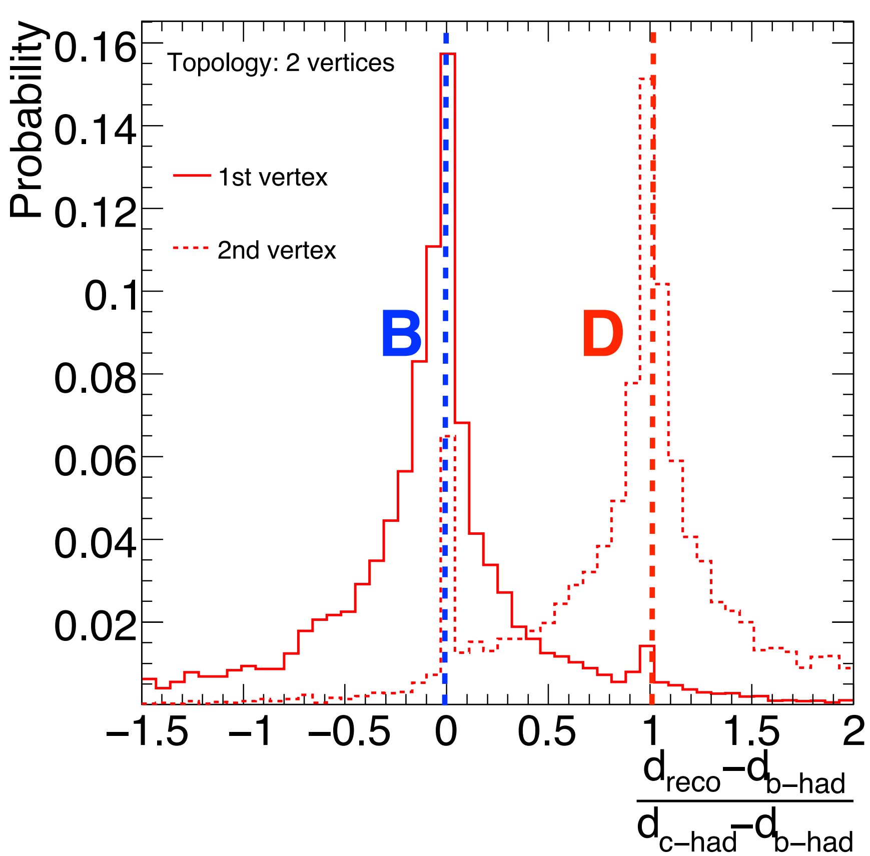

Si strips
beampipe
pixels
Jet
(1) IP tagger:
tracks with high
impact parameter
(2) SV tagger:
inclusive secondary
vertex

(3) “JetFitter”



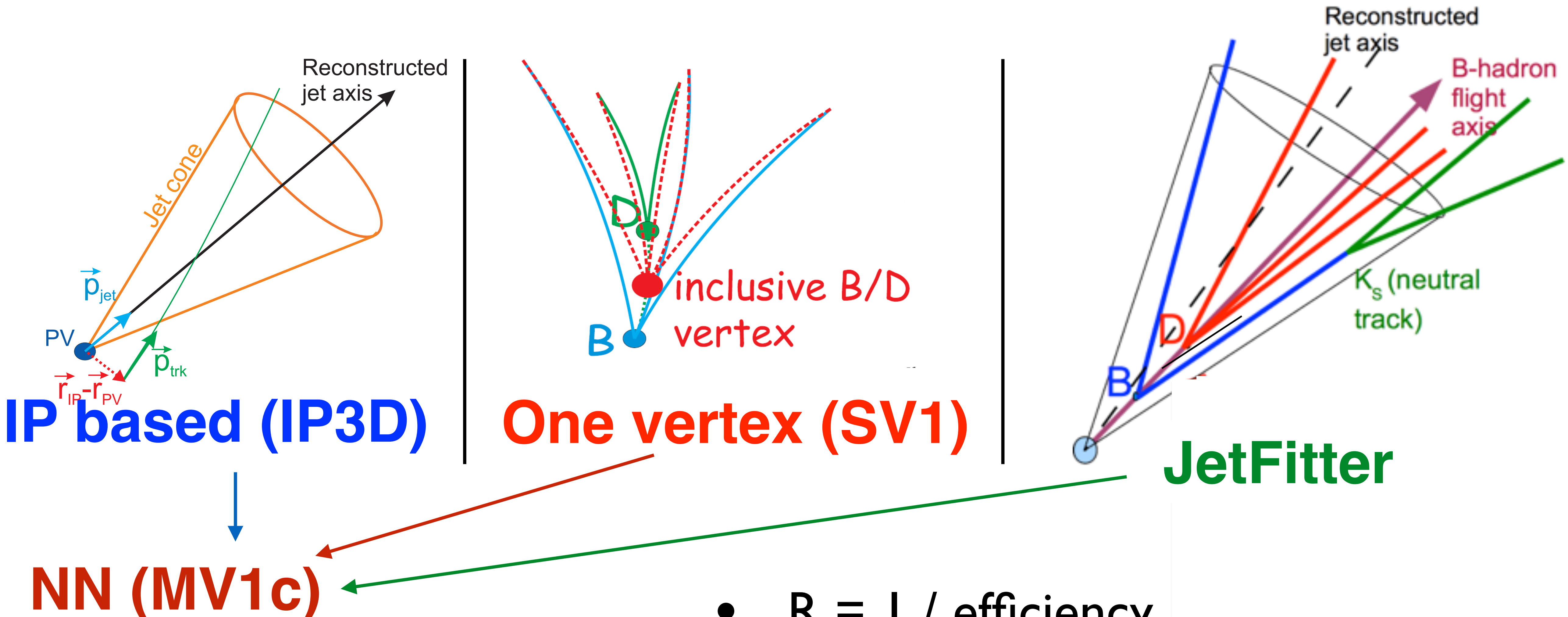


- Kalman filter to fit
  PV to b to c decay chain
- Exploits that c-hadron decay vertex lies approximately on b-hadron flight direction
  - analogous to ghost-track approach at SLD
- In Run-1, can separate the b- and c-hadron vertices in ~20% of b-jets



[GP et al,
J. Phys.: Conf. Ser. 119:032032,
J. Phys.: Conf. Ser. 219:032019,
ATL-CONF-2011-102]

Combined algorithm (MV1c)



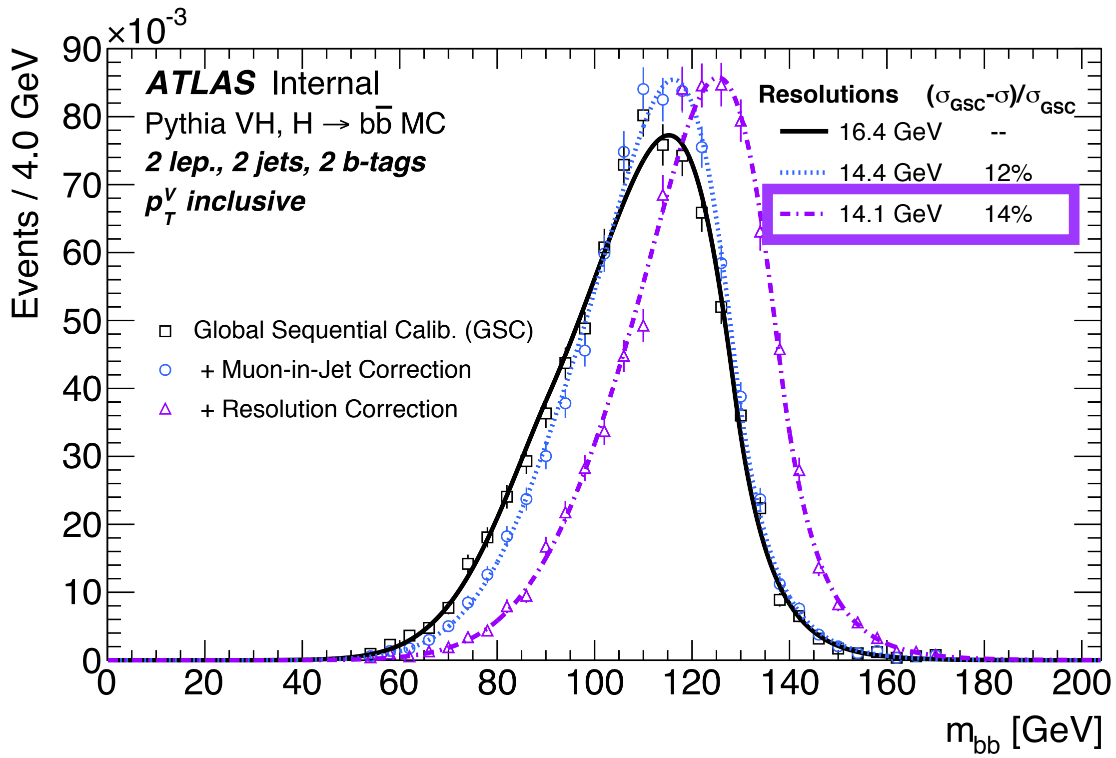
ε(B)	R(c)	R(light)
80%	~3	~29
70%	~5.3	~136
60%	~10.5	~450
50%	~26	~1400

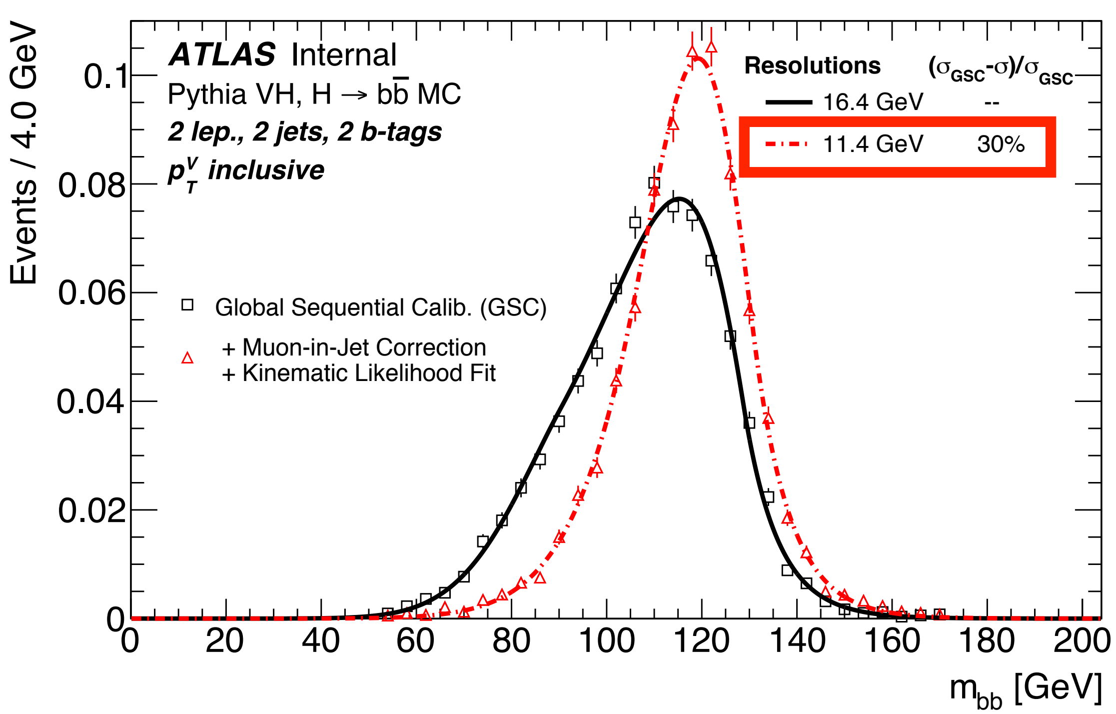
- R = 1 / efficiency
- Optimized to reject c-jets (improves 1-lepton channel!)
- Use “continuous b-tagging: simultaneous use of several working points

