IHEP EPD Seminar (Jan 9th, 2020)

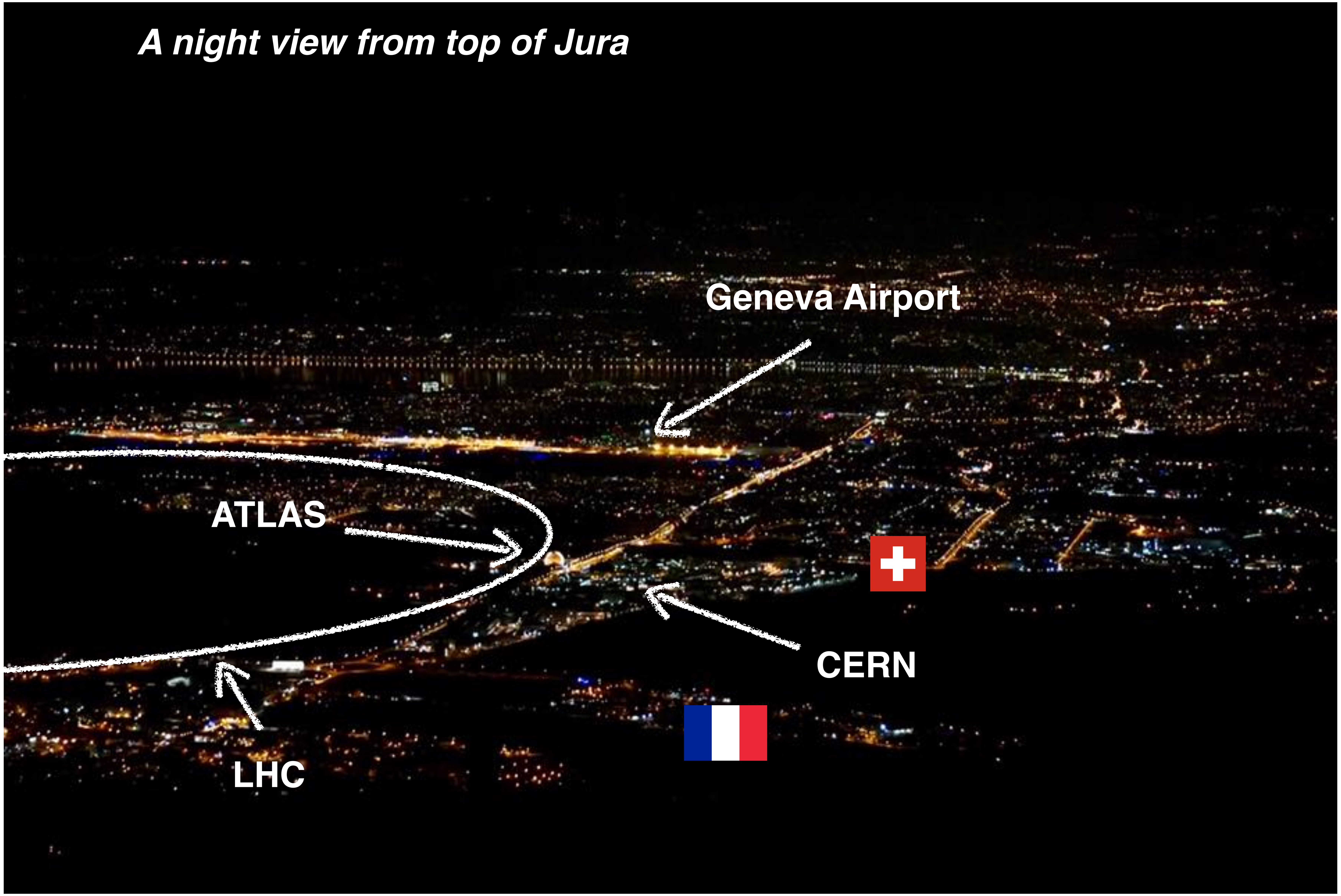
Long-lived Particles in Standard Model and Beyond

Bingxuan Liu[1]

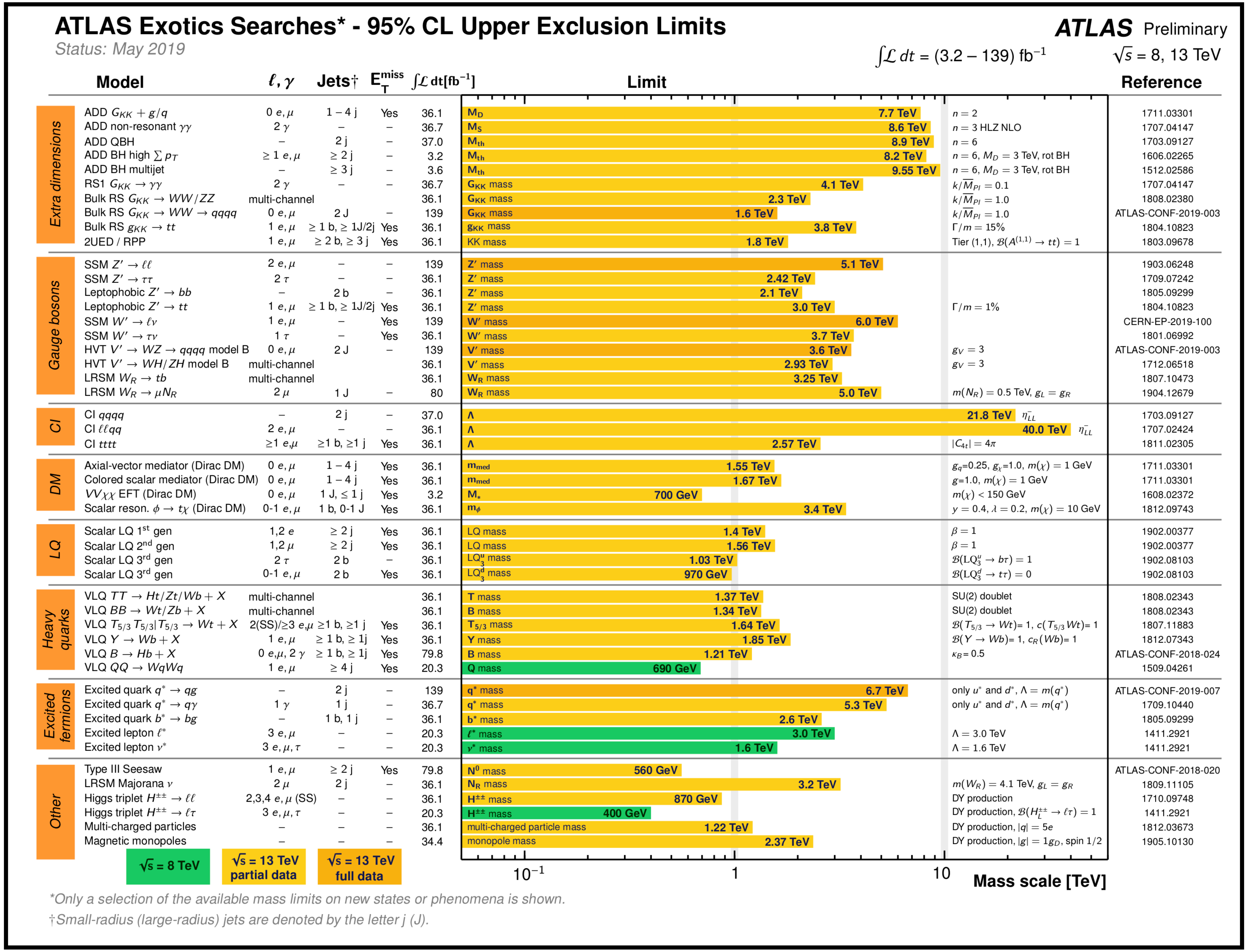
[1] Argonne National Laboratory

LHC and ATLAS and CMS

CMS



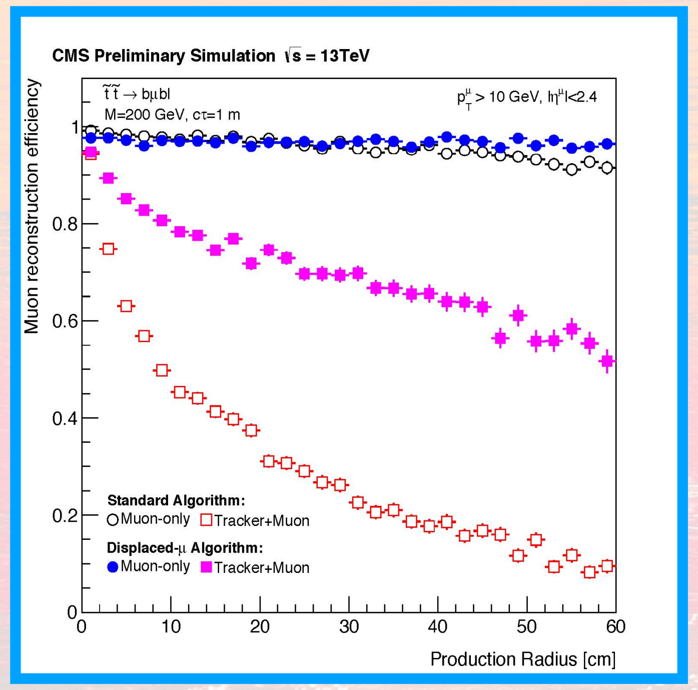
Physics Programs in ATLAS and CMS



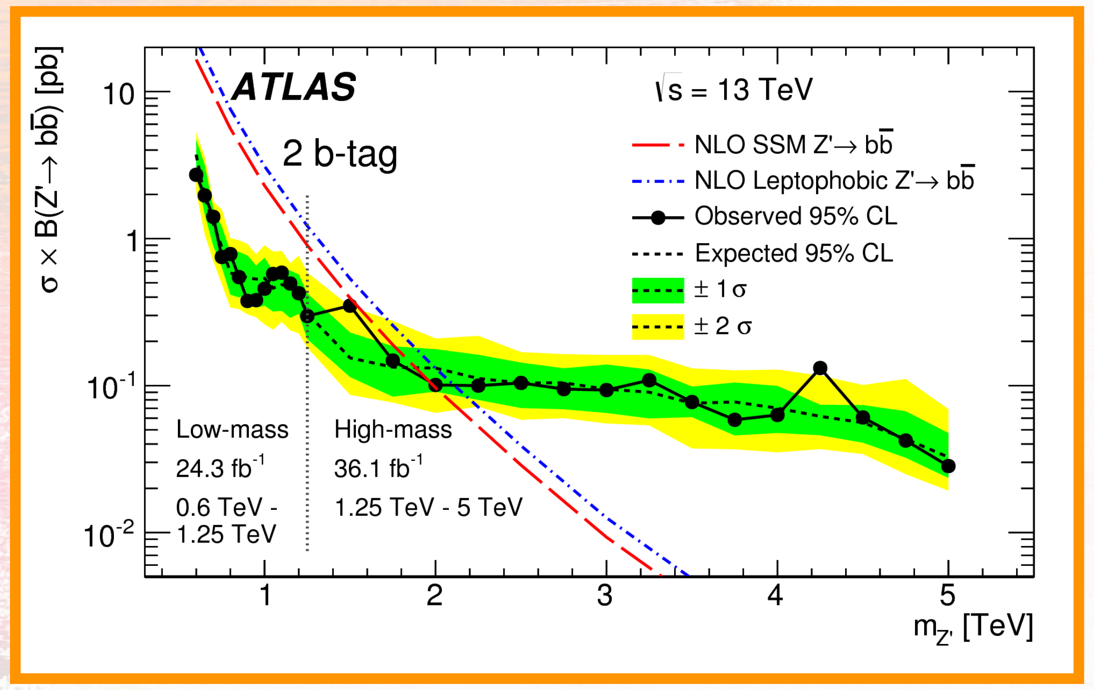
- Over the past decade, both CMS and ATLAS have produced a large number of interesting results
- This rich table comes from just one physics group (EXOTICS) in one collaboration (ATLAS)!
- What have I done?