[GP et al, ATL-COM-PHYS-2014-035]

3. Improved m_{bb} resolution…

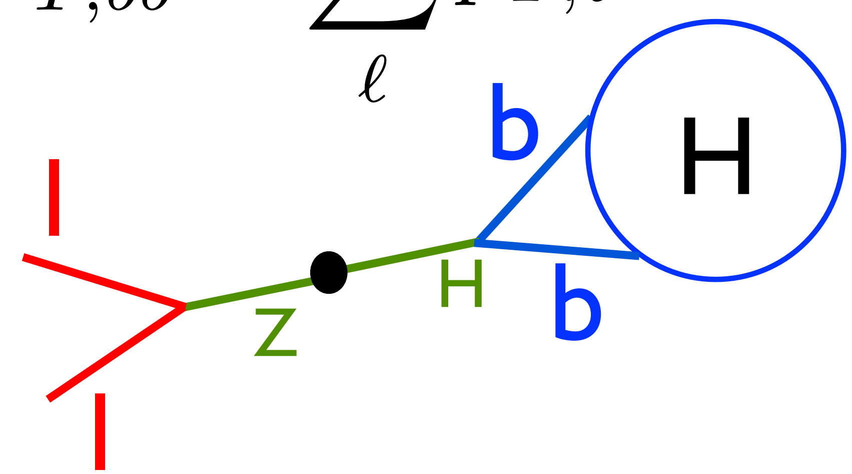
Mass resolution





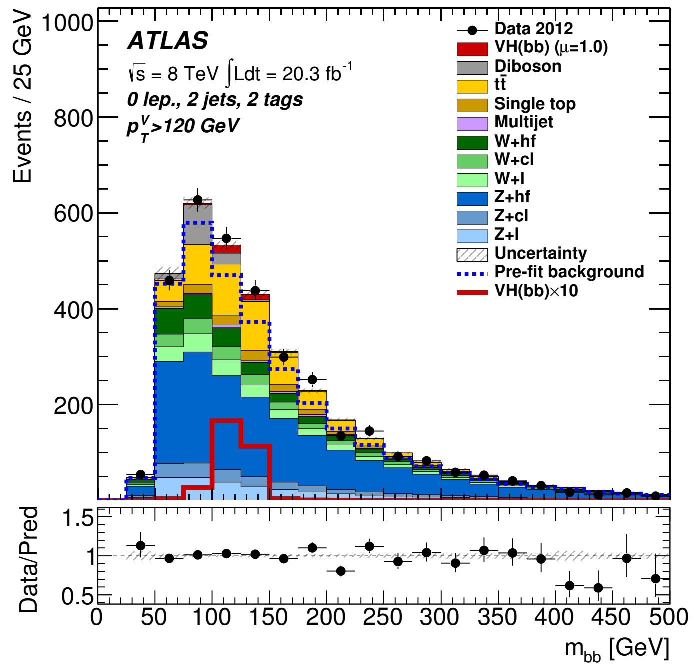
- Sharpening signal mass peak improves sensitivity
- Use track- and jet shape-variables to improve jet energy resolution
- Add muon-in-jet
- Then apply resolution correction based on average energy response in signal
- For 2-lepton channel, use full kinematic likelihood fit, exploiting constraint:

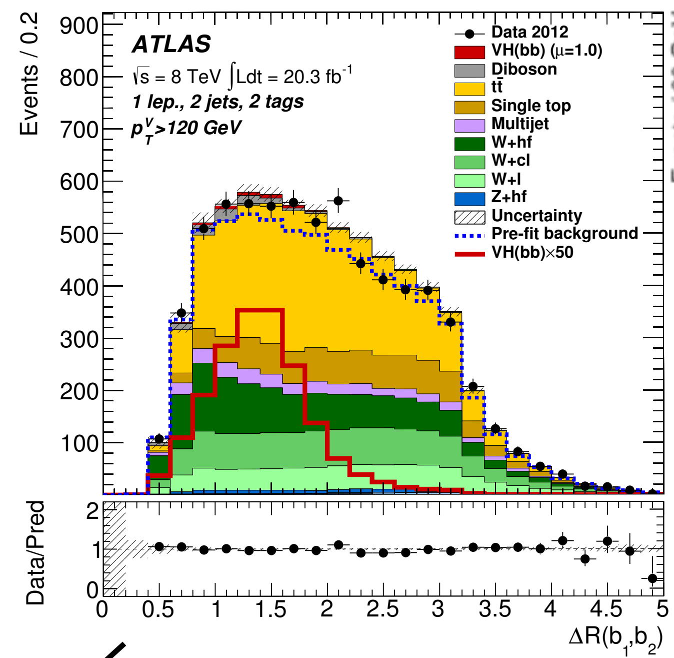
$$\vec{p}_{T,b\bar{b}} = \sum_{\ell} \vec{p}_{T,\ell}$$

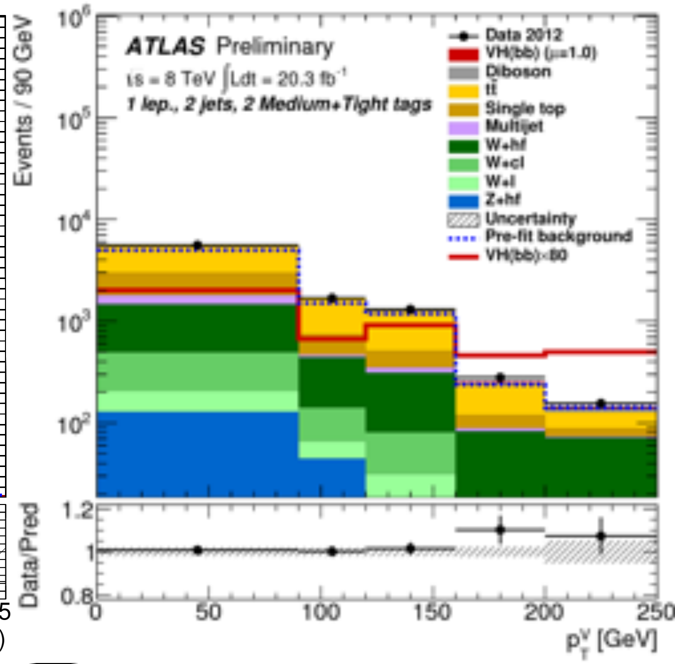


4. Multivariate analysis (MVA) techniques…

MVA

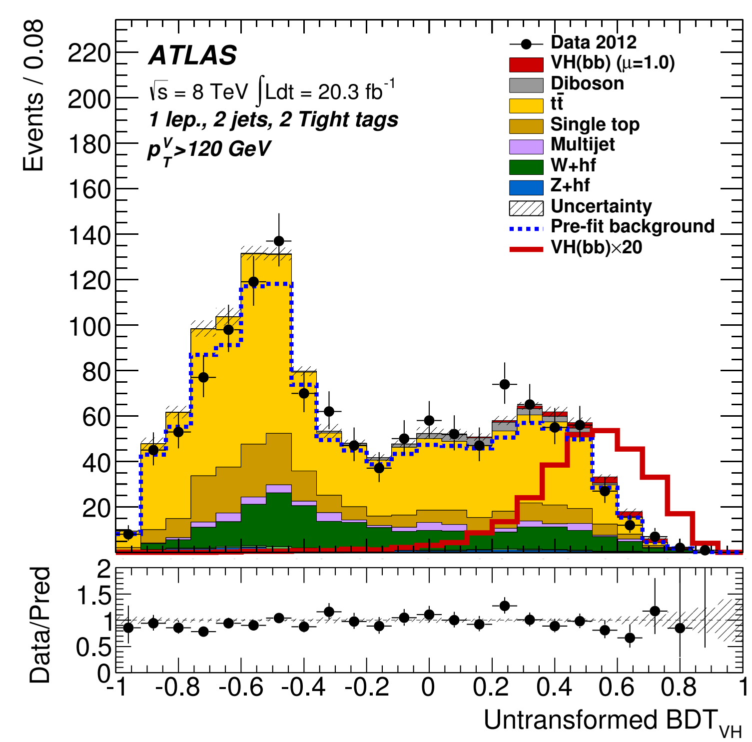






Variable	0-Lepton	1-Lepton	2-Lepton
p_T^V		×	×
E_T^{miss}	×	×	×
$p_T^{b_1}$	×	×	×
$p_T^{b_2}$	×	×	×
m_{bb}	×	×	×
$\Delta R(b_1, b_2)$	×	×	×
$\lvert\Delta\eta(b_1, b_2)\rvert$	×		×
$\Delta\phi(V, bb)$	×	×	×
$\lvert\Delta\eta(V, bb)\rvert$			×
H_T	×		
$\min[\Delta\phi(\ell, b)]$		×	
m_T^W		×	
$m_{\ell\ell}$			×
$MV1c(b_1)$	×	×	×
$MV1c(b_2)$	×	×	×
	Only in 3-jet events		
$p_T^{jet_3}$	×	×	×
m_{bbj}	×	×	×

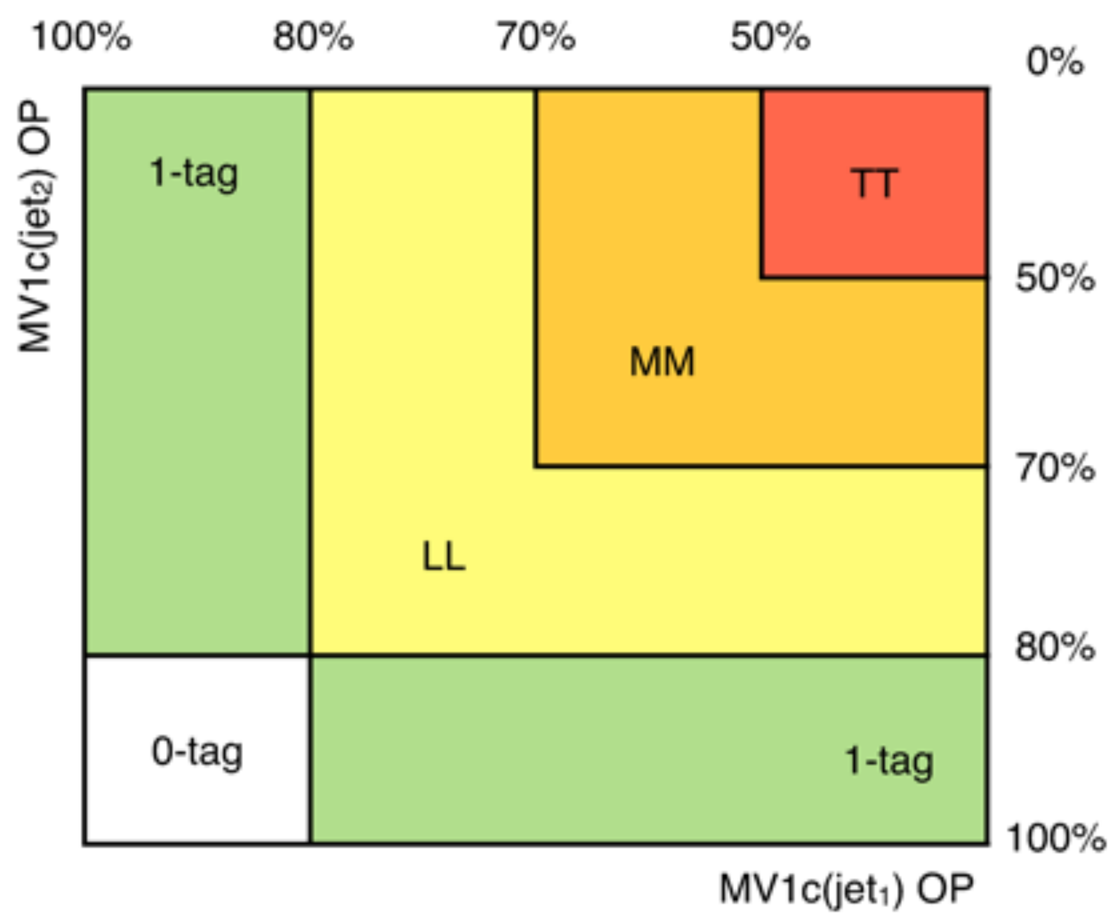
- **Multivariate approach**
  - Loose selection, then use multi-variate technique (BDT) as final discriminant in likelihood fit



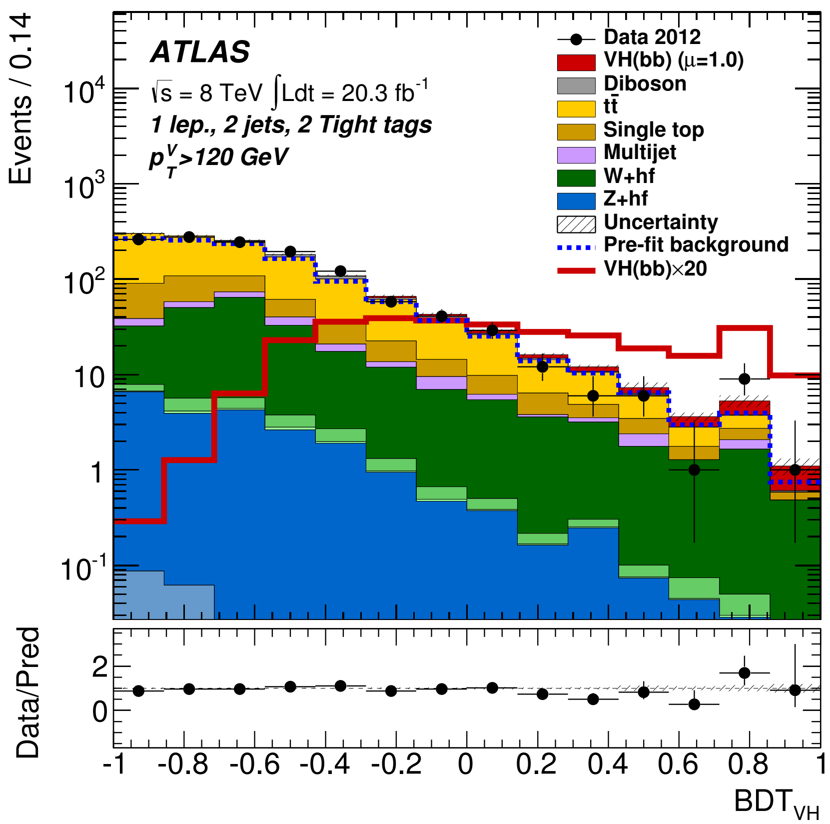
Combining all improvements…

Analysis categories

- Three channels: **0-lepton**, **1-lepton** and **2-lepton**
- **Two** pT(W/Z) regions
  - <120, >120 GeV
- **Four** b-tag regions (1-tag, LL,MM,TT)
- **Two** jet bins (2 and 3 jets)
- Discriminating variables in fit
  - 1-tag: **MV1c**
  - 2-tag: **BDT**