My Research Timeline

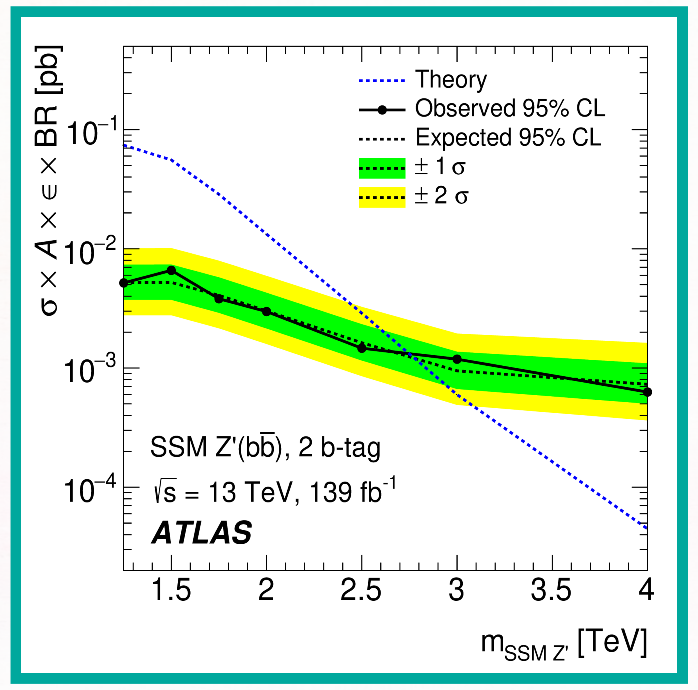
Displaced Muon Algorithm



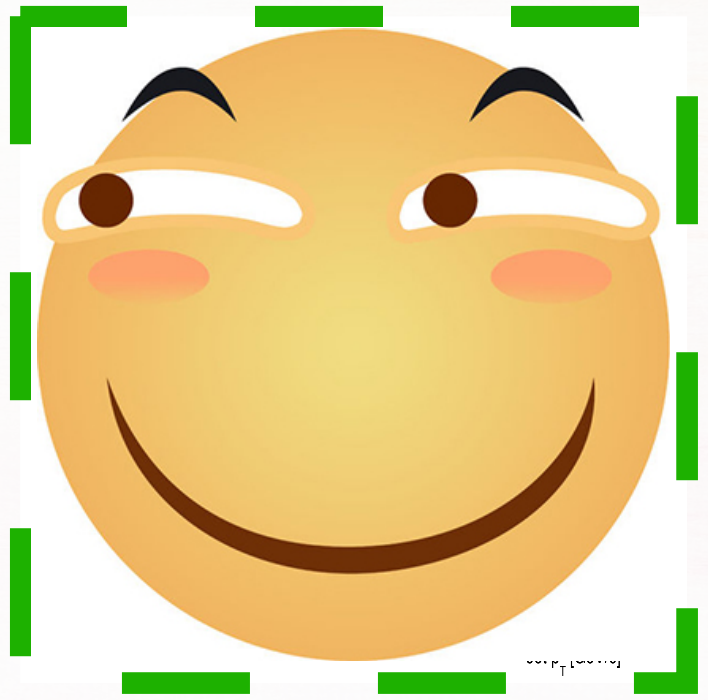
Di-b-jet 2015-2016



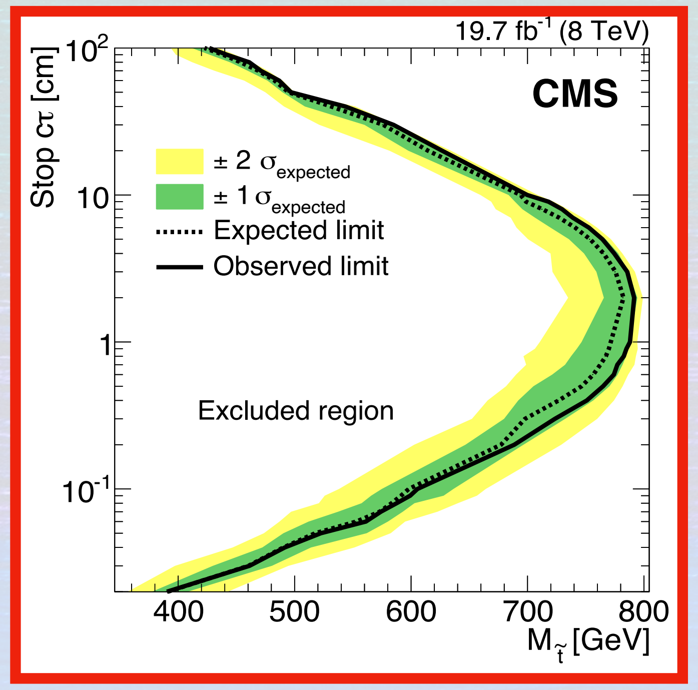
Di-(b)-jet Full Run2

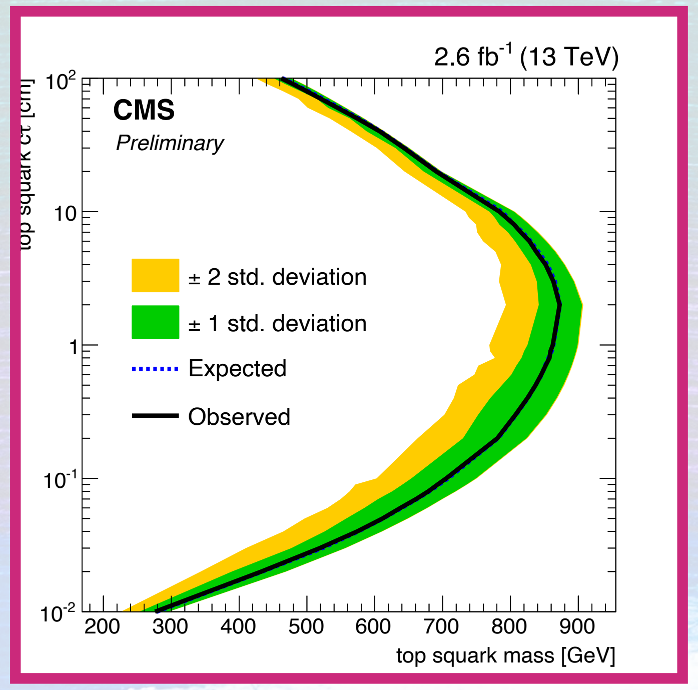


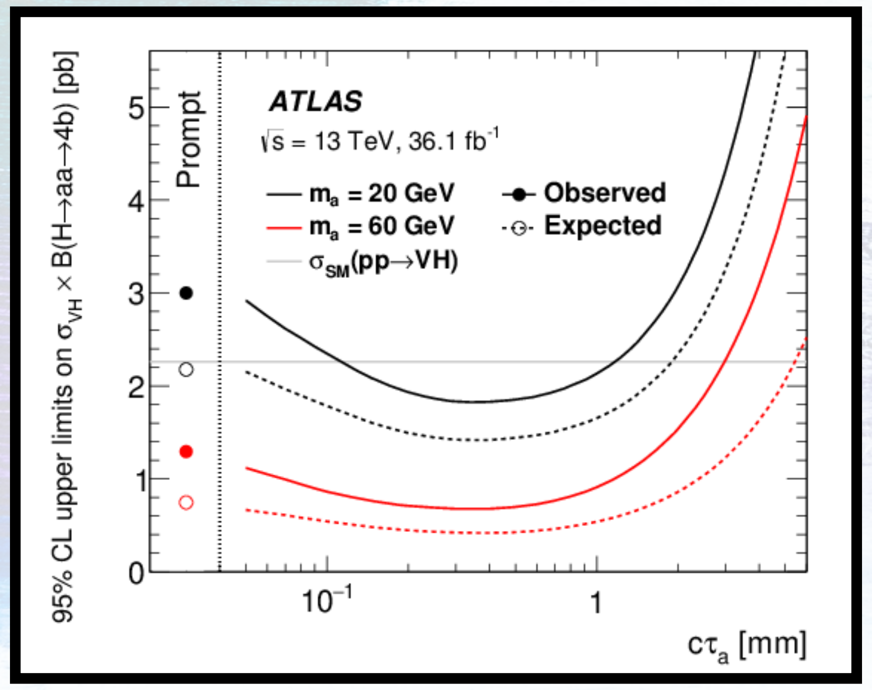
p_T^{rel} b-tagging Calibration

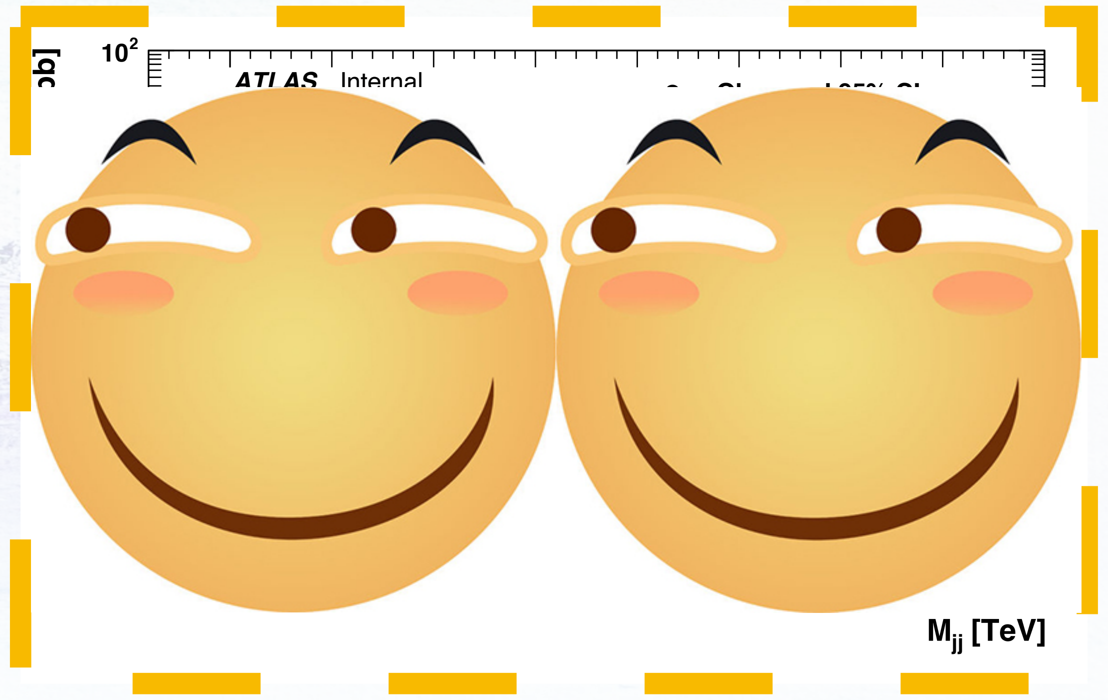


2011 2014 2015 2016 2018 2019









Displaced Lepton Run1

CMS Ph.D OSU

Displaced Lepton Run2

VH4b LLP Reinterpretation

ATLAS Postdoc ANL

Multi-b-jet Resonance

High p_T b-tagging Calibration

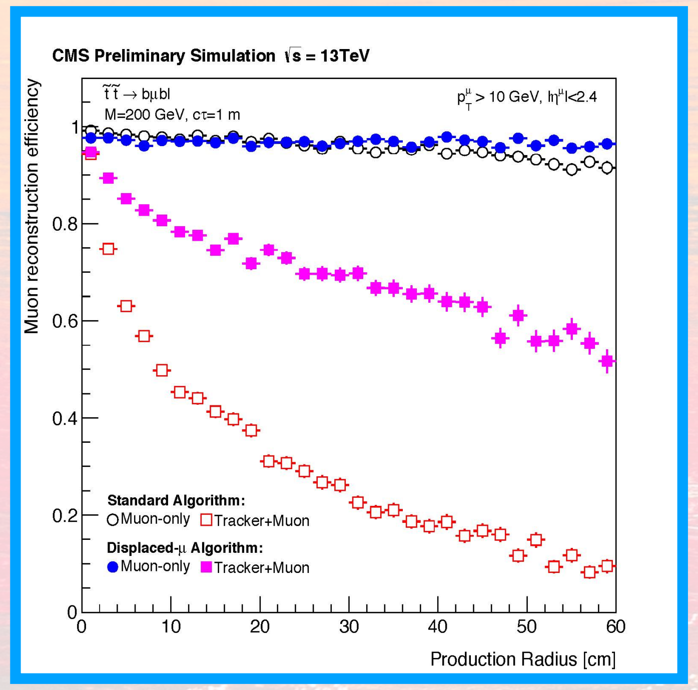
Phys. Rev. Lett. 114, 061801
CMS DP2015/015
CMS-PAS-EXO-16-022

Phys. Rev. D 98, 032016
J. High Energ. Phys. (2018) 2018: 31
Submiitted to JHEP

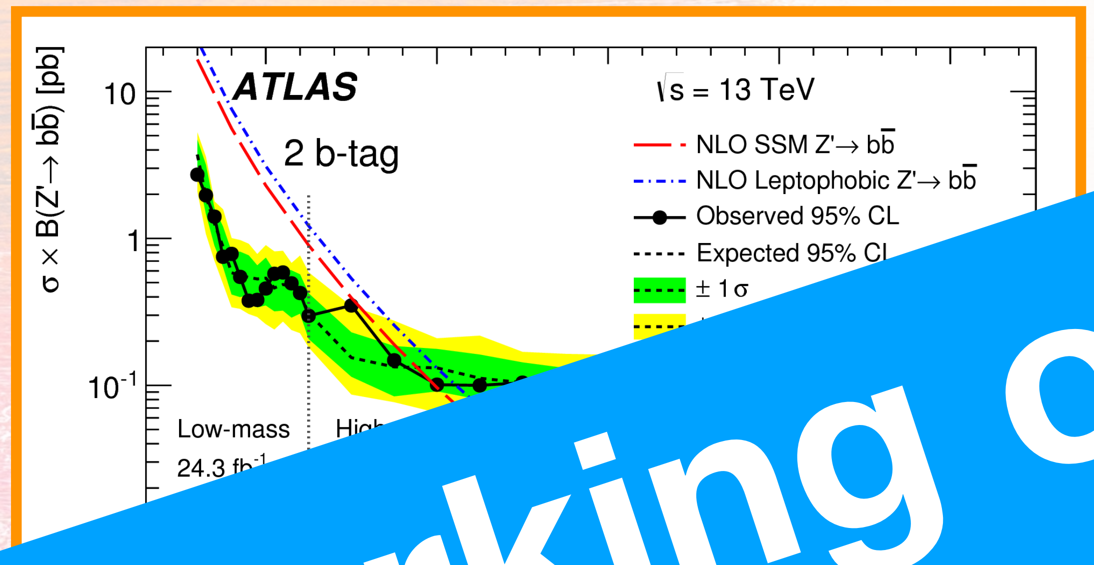
ANA-EXOT-2018-09
ANA-FTAG-2018-06
High b-tagging Calibration Twiki

Research Timeline

Displaced Muon Algorithm



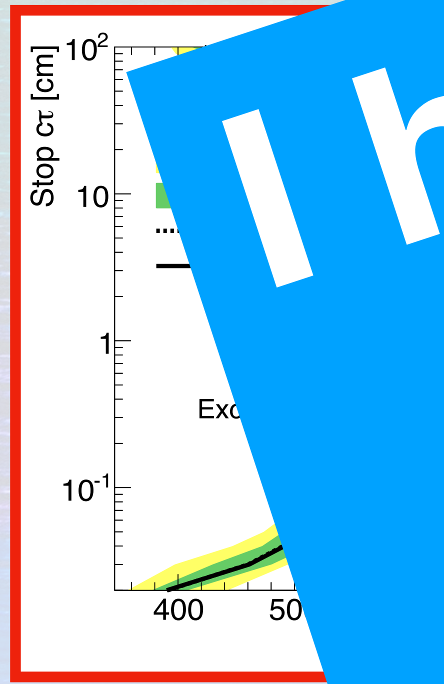
Di-b-jet 2015-2016



Di-(b)-jet Full Run2

…agging …tion

2011 2014



I have been working on BSM long-lived particle searches and searches/calibrations involving b-hadrons, long-lived particles in SM

Displac… Lepton R…

…H4b LLP Reinterpretation

ATLAS Postdoc ANL

Multi-b-jet Resonance

High p_T b-tagging Calibration

Phys. Rev. …

CMS DP201…

CMS-PAS-EXO-16-022

Phys. Rev. D 98, 032016

J. High Energ. Phys. (2018) 2018: 31

Submiitted to JHEP

ANA-EXOT-2018-09

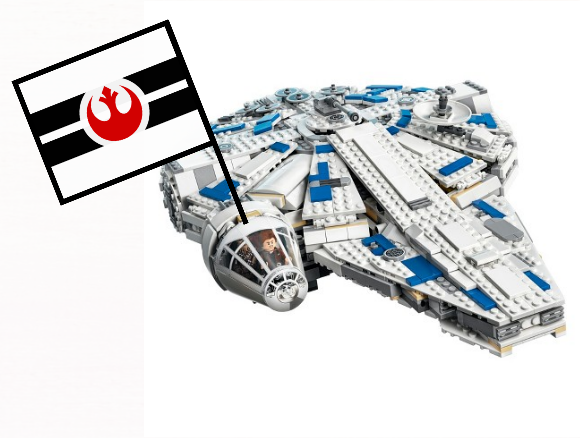
ANA-FTAG-2018-06

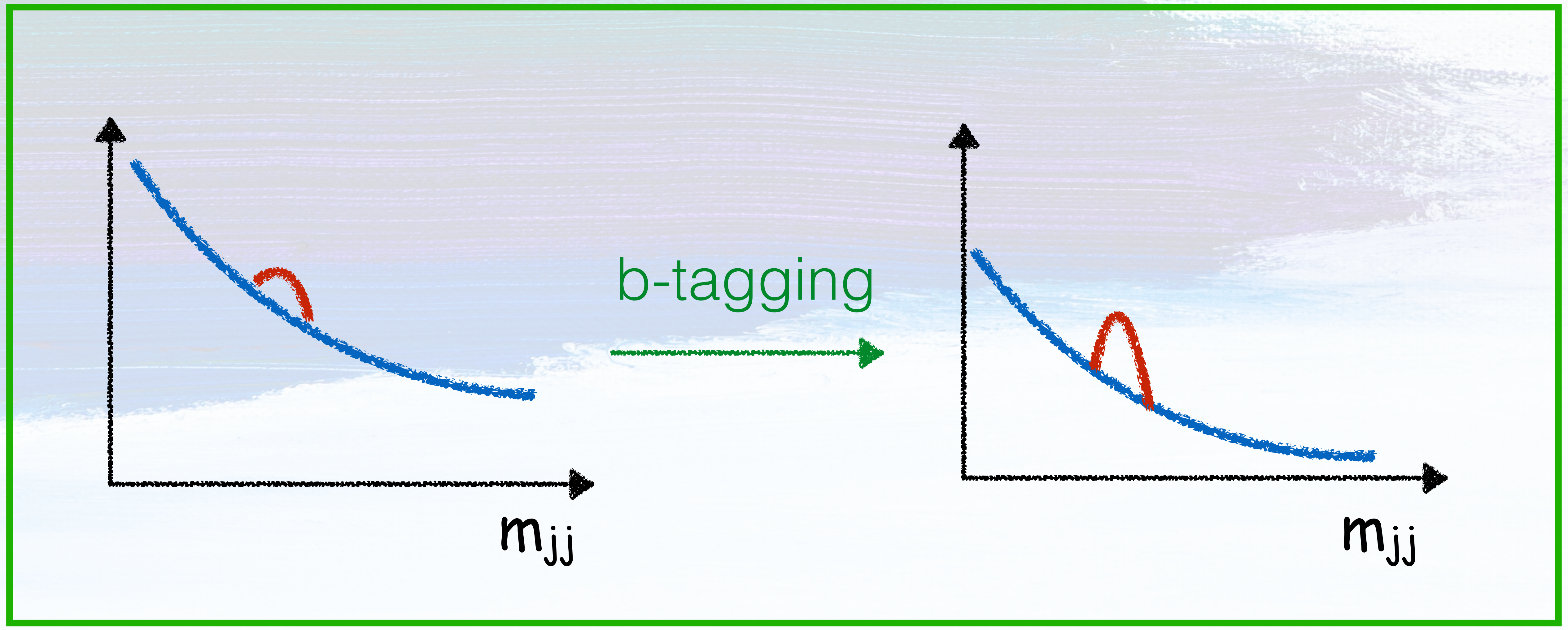
High b-tagging Calibration Twiki

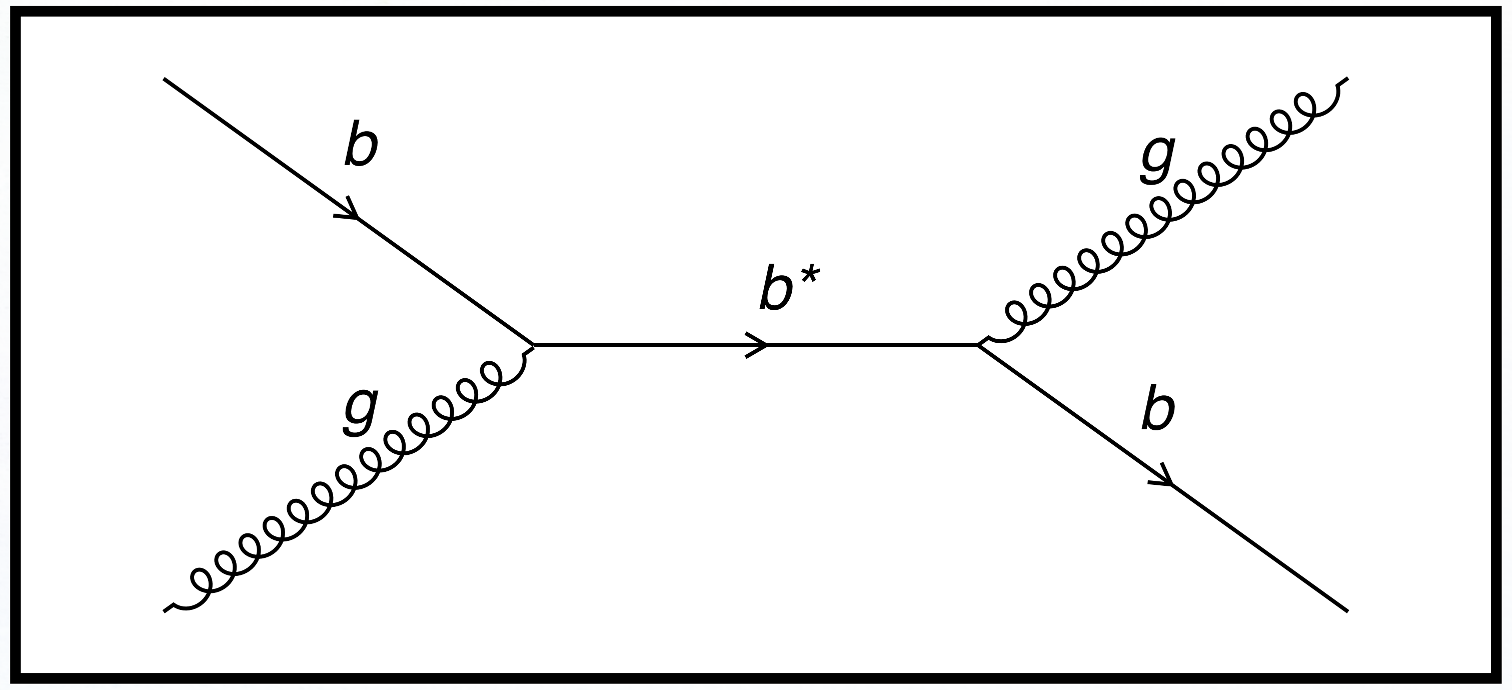
Exotic Search with B-tagging…

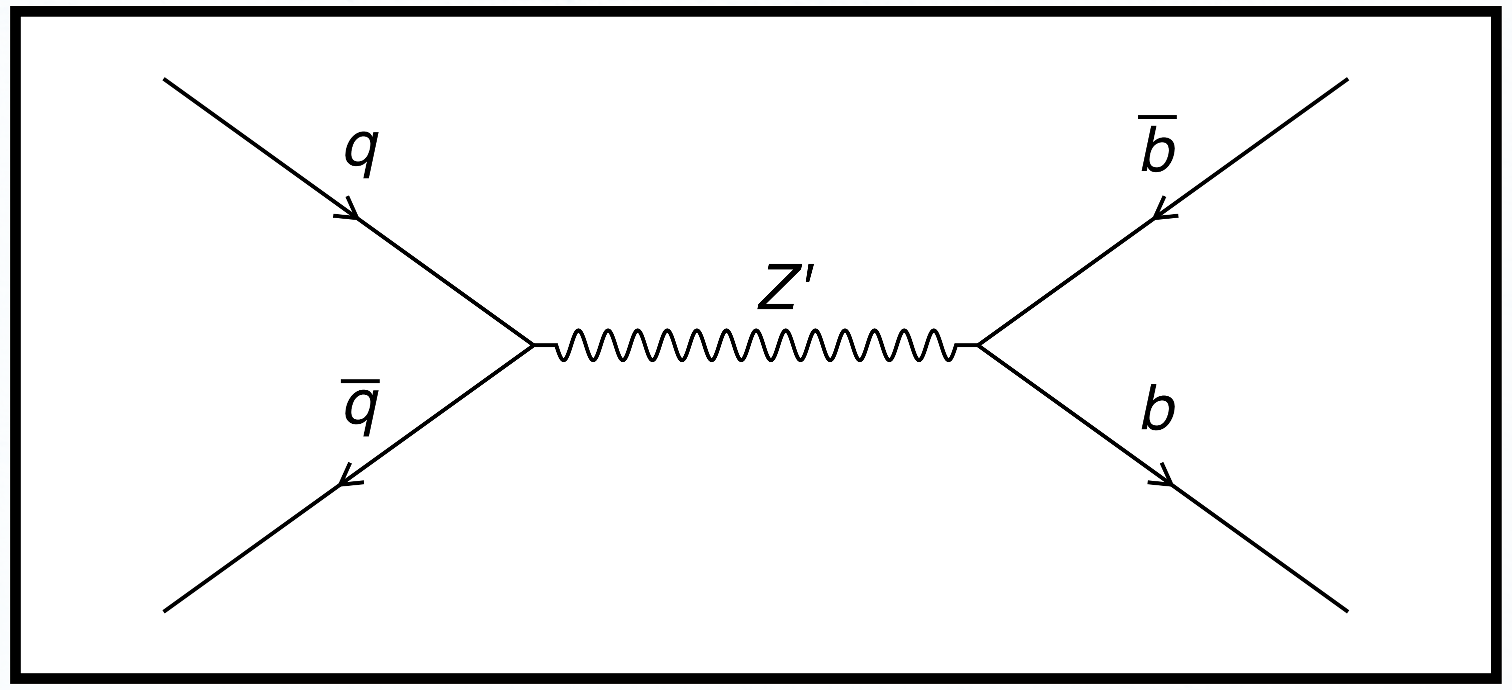
Resonance Search with b-tagged Jets

- Search for heavy resonances in the final states with two jets has been the flagship analysis in hadron colliders for decades
  - The most inclusive search
- A natural extension is to apply b-tagging on the jets
  - More sensitive to new physics where the heavy resonance has larger couplings to bottom quarks







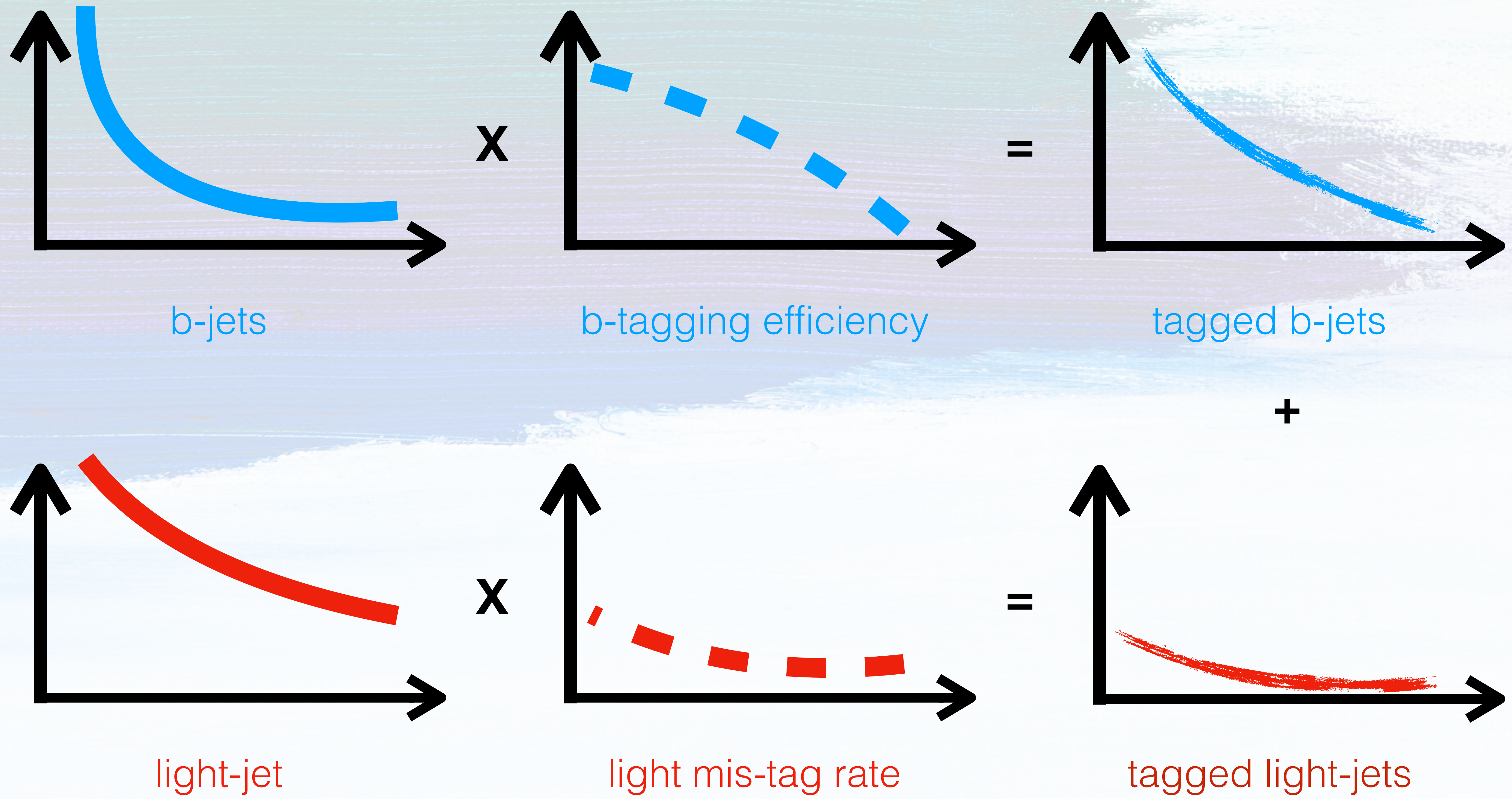


Bingxuan Liu

Analysis Strategy

Sounds really simple!

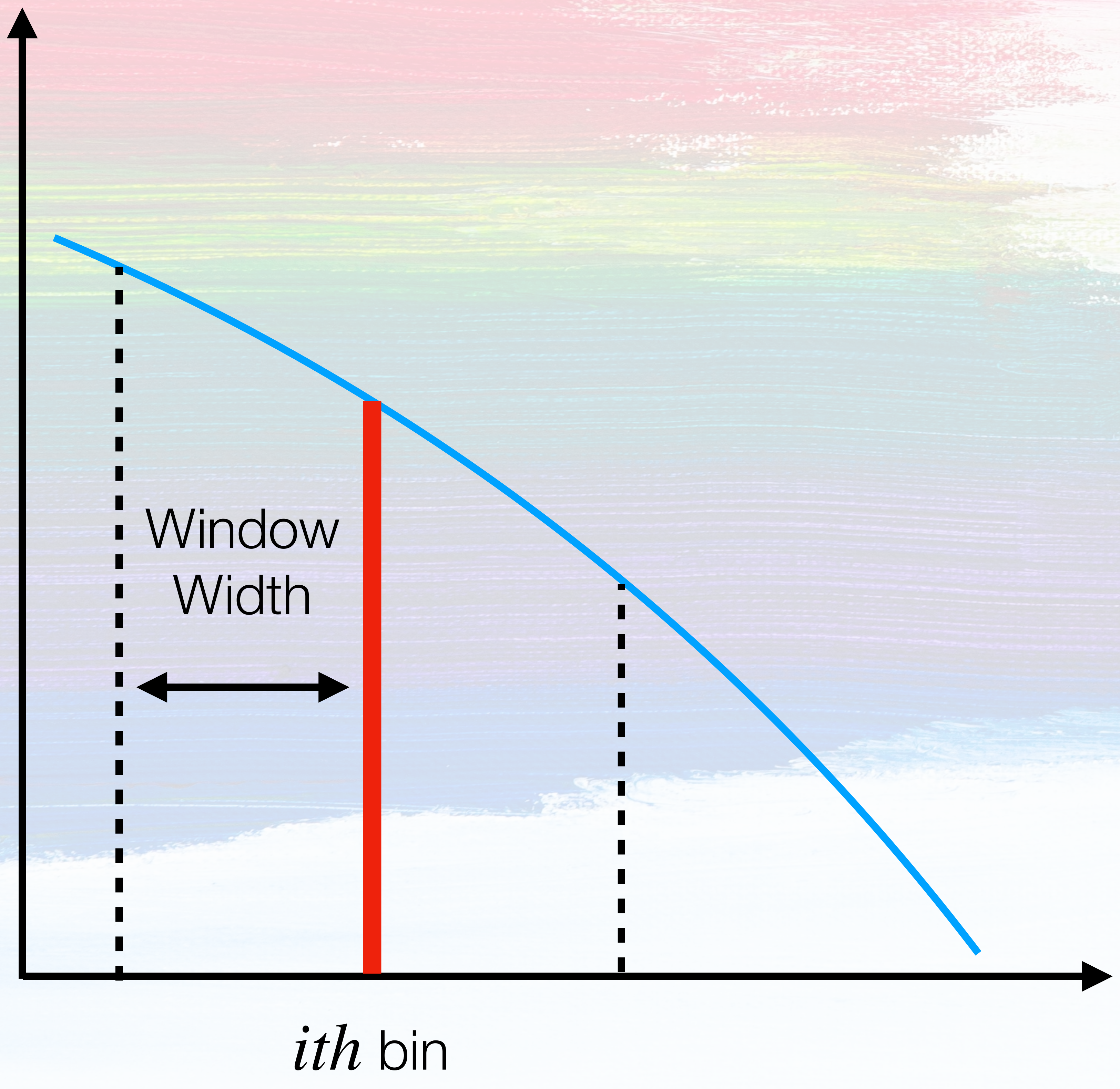
- In five steps:
  - Apply a jet trigger with the lowest threshold
  - Select two good jets
  - Apply signal enhancement selections: $|y^*| < 0.8$ and b-tagging
  - *Fit the data*
  - Interpretation