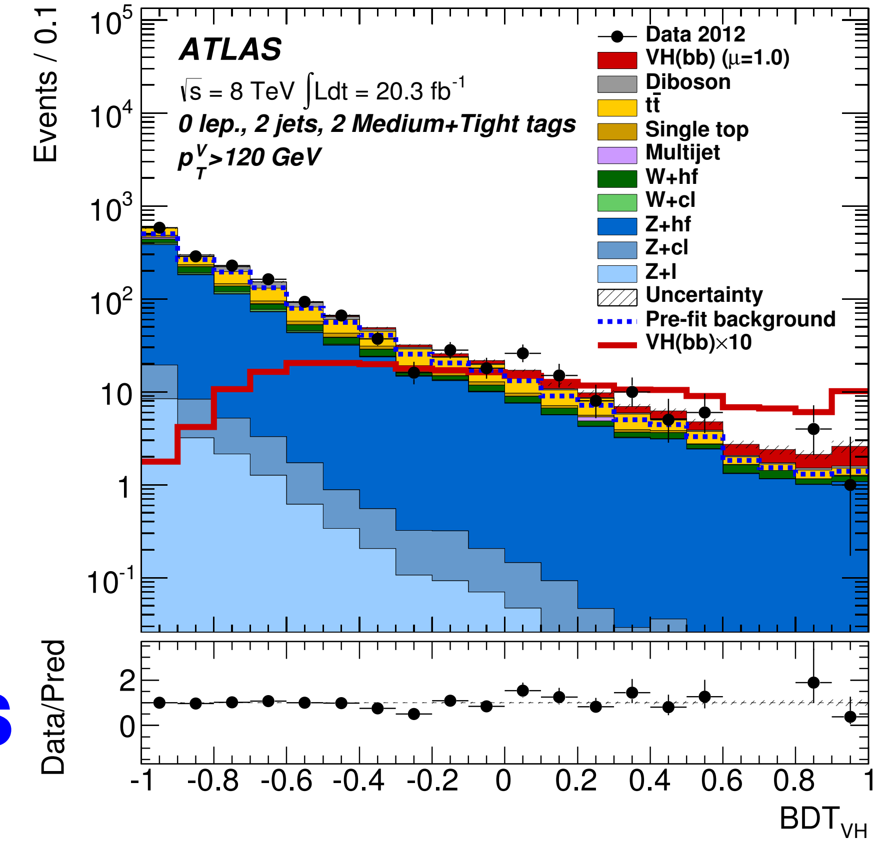


Signal extraction

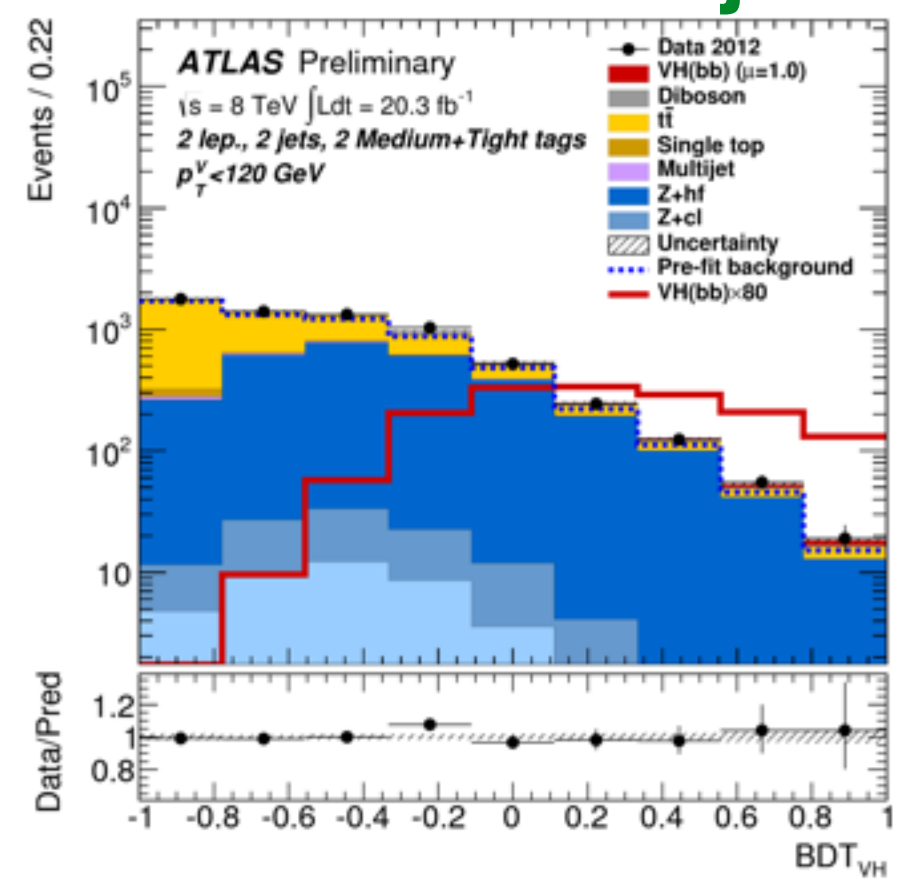


1-lepton
TT 2 jets

0-lepton
MM+TT 2 jets

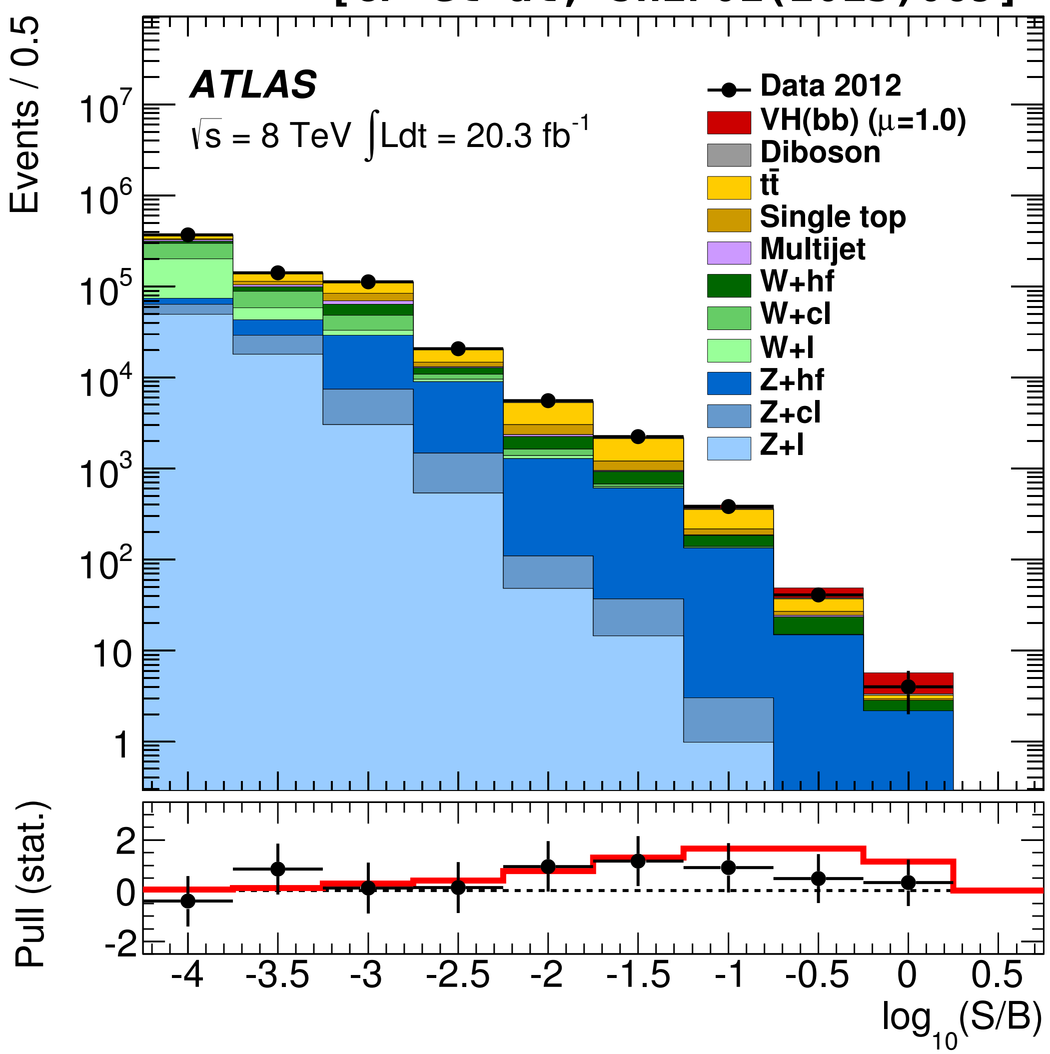


2-lepton
MM+TT 2 jets



- Simultaneous profile likelihood fit to:
  - **2-tag**: 27 signal regions
  - **1-tag**: 11 control regions
- Extract $\mu = \dfrac{\sigma \times \mathrm{BR}}{(\sigma \times \mathrm{BR})_{\mathrm{SM}}}$
- ~170 nuisance parameters to account for systematic effects

[GP et al, JHEP01(2015)069]



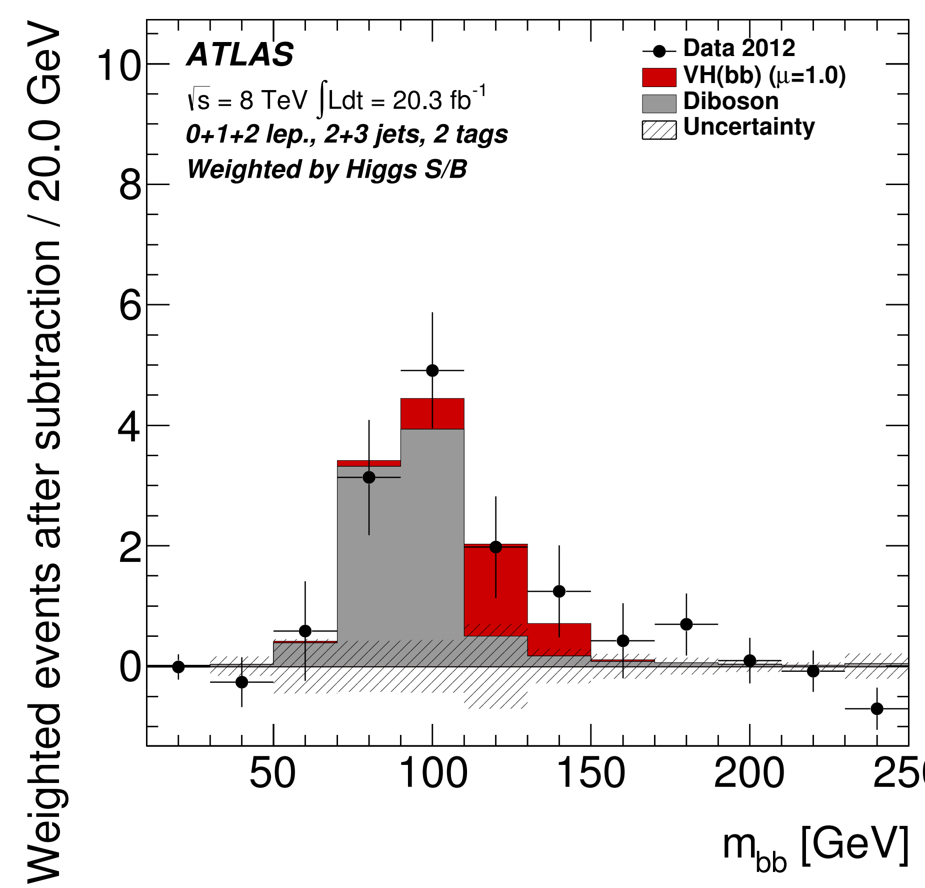
Main result

- 40% expected uncertainty on SM expectation of μ=1
- 60% better than preliminary result
- Expected sensitivity 2.6σ, observed 1.4σ
- Weak hint of a signal, no evidence yet

Signal strength μ

Channel	ATLAS	CMS*
$WH \to \ell\nu b\bar{b}$	$0.80^{+0.66}_{-0.60}$	$1.11^{+0.87}_{-0.83}$
$ZH \to \ell\ell b\bar{b}$	$0.94^{+0.88}_{-0.79}$	$0.70^{+0.79}_{-0.71}$
$ZH \to \nu\bar{\nu}b\bar{b}$	$-0.35^{+0.55}_{-0.52}$	$0.89^{+0.63}_{-0.61}$
Combination	$0.51^{+0.40}_{-0.37}$	$0.89^{+0.47}_{-0.44}$

*numbers from CMS combination paper

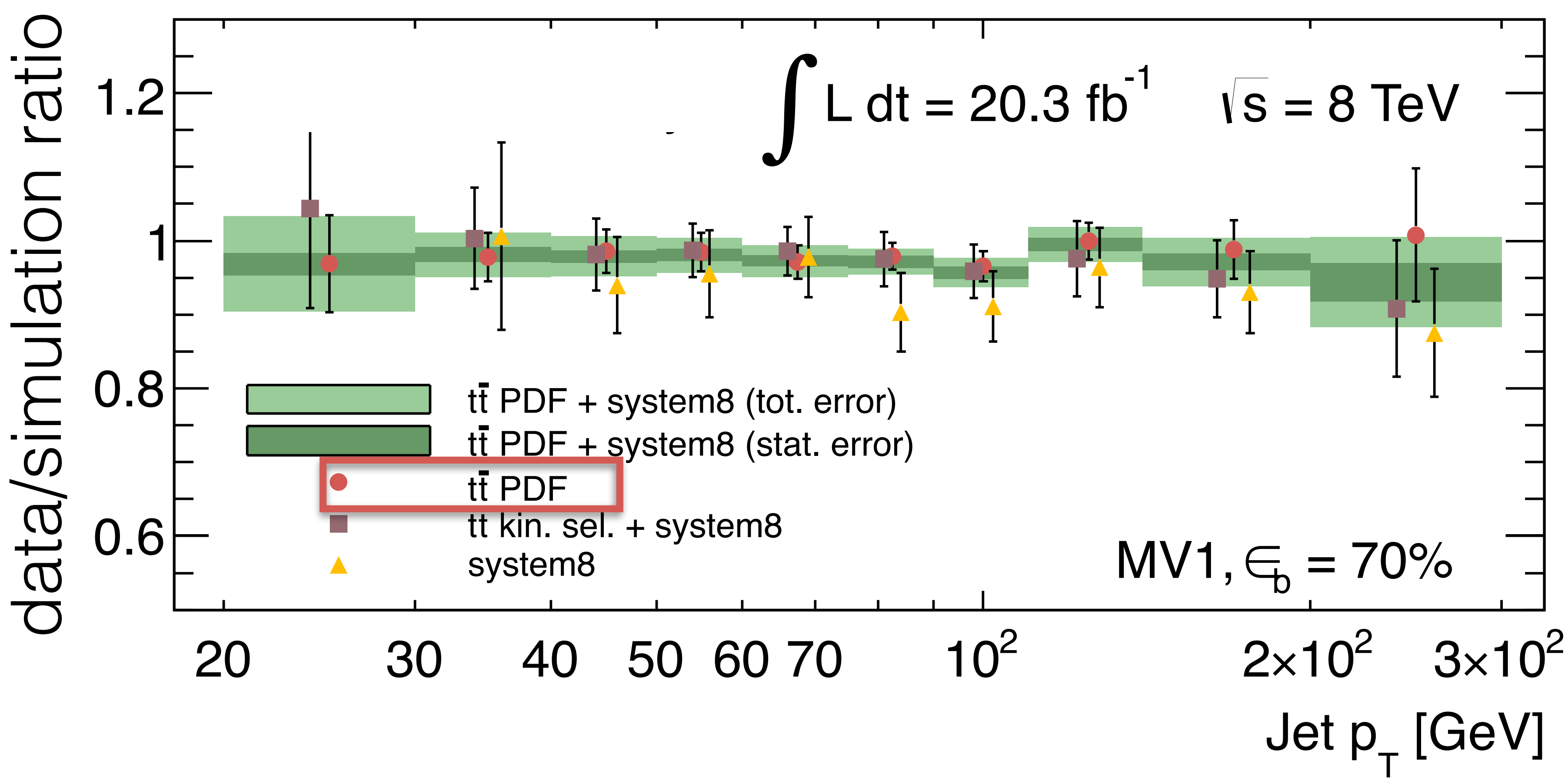


Systematic uncertainties

B-tagging calibration

- The b-tagging efficiency in Monte Carlo is calibrated with data measurements
- **Systematic uncertainty** due to limited precision of calibration
- Calibrate based on high b-jet purity events with di-leptonic top-quarks
- Novel method based on combinatorial likelihood allowed to reduce uncertainty to 2-3% in most of the pT range

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



- From dominant uncertainty in $H \rightarrow bb$ to sub-leading effect!