- A very complex spectrum to fit
- B-tagging applied on a mixture of jets with different flavors (Cartoons only show the light and bottom)

Background Modeling Method

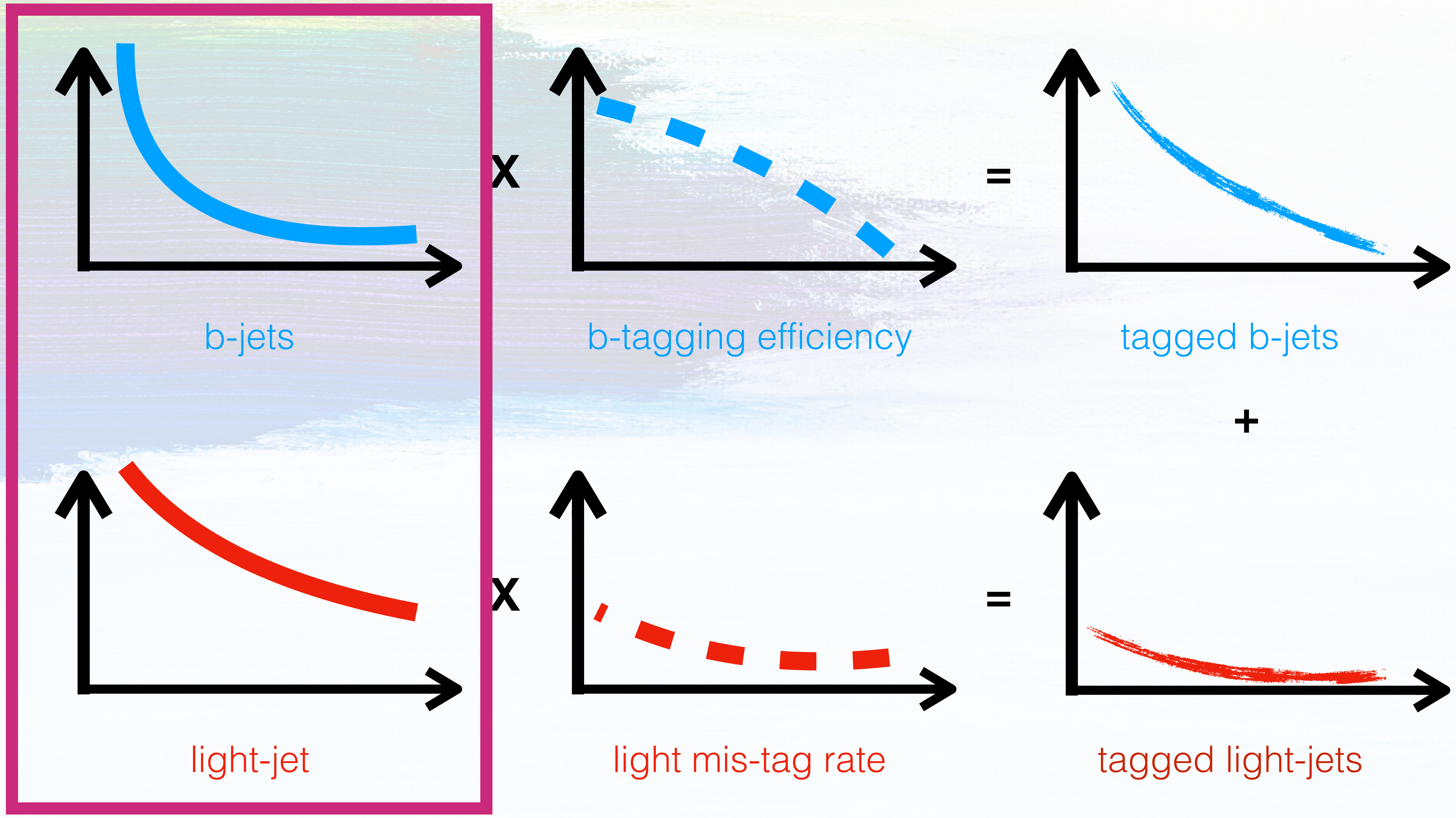
- To fit the background, we apply a Sliding Window Fit (SWiFt) method and validate it using control samples



- The canonical global fit can not describe the background given the complexities
- SWiFt is a numerical approximation where each bin is estimated by performing a global fit within a subset (window) of the full spectrum
- It works but it is a rather complex model with many free parameters

Background Modeling Method

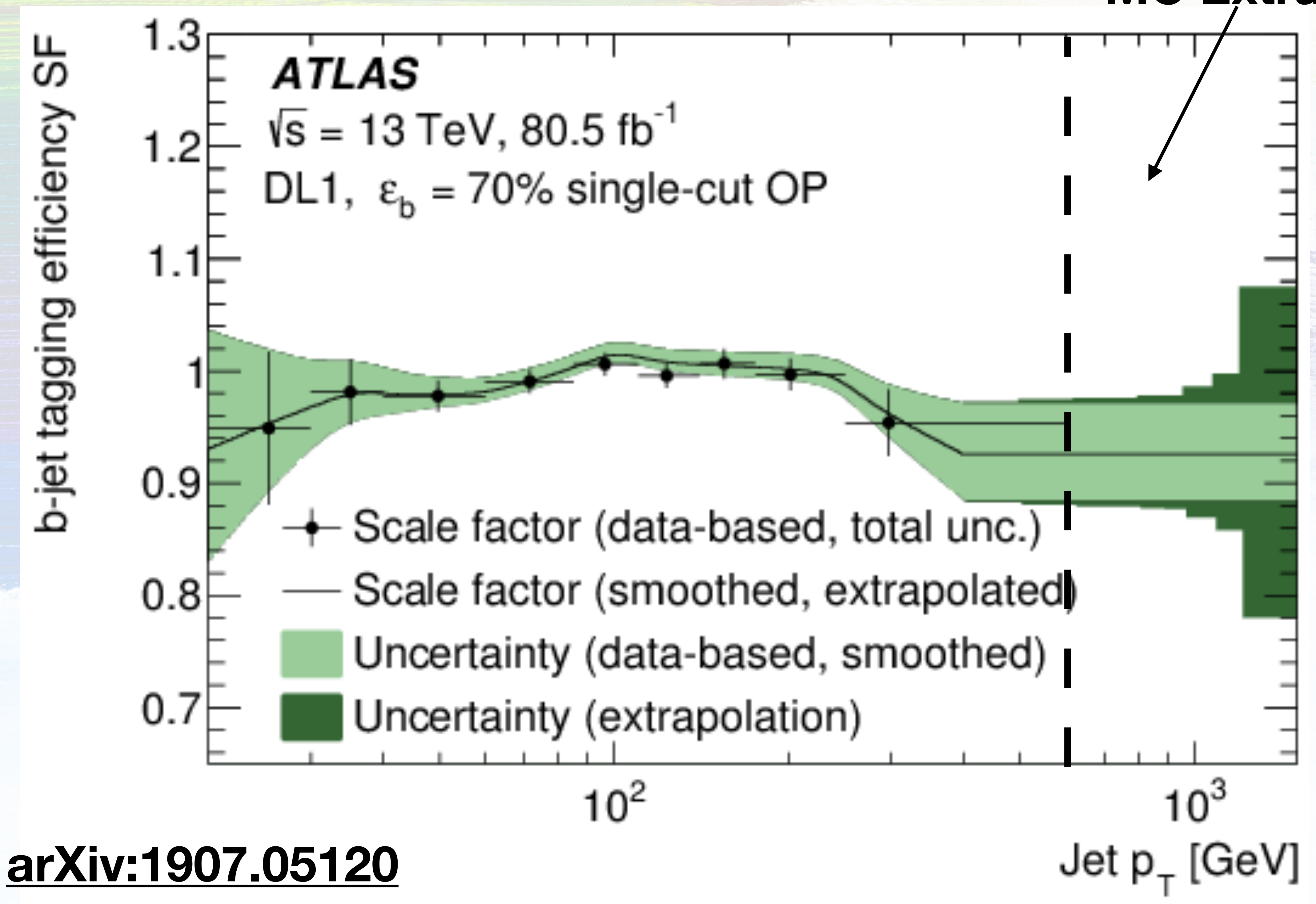
- We have to validate the background modeling method
  - Need background-only control samples
  - Major background, multi-jet, does not have reliable simulations
    - Flavor fractions are not well modeled
      - Last differential $b\bar{b}$ measurement was done in Run1



Background Modeling Method

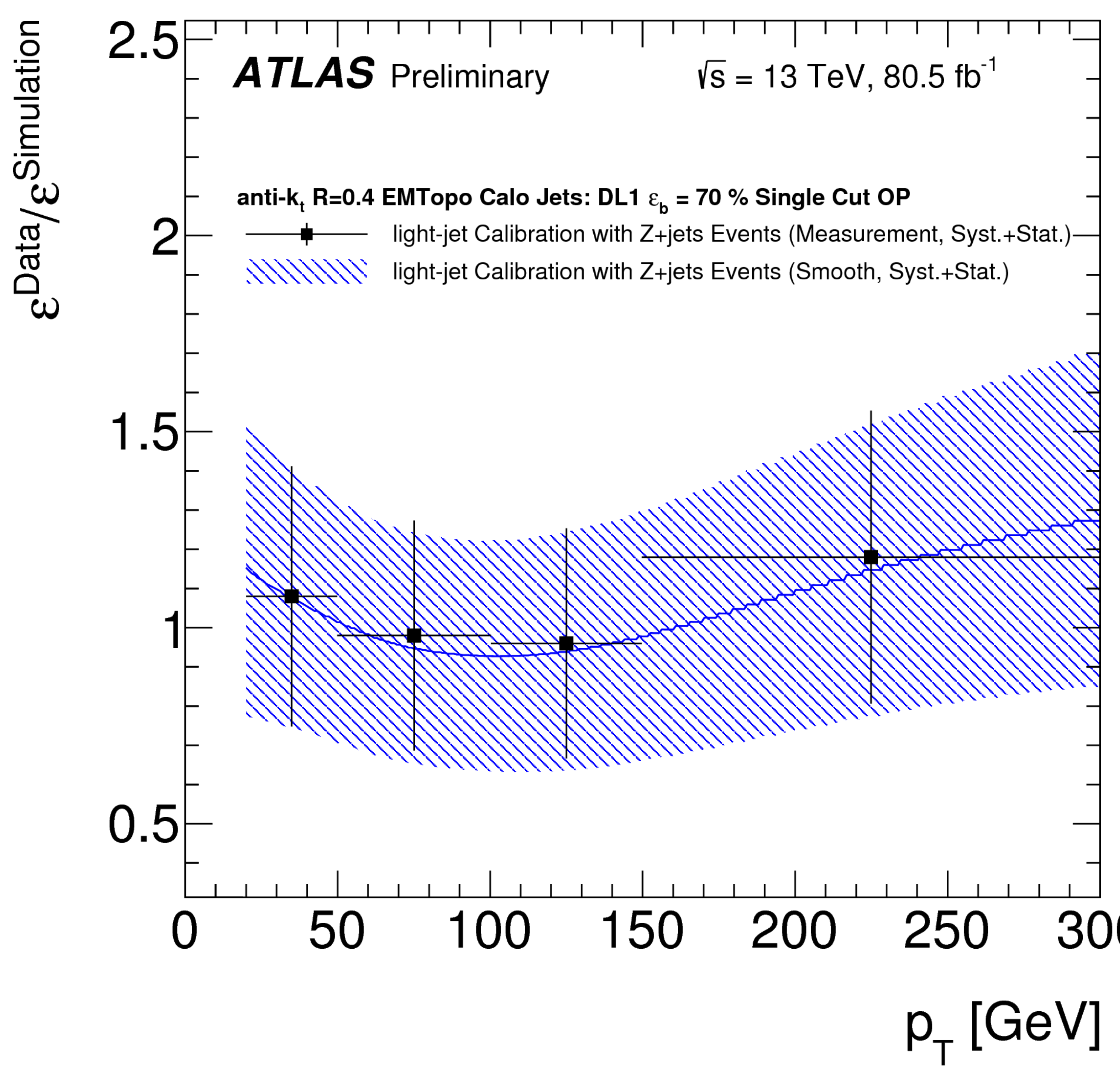
- We have to validate the background modeling method
  - Need background only control samples
  - Major background, multi-jet, does not have reliable simulations
    - b-tagging/mis-tag rate are not calibrated at high p_T

MC Extrapolation



arXiv:1907.05120

FTAG-2019-003



A New "ABCD" Approach

- The major challenge comes from unknown tagging efficiency/mis-tag rate, and flavor compositions in multi-jet events
  - Extract this information from data