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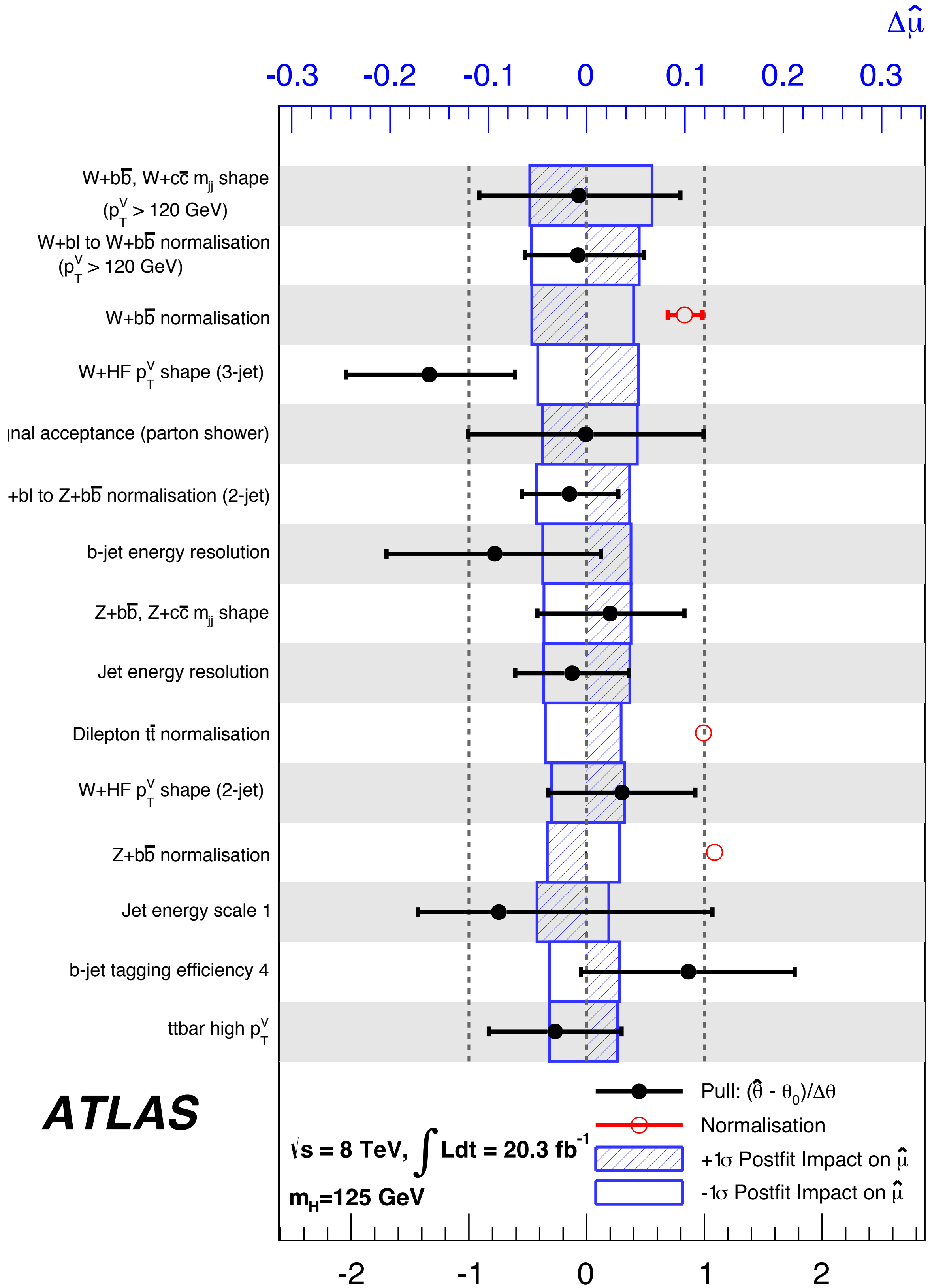
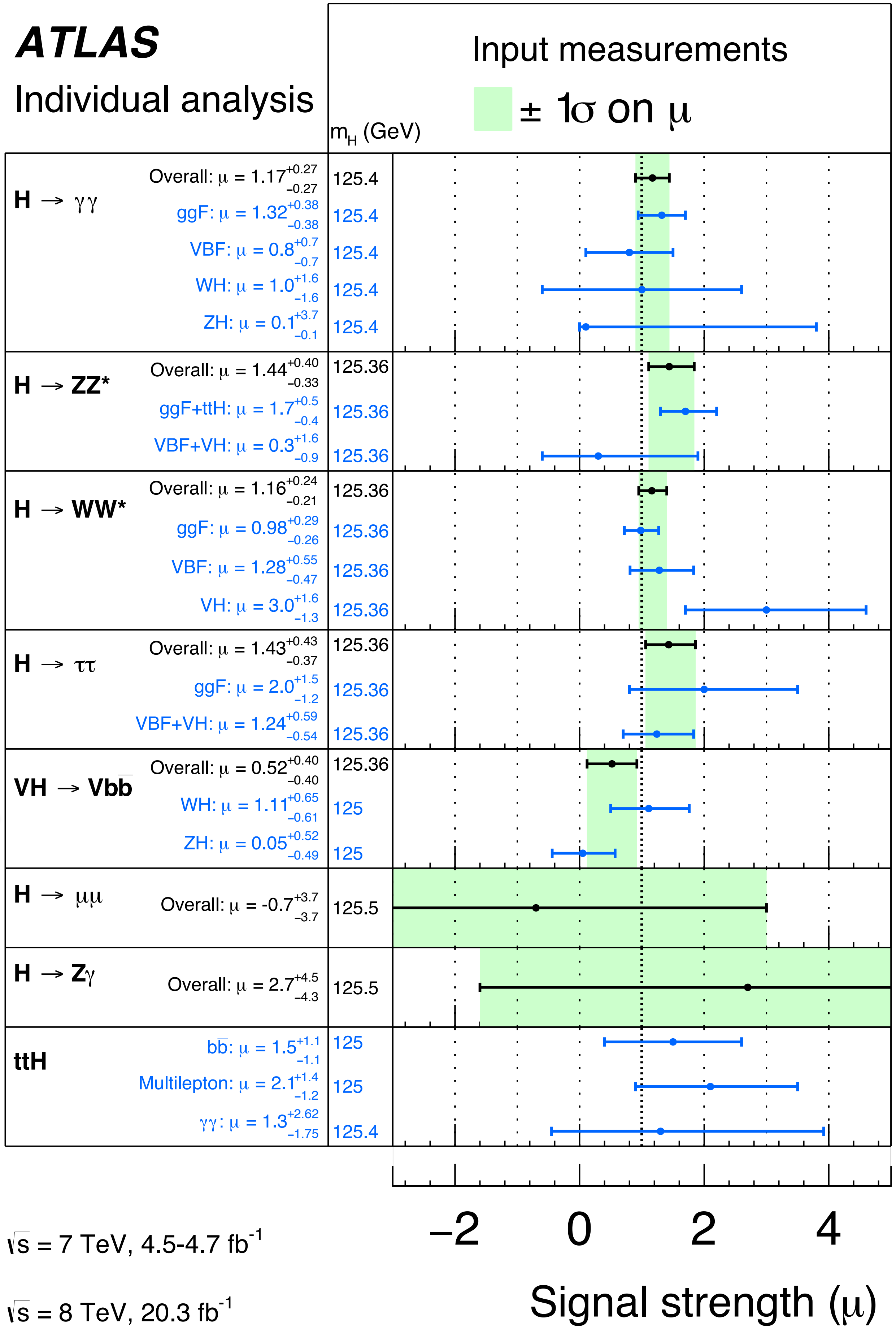
Systematic uncertainties



- Systematic uncertainties degrade sensitivity by ~25%
- Leading uncertainties:
  - **W+b/c theory** (shapes + flavor composition)
  - Signal theory (parton shower)
  - Jet energy resolution
- Important message for Run-2
  - Need improved theory predictions (refined Monte Carlo generators)
  - Plan unfolded measurement of W+bb to test theory modeling

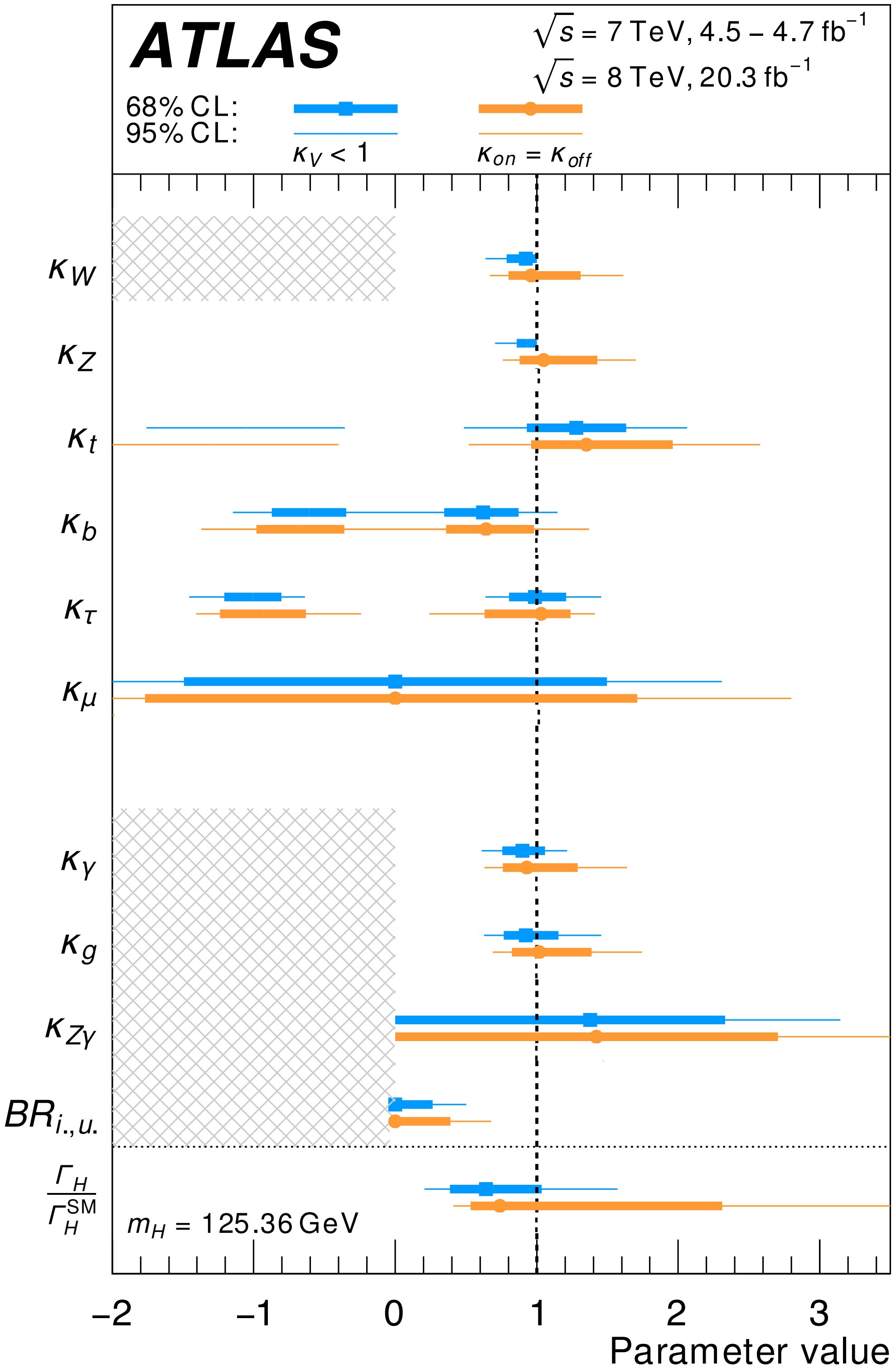
Interpretation in terms of absolute Higgs boson couplings