Two sidebands data scaling method

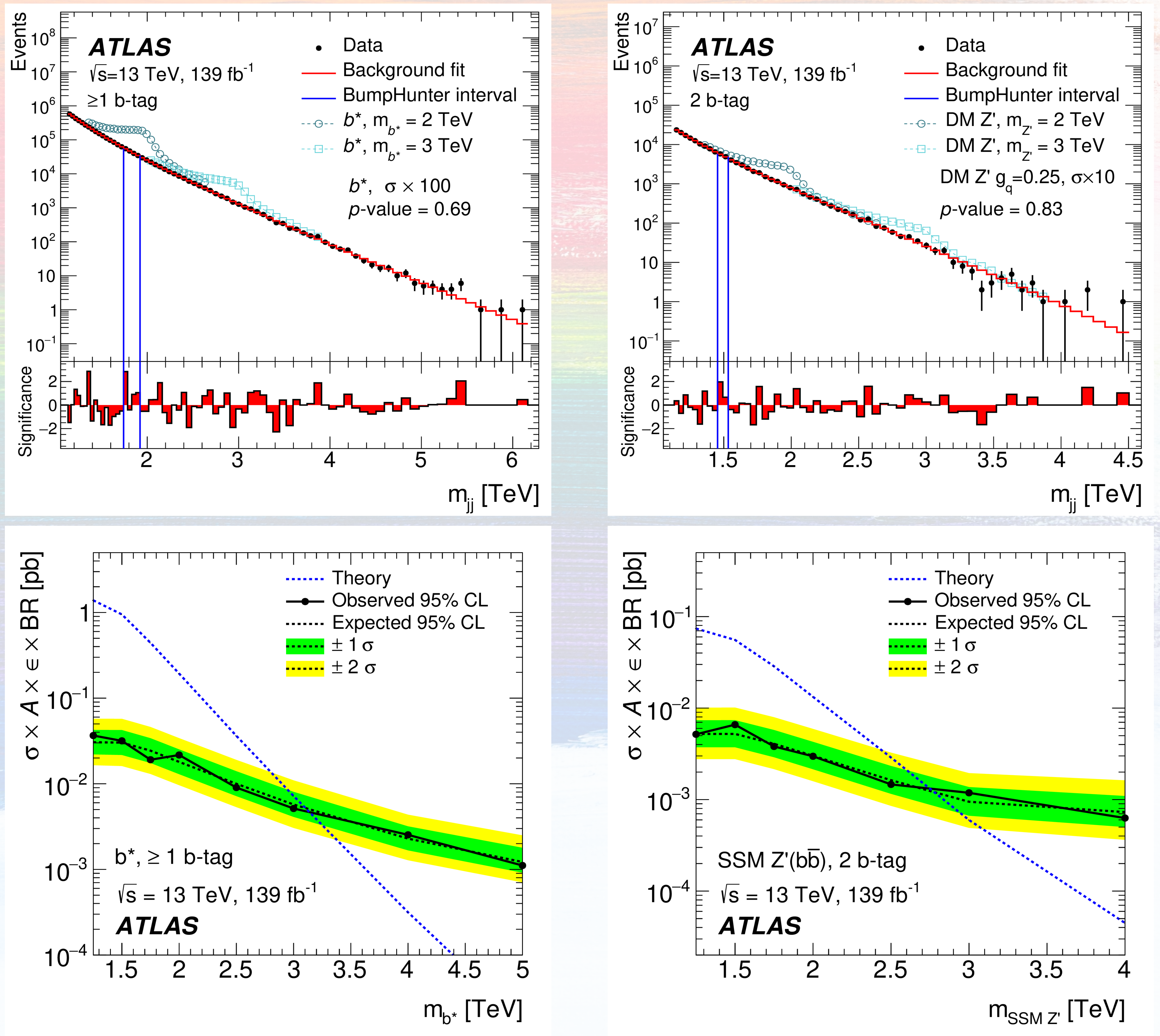
A tagged |y*| > 0.8	**B** tagged |y*| < 0.8
C untagged |y*| > 0.8	**D** untagged |y*| < 0.8

- Obtain per jet tagging efficiencies in |y*| inverted regions (A and C), binned in p_T and η
- Calculate event level tagging efficiencies
- Scale untagged (D) region to tagged region (B)

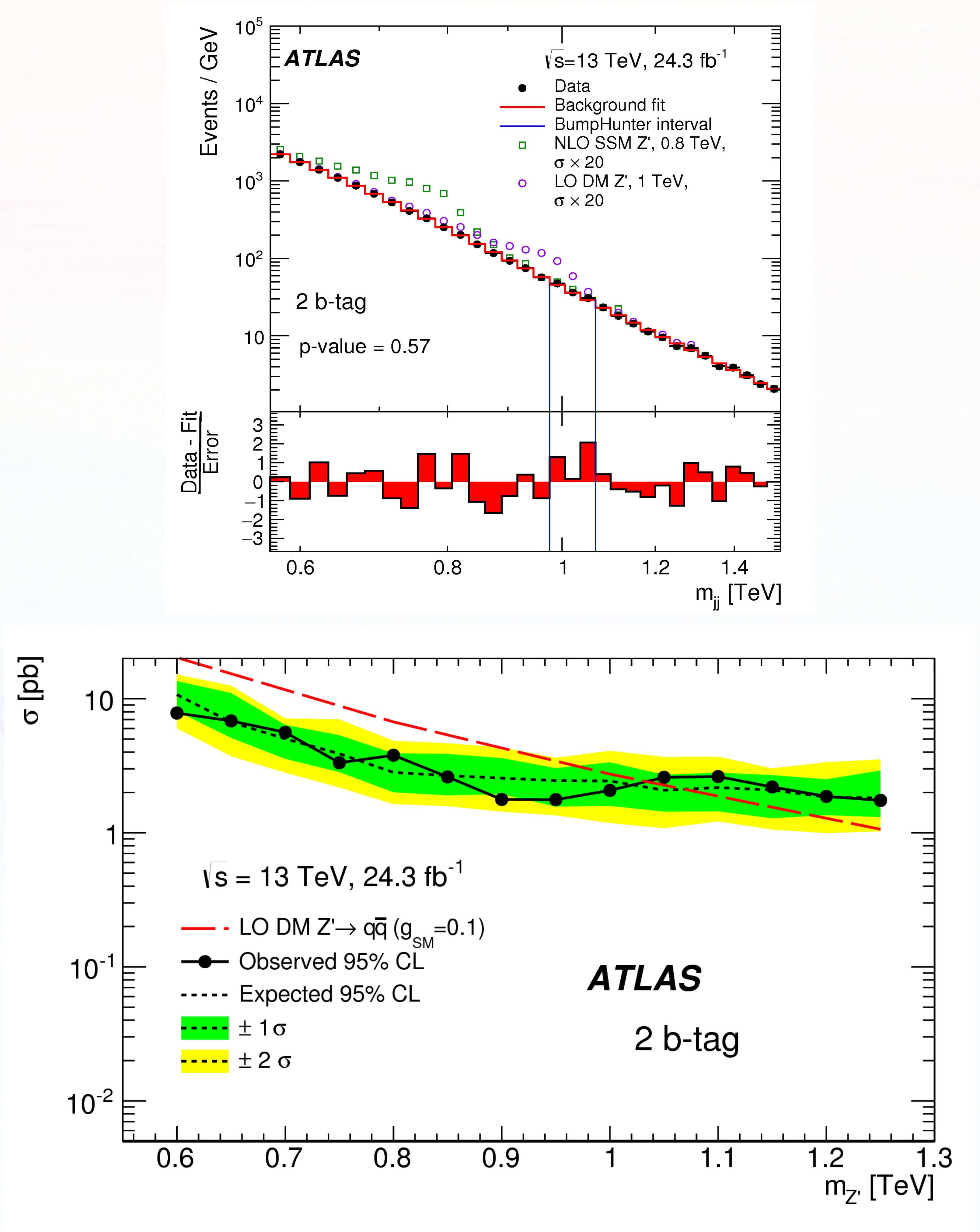
- Inverting |y*| suppresses the signal contaminations, but also alters m_{jj}
- Instead we calculate per-jet tagging efficiency
  - Since the flavor fraction of leading jet is correlated with the sub-leading jet's flavor. Both absolute efficiency and conditional efficiency are calculated:
    - $P(j_1)$, $P(j_2)$ and $P(j_2 | j_1)$
- Event level efficiency is calculated by
  - >= 1 b-tag:
    $P(j_1) + P(j_2) - P(j_1)P(j_2 | j_1)$
  - ==2 b-tag:
    $P(j_1)P(j_2 | j_1)$

Results

- Both 2015 + 2016 di-b-jet search and full Run 2 di-(b)-jet search are public!



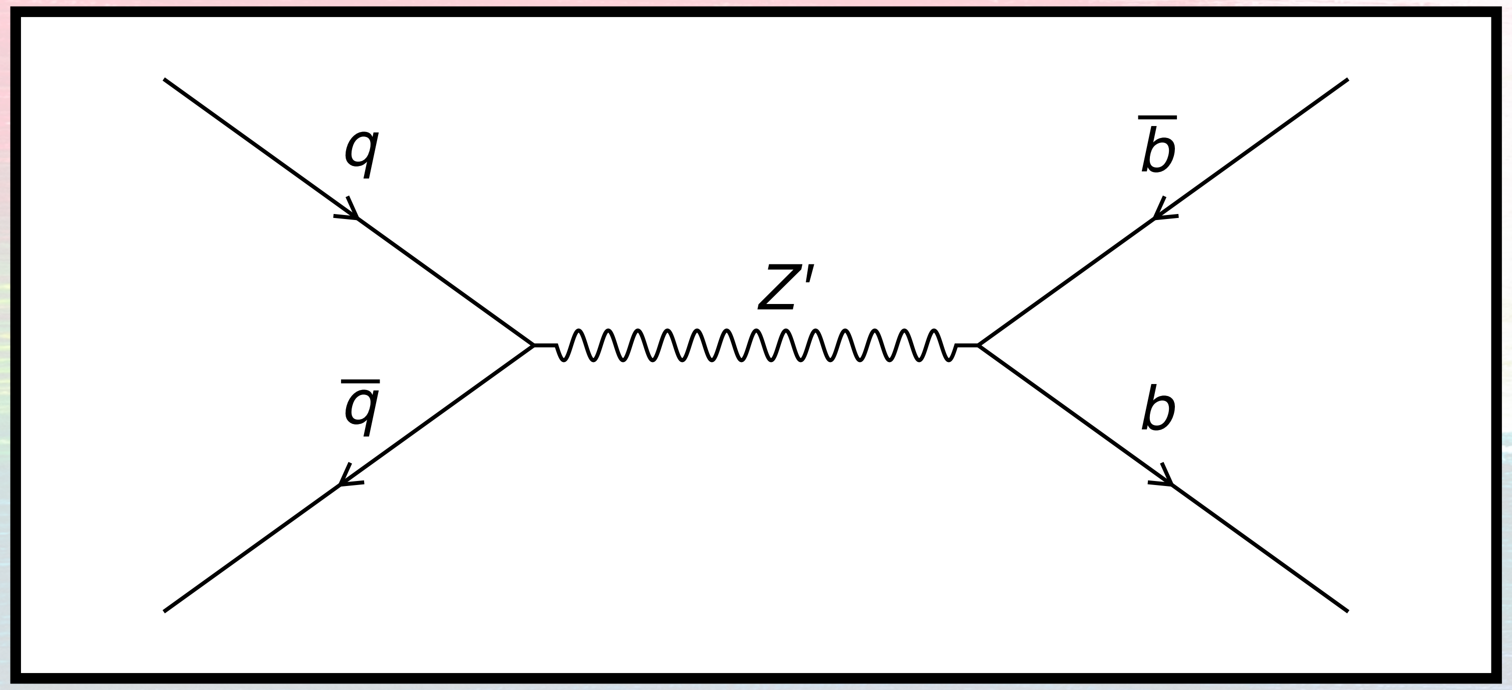
Submiitted to JHEP

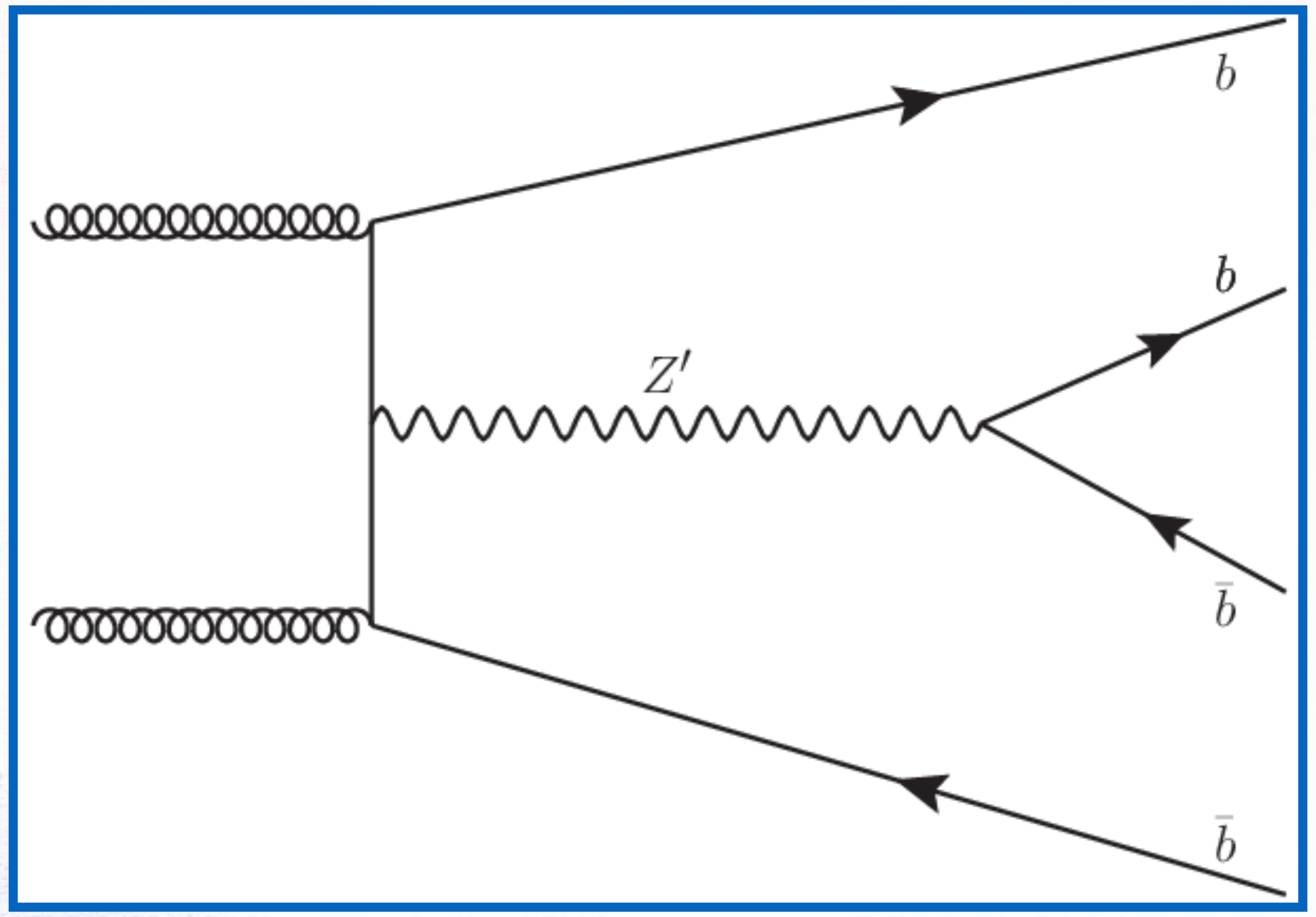


Phys. Rev. D 98, 032016

Resonance Search with More b-tagged Jets

- What if the new heavy resonance is exclusively coupled to third generation fermions?