Input to coupling fits



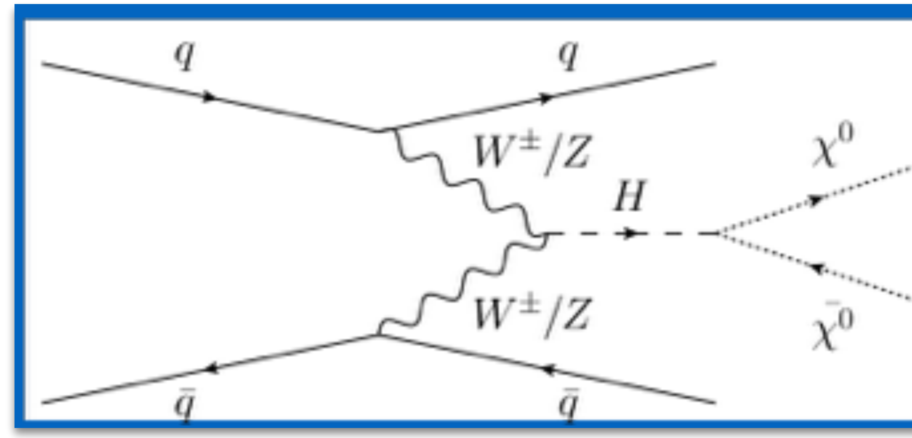
Fit to most generic model

[arXiv:1507.04548v1]



- Fit all visible couplings + for an undetected/invisible decay
- All couplings compatible with SM expectation (typical precision ~20-30%)
- Most couplings shifted down by μ(VH → Vbb)~0.5 result
- Constraint on invisible Higgs decays:
  - $BR_{i.u.}$ < 0.49 (0.68) (at 95% C.L.)

Higgs decays to "invisible"



- $BR_{i.u.}>0$?
- Direct searches complement indirect fits
  - Main search mode
    - 2 jets from vector boson fusion signature + high missing E_T (>150 GeV)

$BR(H \rightarrow \text{invisible}) <$ 29% @ 95% CL (35% expected)

[ATLAS-CONF-2015-004]

- Both direct and indirect measurement still allow for sizable contribution of Higgs decays to invisible
  - Looking forward to Run-2 results!

Towards b-tagging and $H \to bb$ in Run-2…

Inserted new detector (IBL)

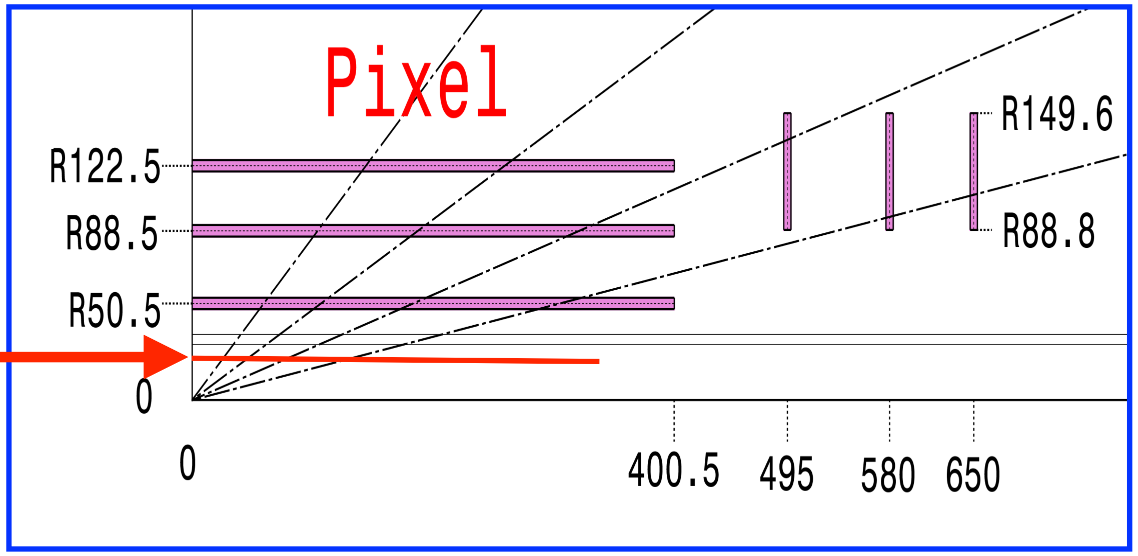
IBL:

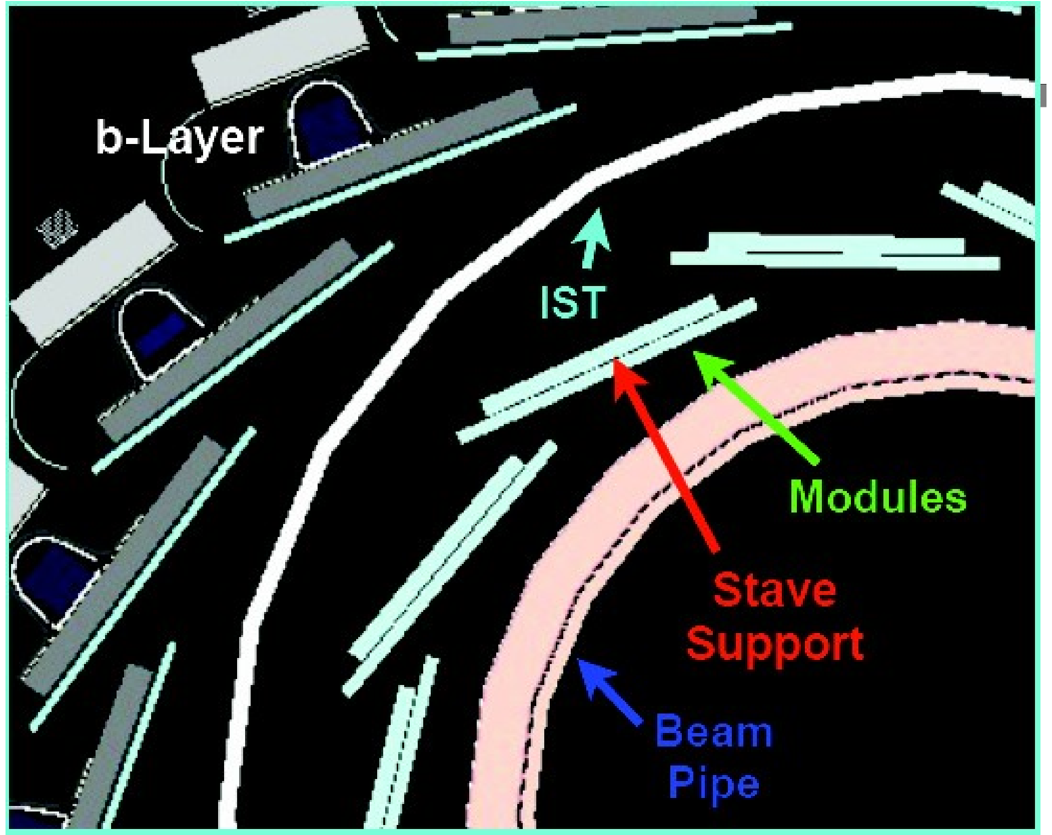
- Additional pixel layer R~3.3 cm
- Pixel size 50x250µm

ATLAS "b"-layer:

- R~5.1 cm, pixel size 50x400µm

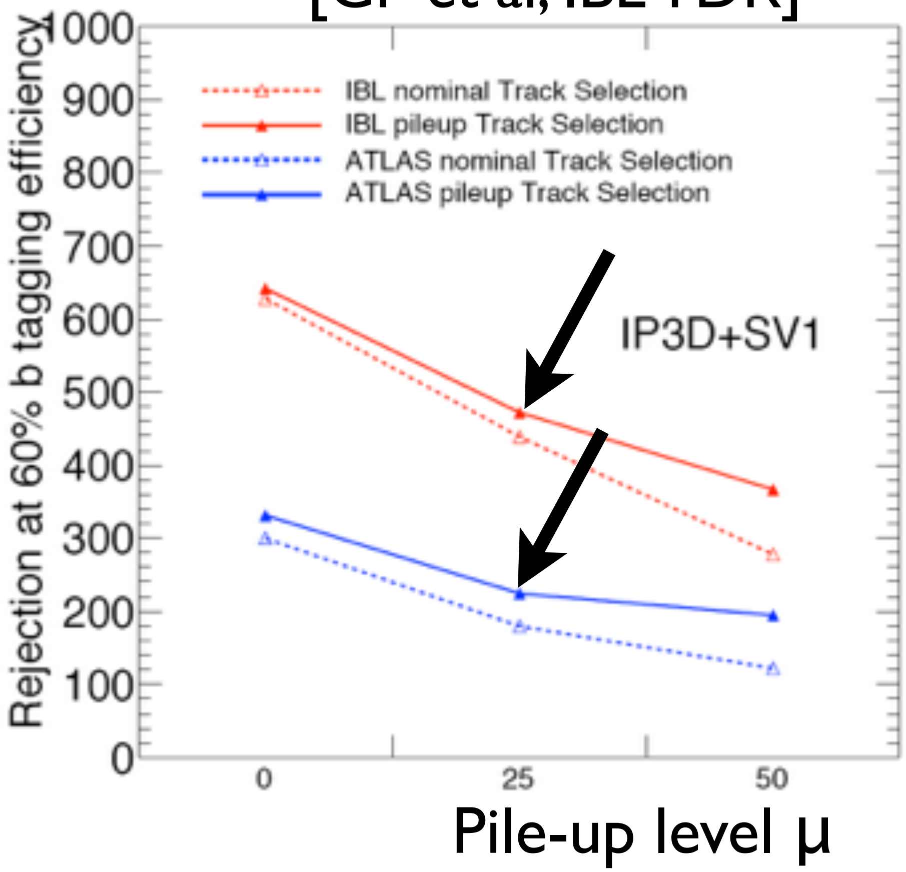
IBL inserted here!



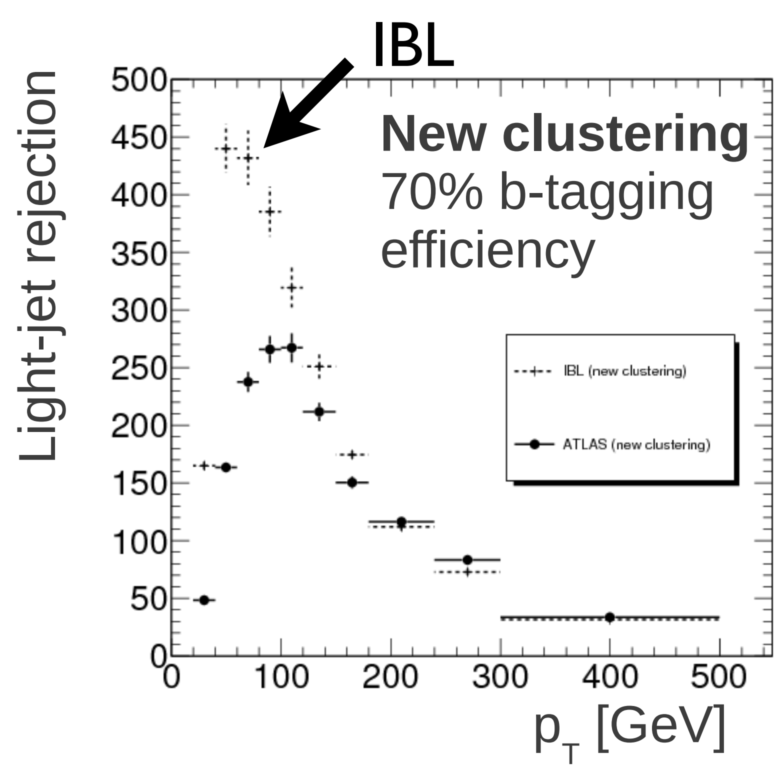


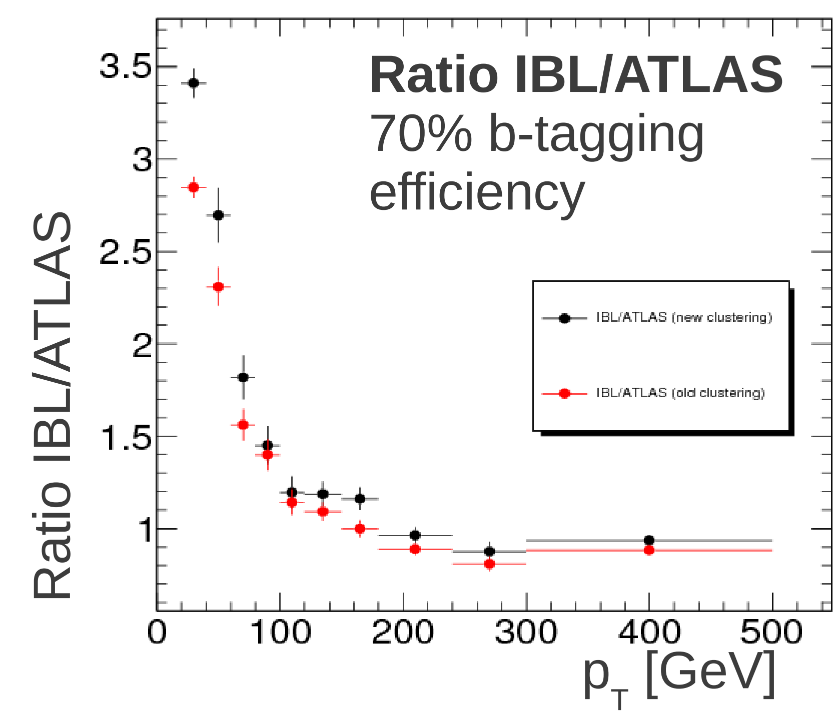
B-tagging performance in IBL TDR

[GP et al, IBL TDR]



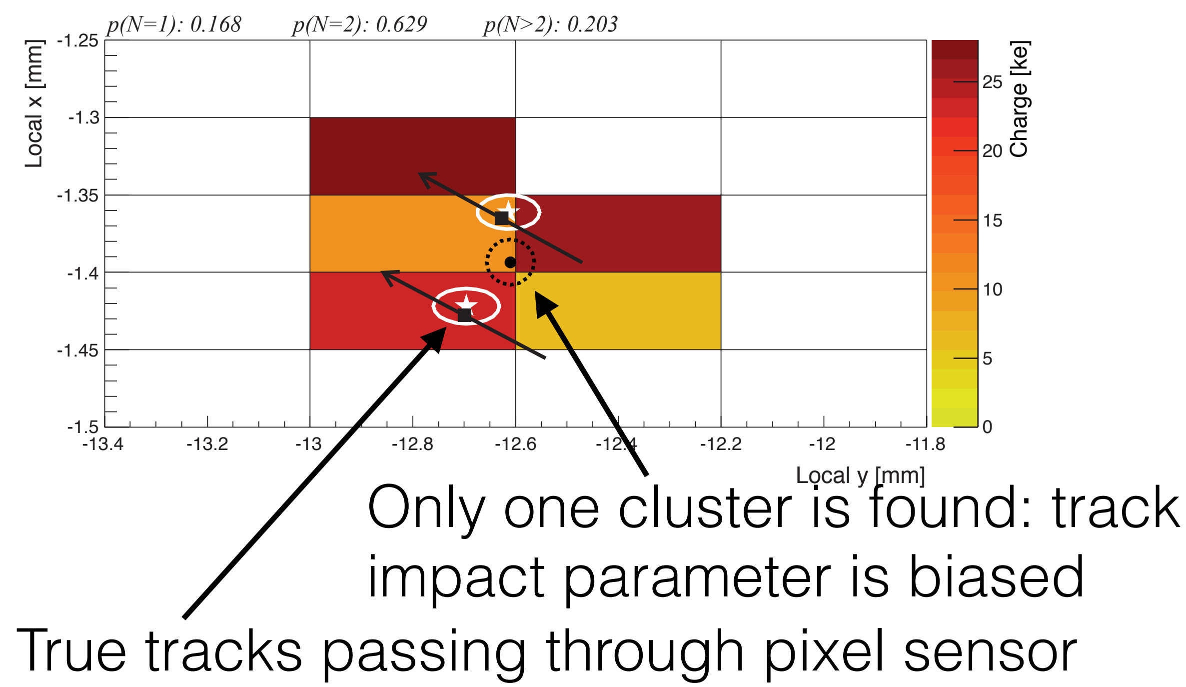
- Tracking performance: significantly improved at low/medium track pT
- B-tagging:
  - factor ~2 overall improvement in light-jet rejection (pT ~ 50 GeV)
  - Improvement mostly at low pT (up to x3.5), but *degradation* at high pT. **Why?**



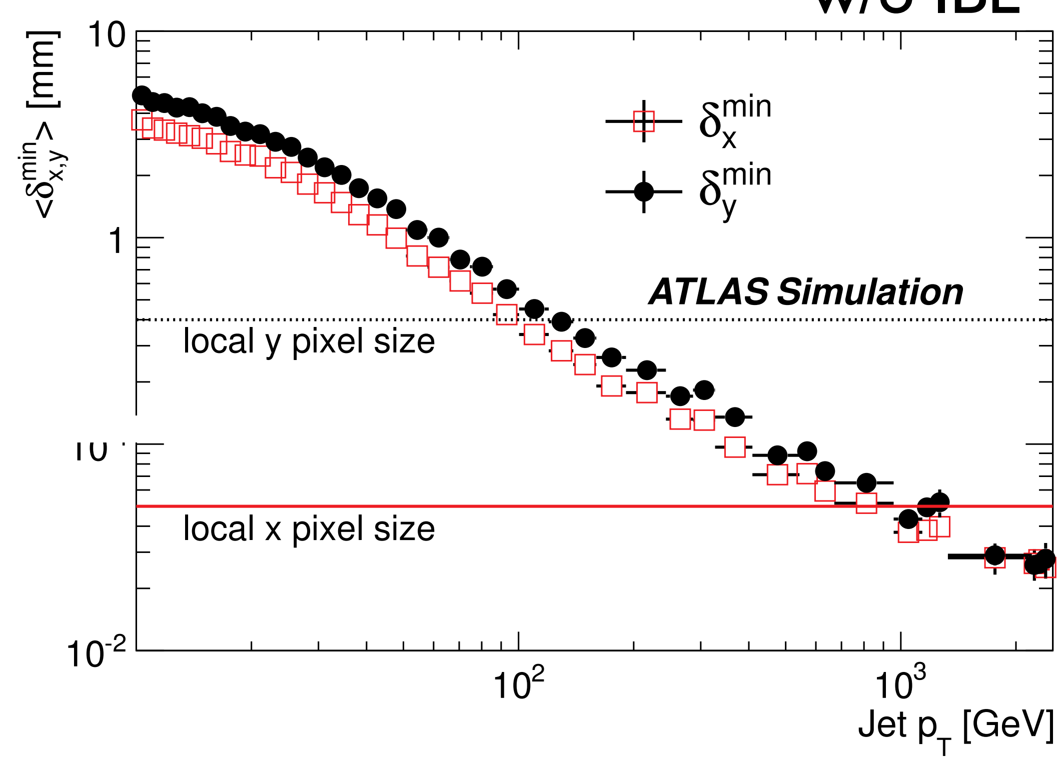


Degradation at high pT

- Several reasons:
  - <u>Leading one</u>: **collimated tracks in high pT jets** have overlapping hits in the first detector layers
  - Too many shared hits cause a track to be discarded
    - More severe with IBL (radius ~ 3cm)
  - <u>Sub-leading</u>: increasing number of fragmentation tracks
- Separation between charged particles can become closer than hit resolution → shared clusters
- Can use charge information within pixel cluster to identify these cases



w/o IBL



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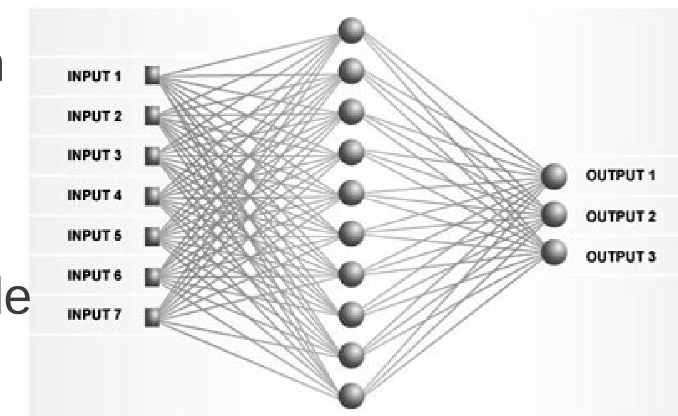
NN Pixel Cluster splitting

- Designed and implemented Neural Network cluster splitting
    - Test and validation within Pixel Clusterization Task Force (PCTF)

INPUT nodes

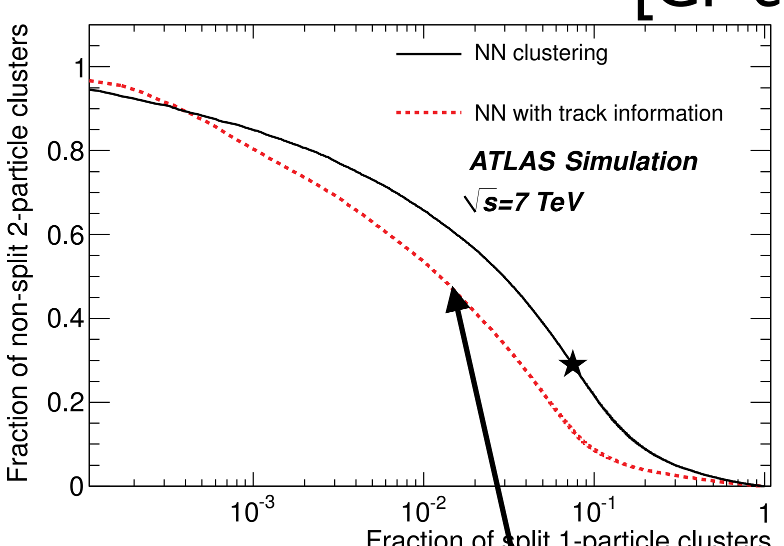
- 7x7 pixel matrix with calibrated charges
- vector of z pitches
- track incidence angle
- layer number