- The new heavy resonance has to be produced in association with two b-quarks
  - Multi-b-jet final state
  - Only considering leading four jets

New Ideas Deployed I: Efficiency Scaling Method

- The "ABCD" approach does not work any more in this final state as now we are considering NLO multi-jet processes
- I developed a new approach

$$N_{tag} = N_{inclusive}\epsilon_{tag}$$

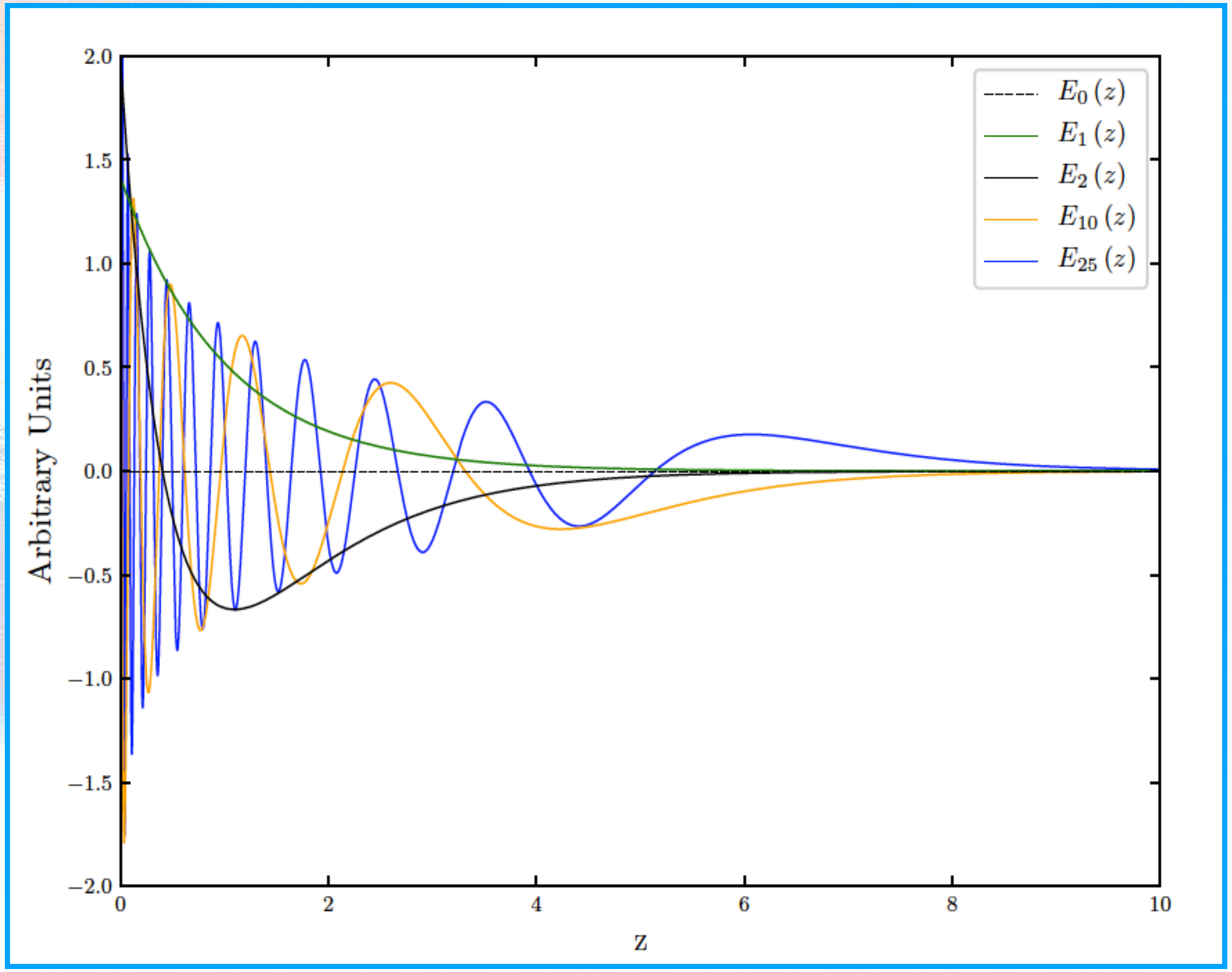
- By fitting the signal region selection efficiency (simple polynomial fit), we smear the influence from potential signal
  - The impact from signal is found to be small in stress tests
- Produce bkg-only pseudo-data samples to validate the background modeling strategy

New Ideas Deployed II: Functional Decomposition

- We have been using empirical functions to fit the di-jet invariant mass spectra in history

New Method:

- Functional Decomposition
  - Using a truncated series to describe the spectrum
  - Analogous to Fourier Analysis



arXiv:1805.04536

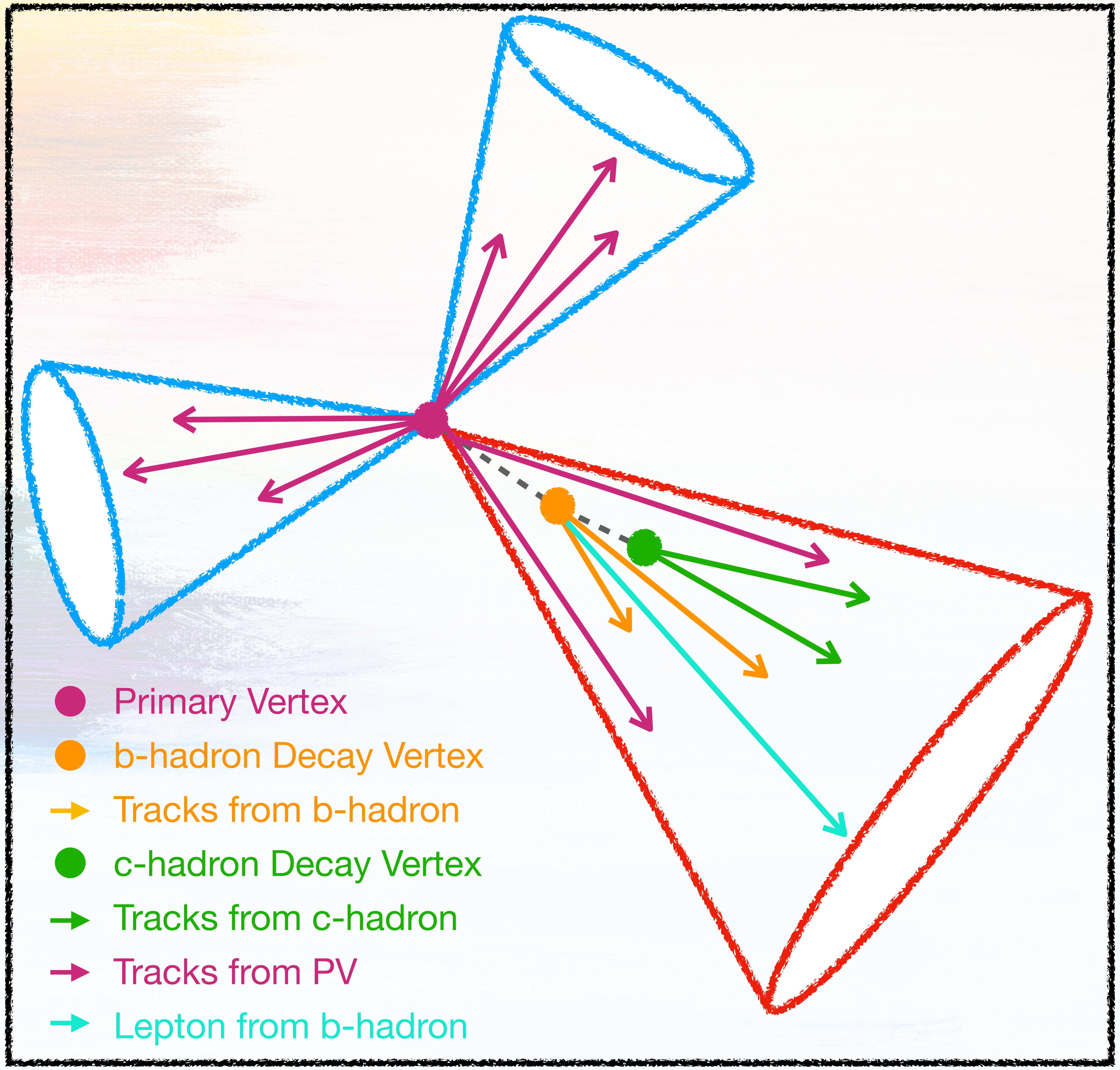
The Future Of “Simple” Search

- LHC has accumulated ~140 fb^{-1} data
  - It will take LHC a while to double the integrated luminosity
- Search strategies need to be thoroughly re-evaluated and improved
  - Differential measurements are in their way
- Search with tagging techniques can benefit significantly from CP development
  - Di-b-jet search is limited by the b-tagging performance at high p_T and the corresponding calibrations

So, Flavor Tagging…

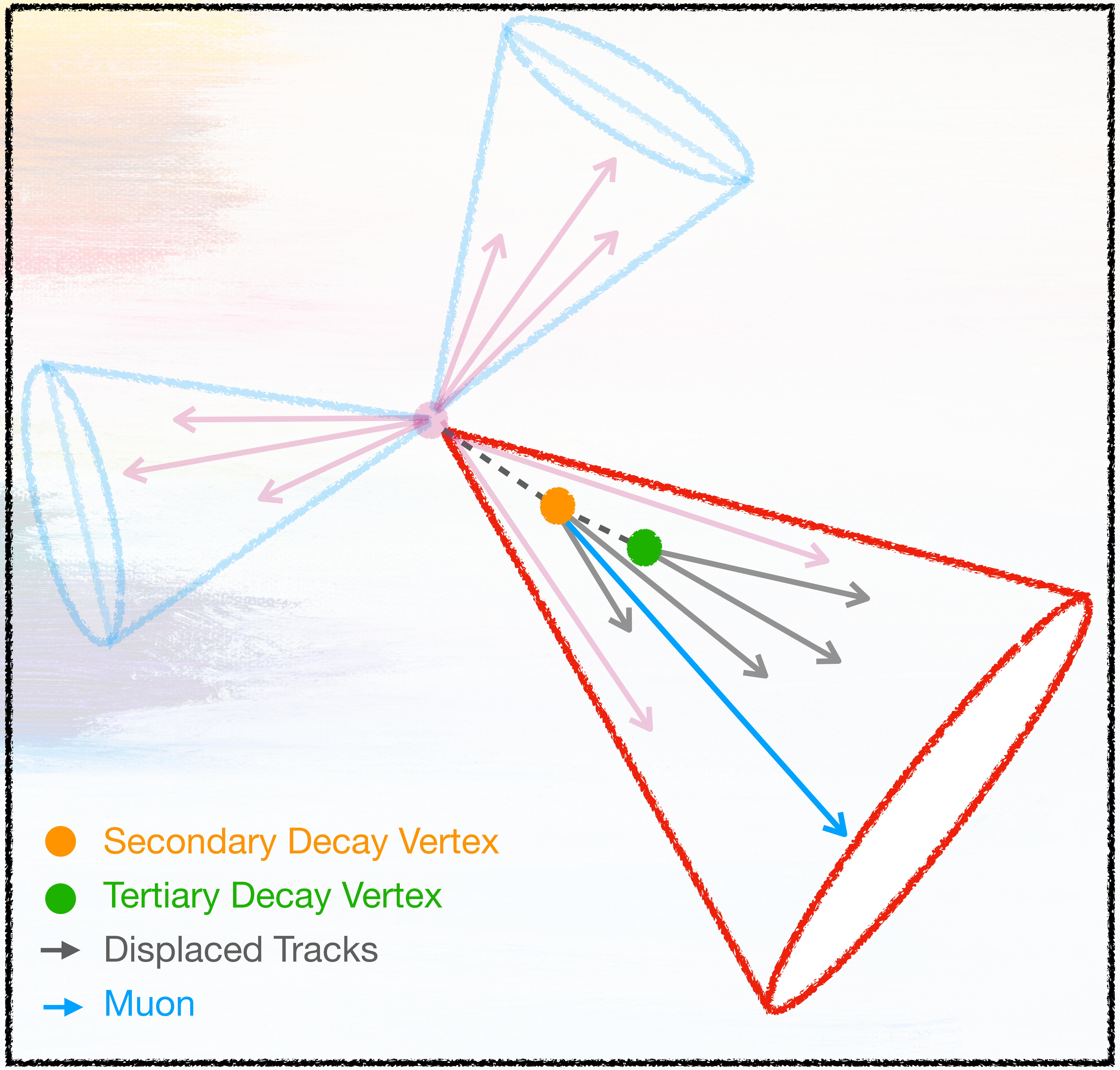
B-hadron Properties

- b-hadrons have:
  - Majority of the energy from hadronization (~80%)
  - Relatively large mass (~5 GeV)
  - Significant lifetime (~1.5 ps)
  - High decay multiplicity (~5 charged particles)
  - Relatively large $b \to \mu + X$ branching ratio (~20%)
- b-tagging algorithms are constructed based on the above properties