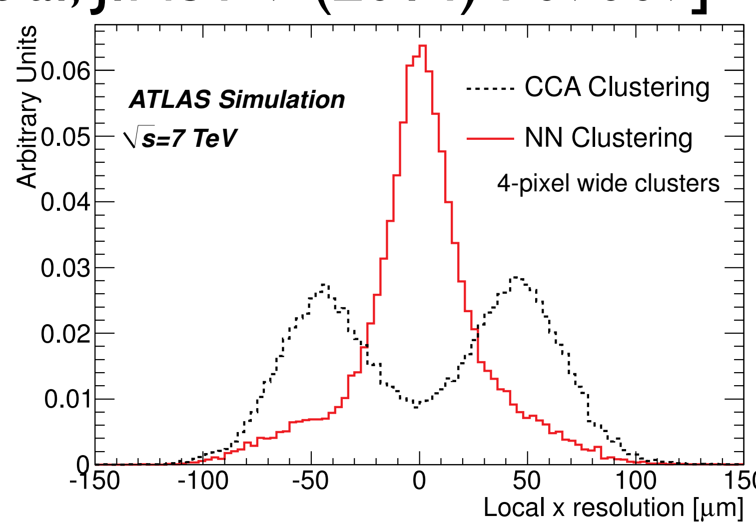


OUTPUT nodes

- How many subclusters?
- What is their position?
- What is their associated distribution? → (error)

[GP et al, JINST 9 (2014) P09009]





with track information only

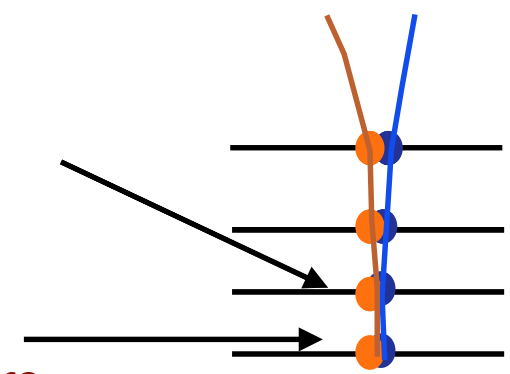
- At the cost of "wrongly splitting" ~10% of single-particle, can split correctly ~70% of two-particle clusters
- Improved single-particle resolution for wide clusters (e.g. in case of δ-rays)

Tracking optimization

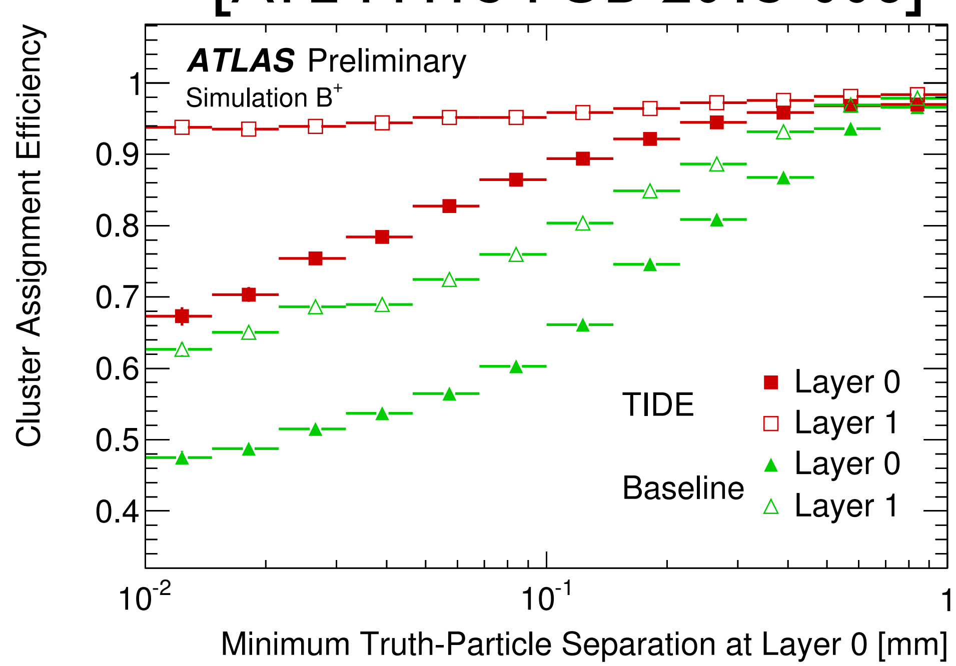
- Track reconstruction re-optimized to fully profit from updated pixel clustering (**Tracking in Dense Environment** group):
  - Move NN clustering stage later in the chain (during “ambiguity solving”)
  - Correlate NN cluster splitting information across different layers

satisfies NN **shareable** condition

fails NN **shareable** condition
treat as sharable as *likely* NN inefficiency



[ATL-PHYS-PUB-2015-006]

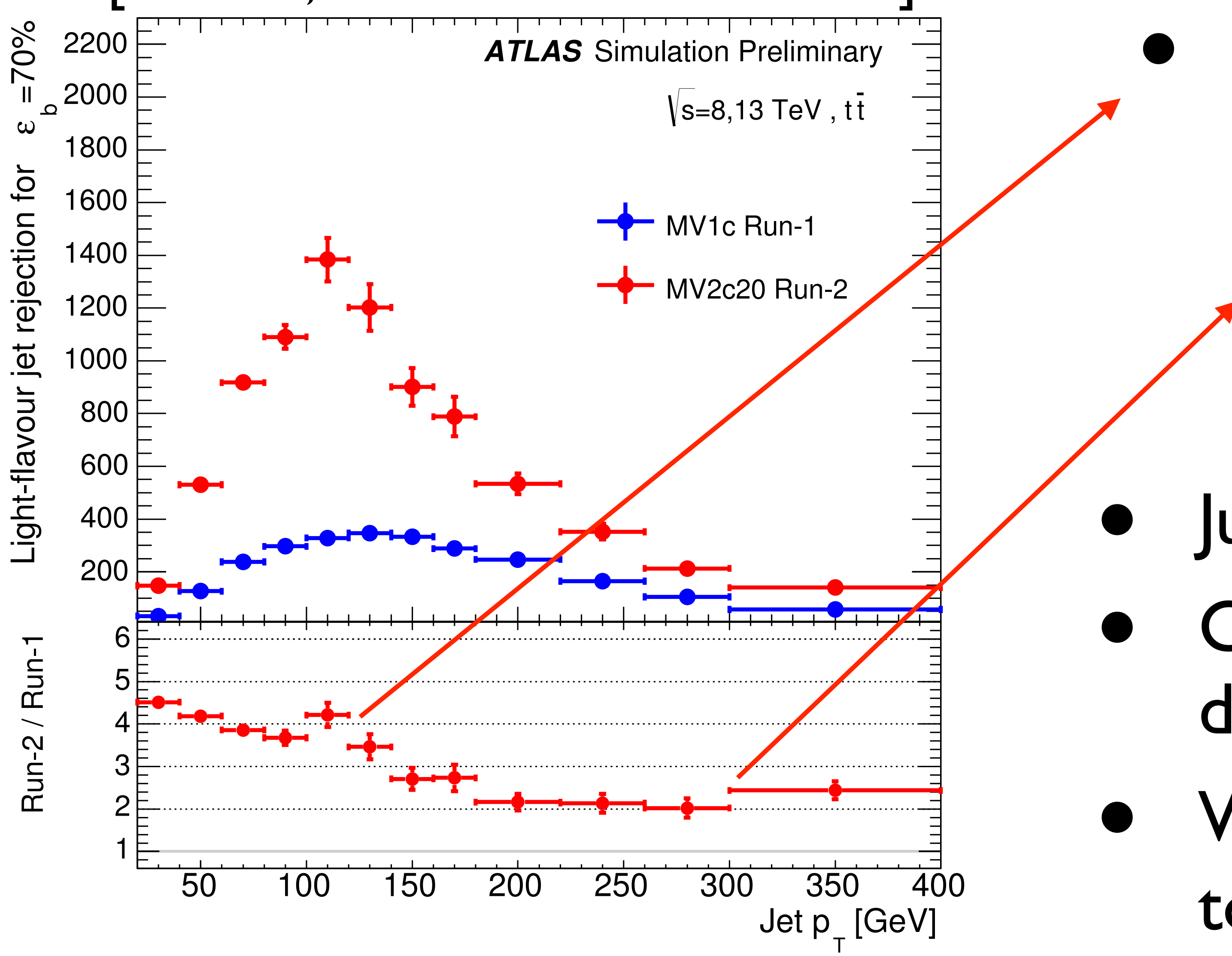


- Significant improvement seen in efficiency to correctly reconstruct and assign clusters from B^+ meson decays

Run-2 b-tagging

- Further optimization performed in the b-tagging group
  - E.g. new multivariate tagger (MV2)

[GP et al, ATL-PHYS-PUB-2015-006]



- x4 better rejection at low jet pT
  - now also x2 better rejection at high jet pT!
- Just presented at EPS
- Commissioning with Run-2 data ongoing…
- Will increase sensitivity to H → bb signals!

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Prospects for H → bb in Run-2

- Increased centre of mass energy of $\sqrt{s}$=13 TeV
  - VH cross section increased by x2
  - Backgrounds increase more: ttbar by x4, W/Z+jets by x2.5
- Sensitivity estimates are based on the five purest bins of the BDT
  - Assuming same performance and same systematics as in Run-1
  - S/B degrades by 15-30%, significance improves by ~20%

Approximate estimates

	Run-1 8 TeV 20 fb^{-1}	Run-2 13 TeV 20 fb^{-1}	Run-2 13 TeV 80 fb^{-1}
Sensitivity w/o systematics	3.1σ	~4σ	~8σ
Sensitivity with systematics	2.5σ	~3σ	~4.5σ

Reducing systematics will become crucial!!

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Conclusions

- Higgs boson discovery through decays to bosons, but decays to fermions equally important to test nature of Higgs boson
  - Probe Yukawa couplings
  - BR(bb) ~ 57% implies H → bb crucial to measure absolute couplings
- Thanks to advancements in algorithms and analysis techniques, reduced uncertainty on H → bb signal to 40% of SM expectation
  - But no clear evidence of a signal yet
- All measured couplings compatible with SM within 20-30%
  - Still a lot of space for Higgs boson decays to invisible!
- Run-2 will allow us to observe a H → bb signal, if there (>5σ expected), and measure Higgs boson couplings more precisely
  - Profit from enhanced b-tagging due to new detector and new algorithms