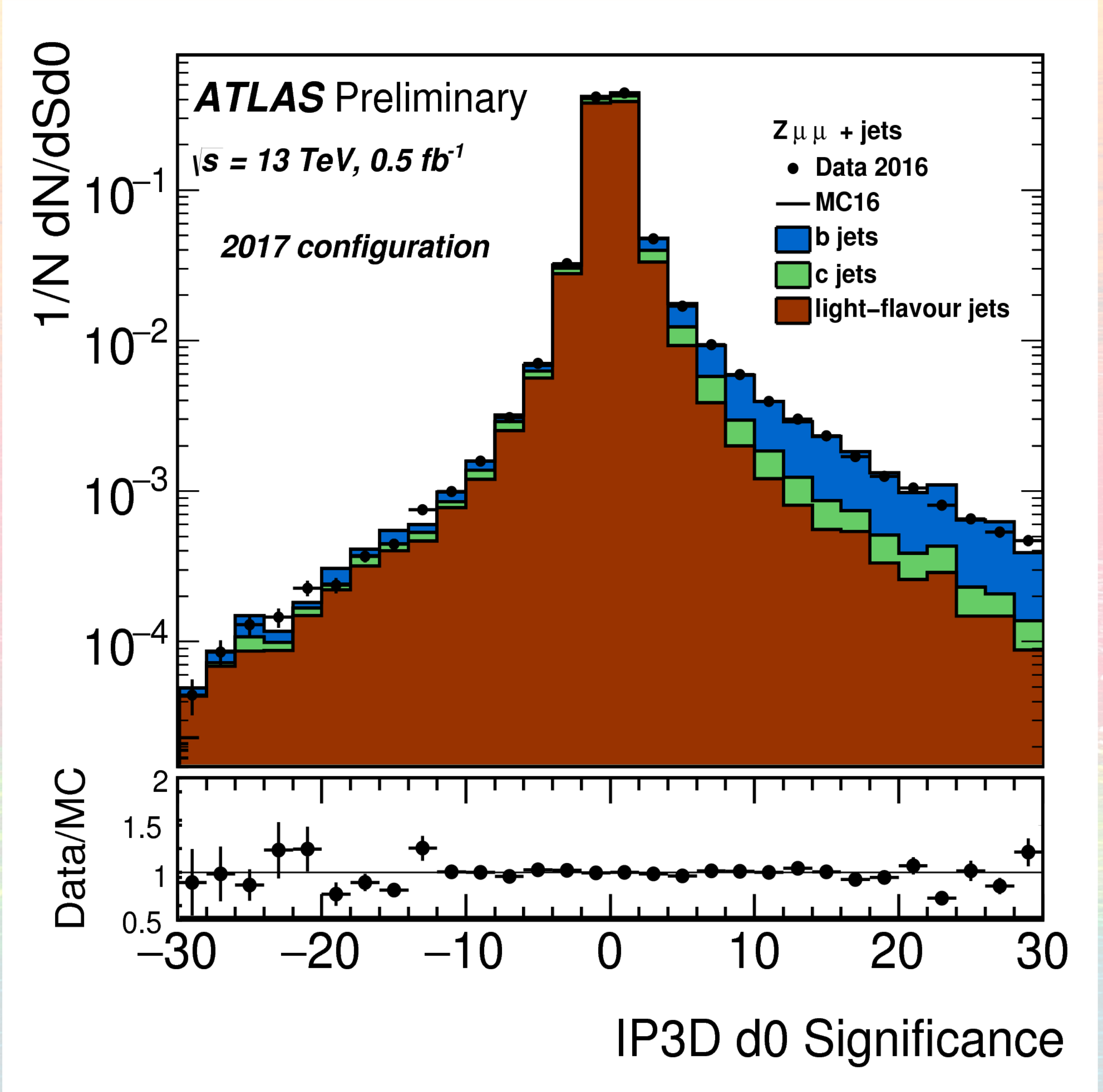
Low Level Taggers

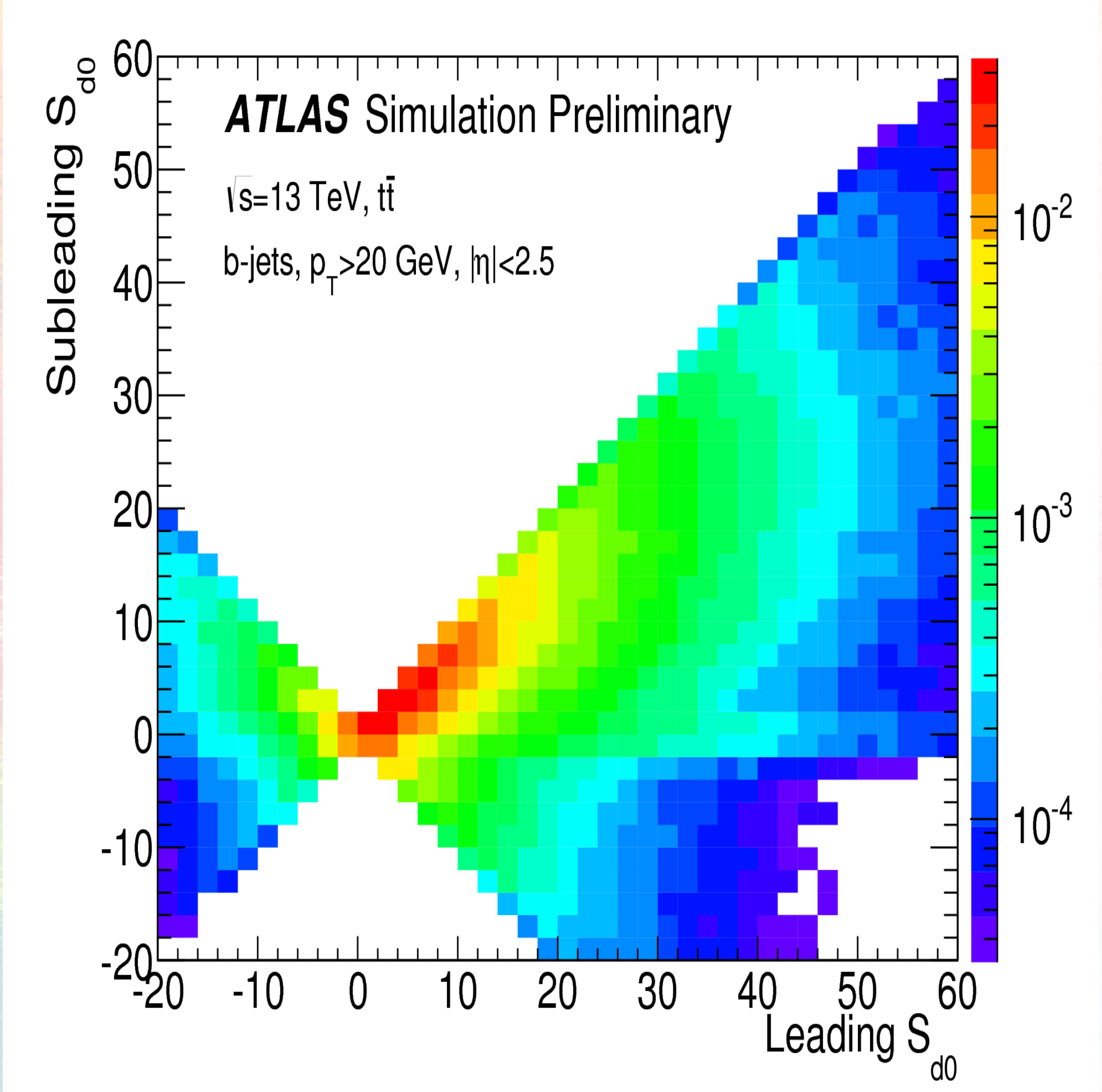
- Experimental signatures:
  - Secondary Vertex
  - Heavier Vertex Mass
  - Tertiary Vertex
  - Displaced Tracks
  - Larger Track Multiplicity
  - Muon
- Low level taggers:
  - Track based:
    - IP2D, IP3D and RNNIP
  - Secondary vertex based: SV1
  - Decay topology based:
    - JetFitter
  - Muon based: SMT

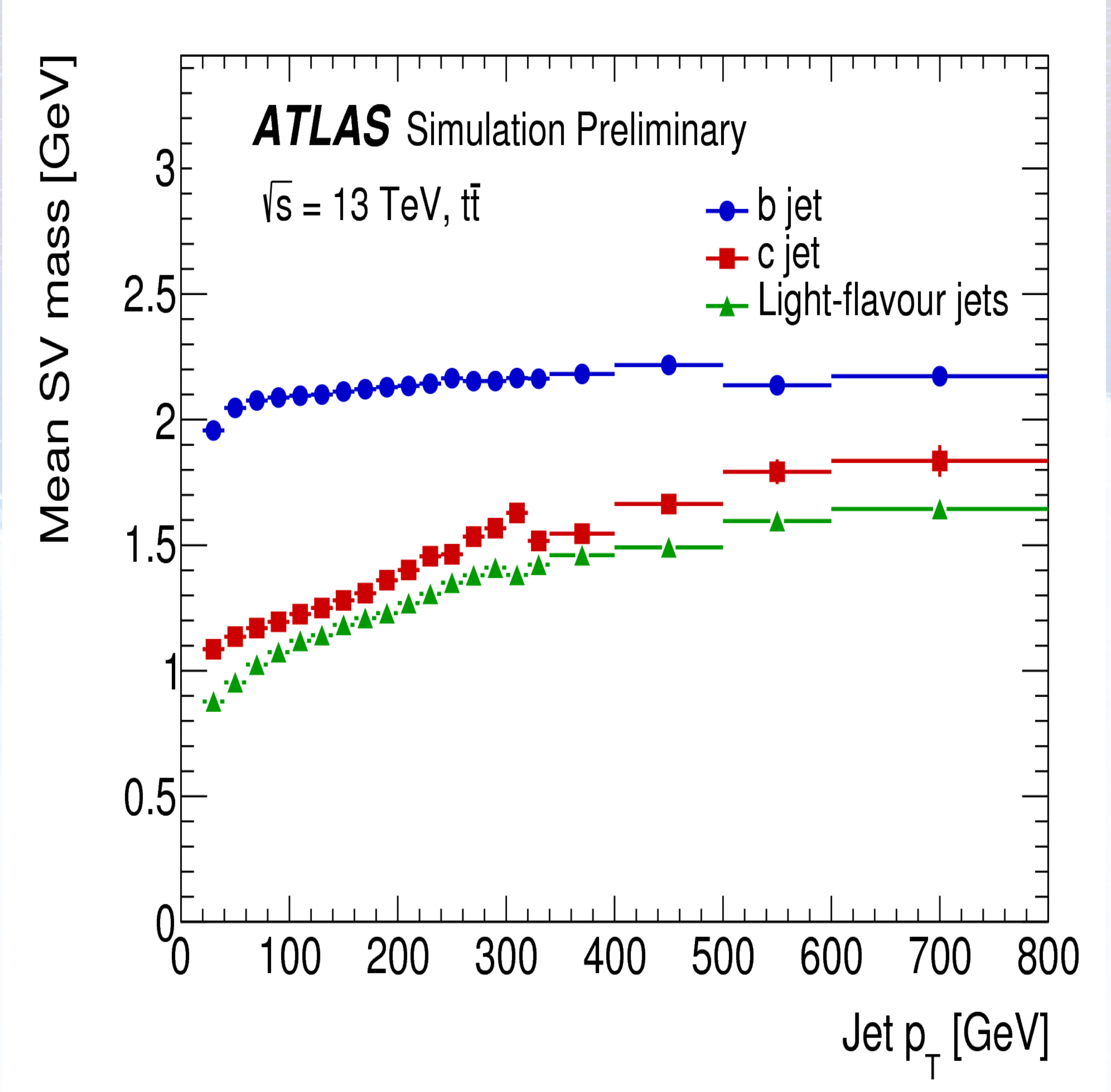


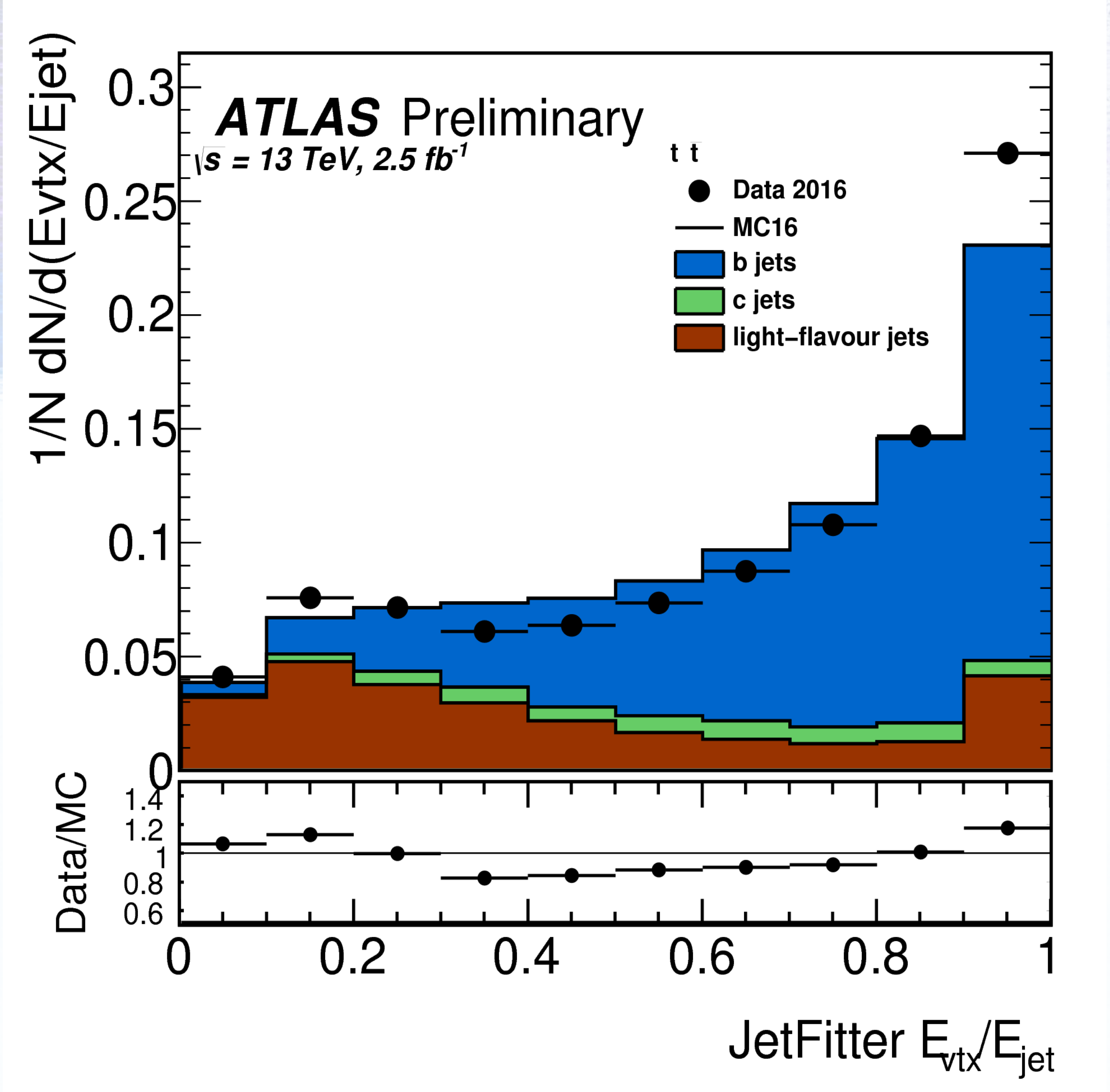
Low Level Taggers

ATL-PHYS-PUB-2017-013
ATL-PHYS-PUB-2017-003
ATL-PHYS-PUB-2018-025



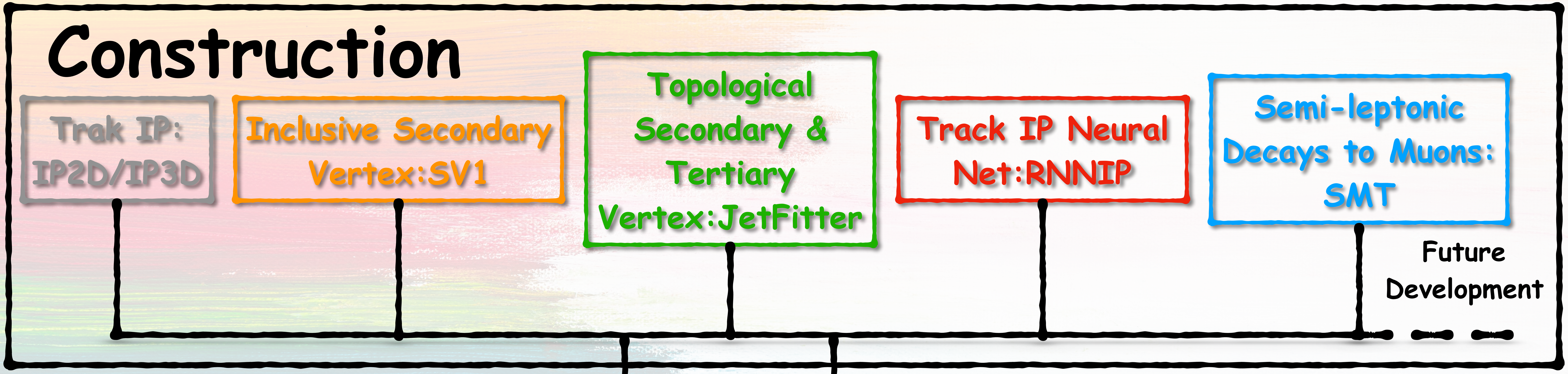






- IP2D and IP3D
  - Consider the IP parameters of individual track
- RNNIP
  - Explore the correlations between tracks
- SV1
  - Explore properties of the secondary vertex such as vertex mass
- JetFitter
  - Explore decay properties such as energy ratio

High Level Taggers



Training

BDT: MV2 | NN: DL1

Trained on multiple jet collections:

- AK4EMTopo Jets (Phasing out)
- AK4EMPFlow Jets
- Variable Radius Track Jets

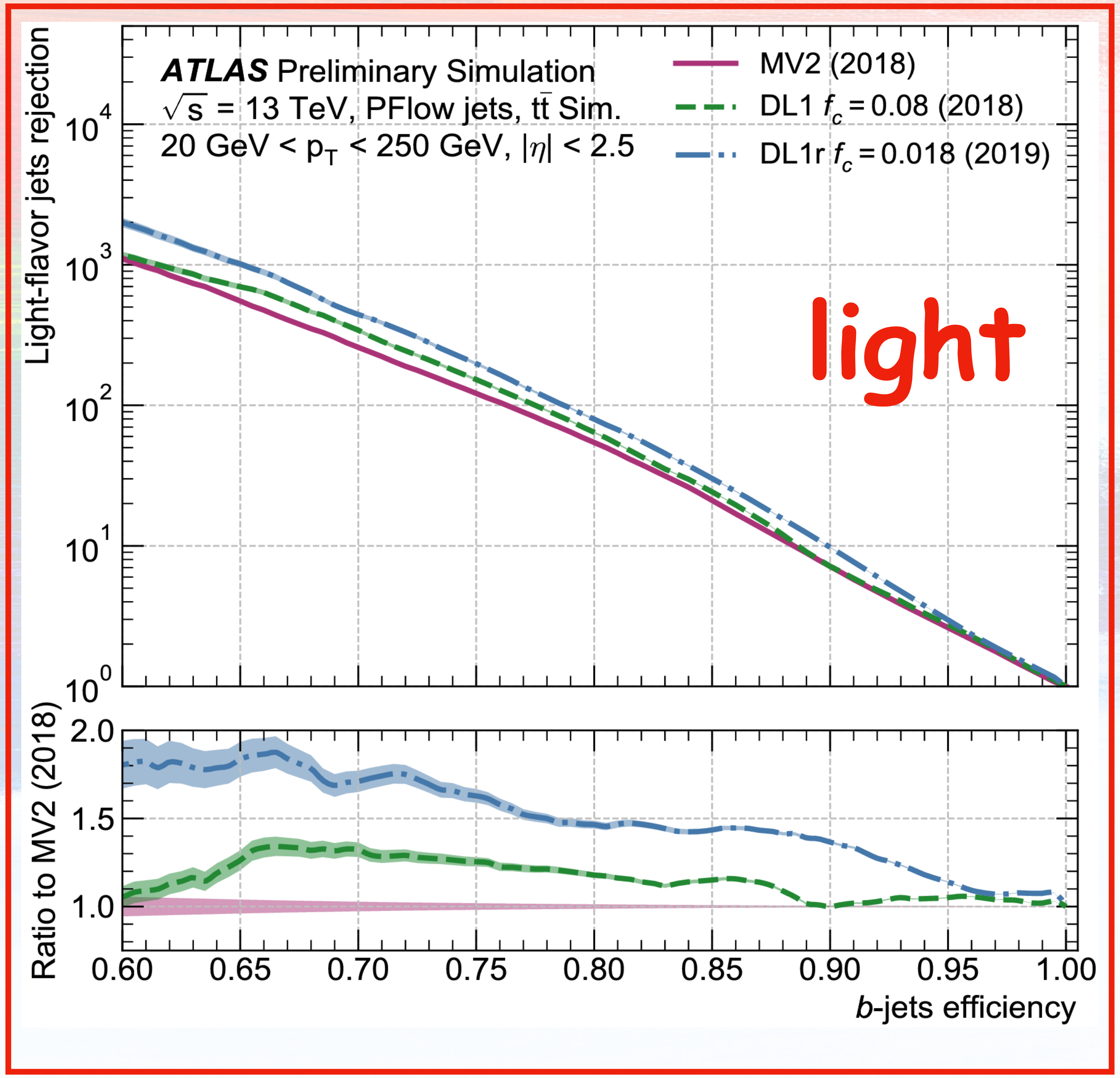
Using Hybrid Sample
$t\bar{t}$ and Z'

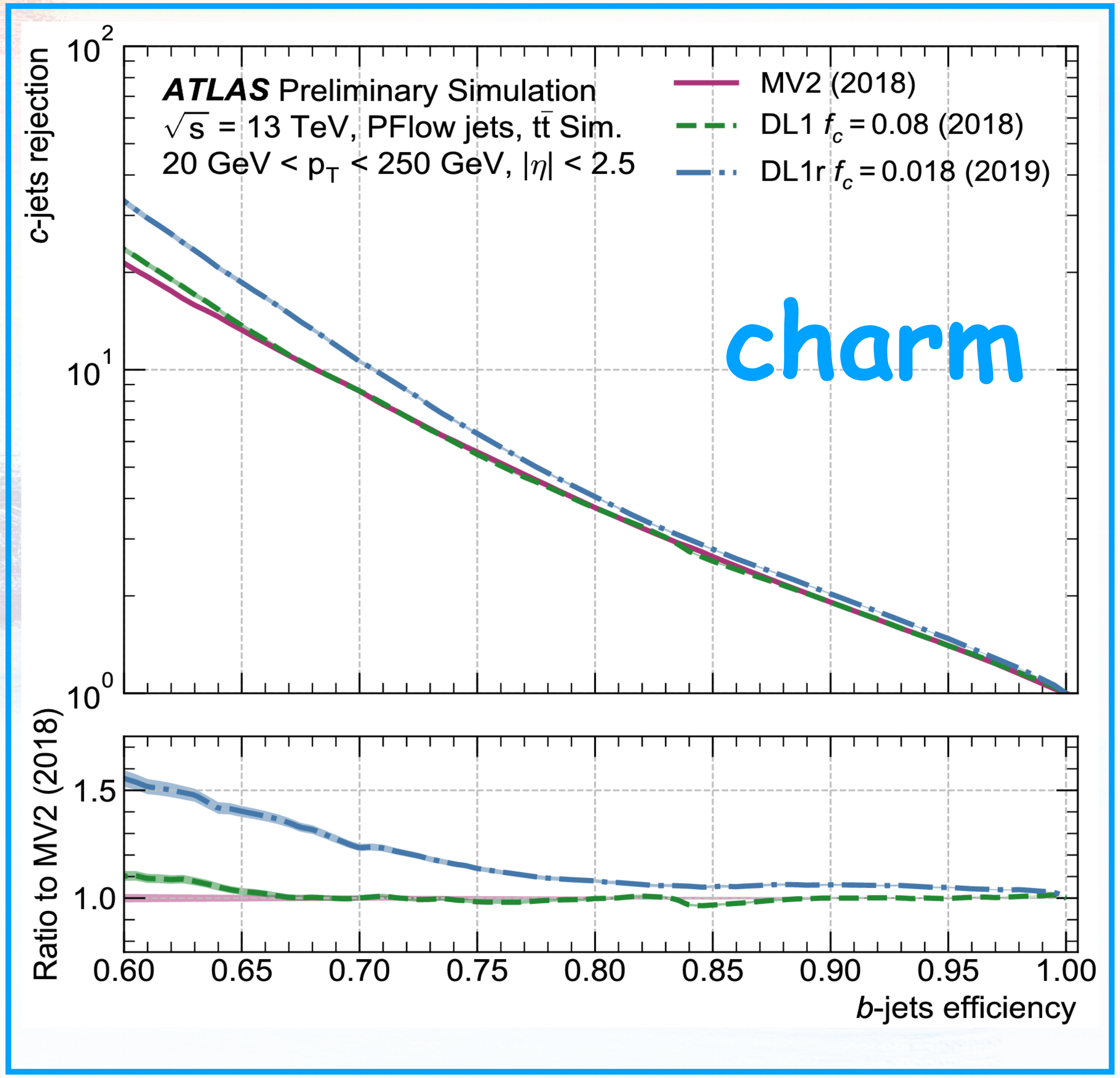
- Both MV2 and DL1 have various versions
  - MV2r and DL1r (Recommended)
    - Including RNNIP
  - MV2 and DL1 (Backup)
  - MV2mu and DL1mu (R&D)
    - Including SMT
  - MV2rmu and DL1rmu (R&D)
    - Including RNNIP and SMT

Performance

FTAG-2019-005

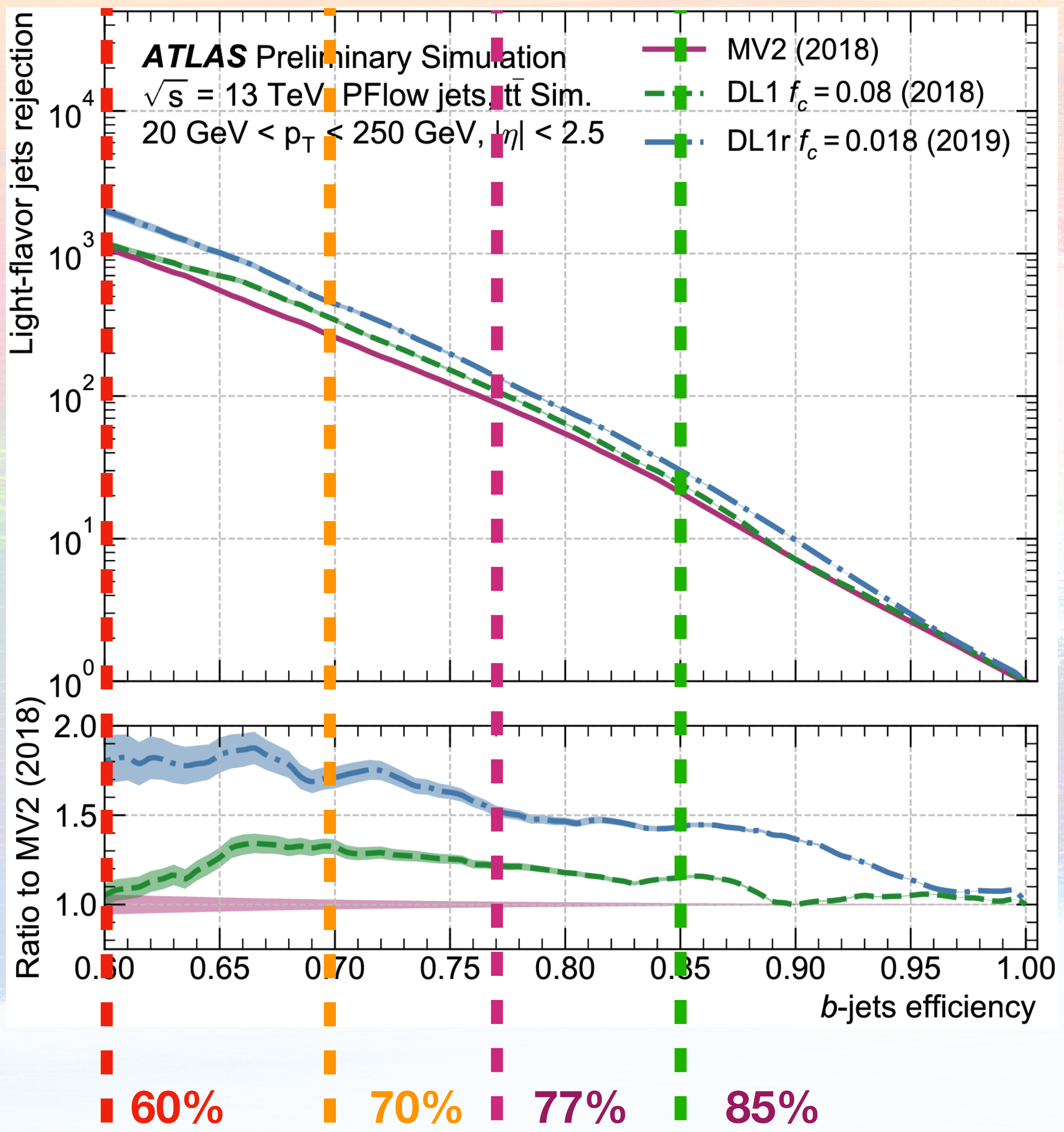
- Recent training campaign gives us the best performance so far



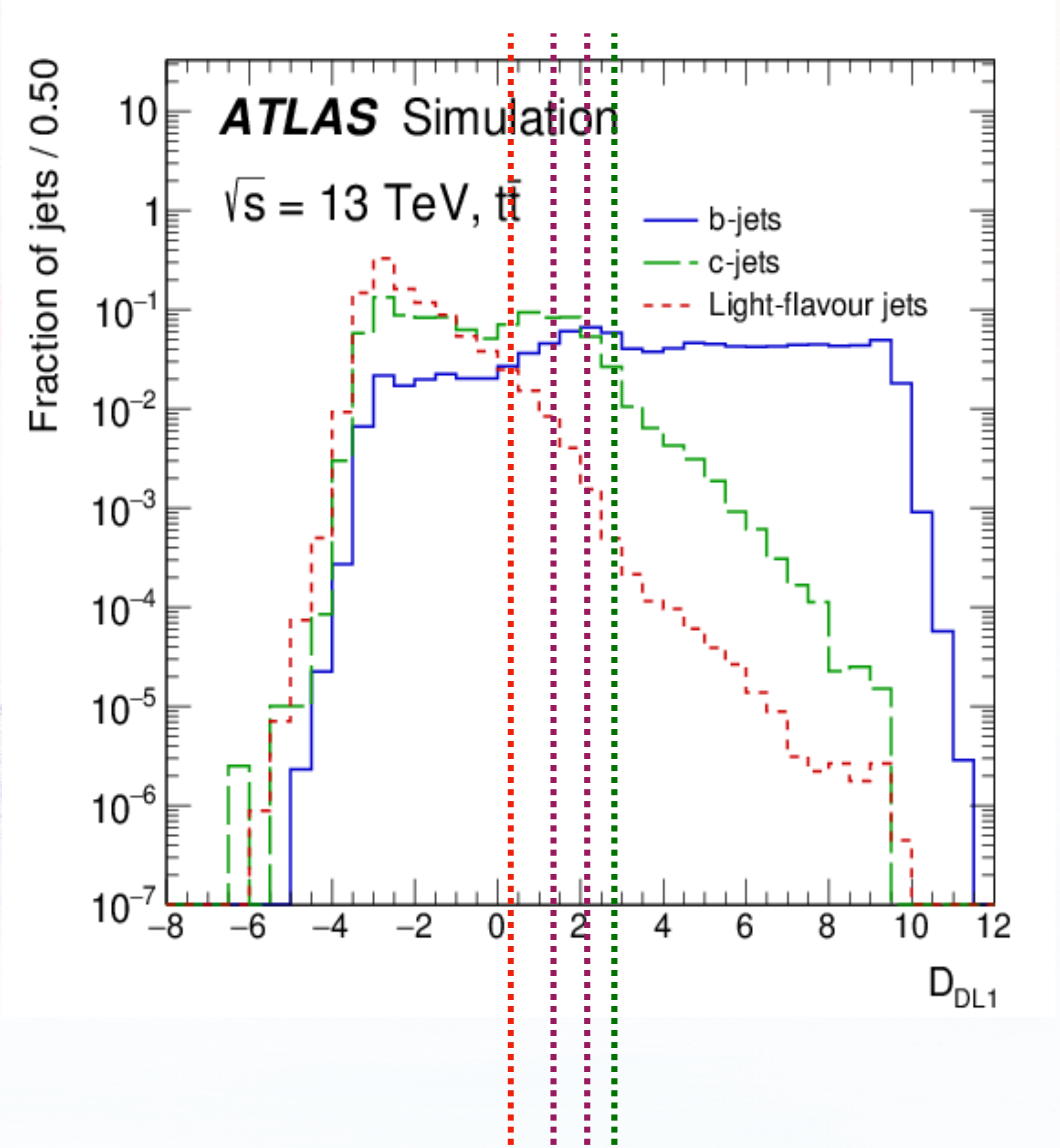


Working Points (WPs)

FTAG-2019-005



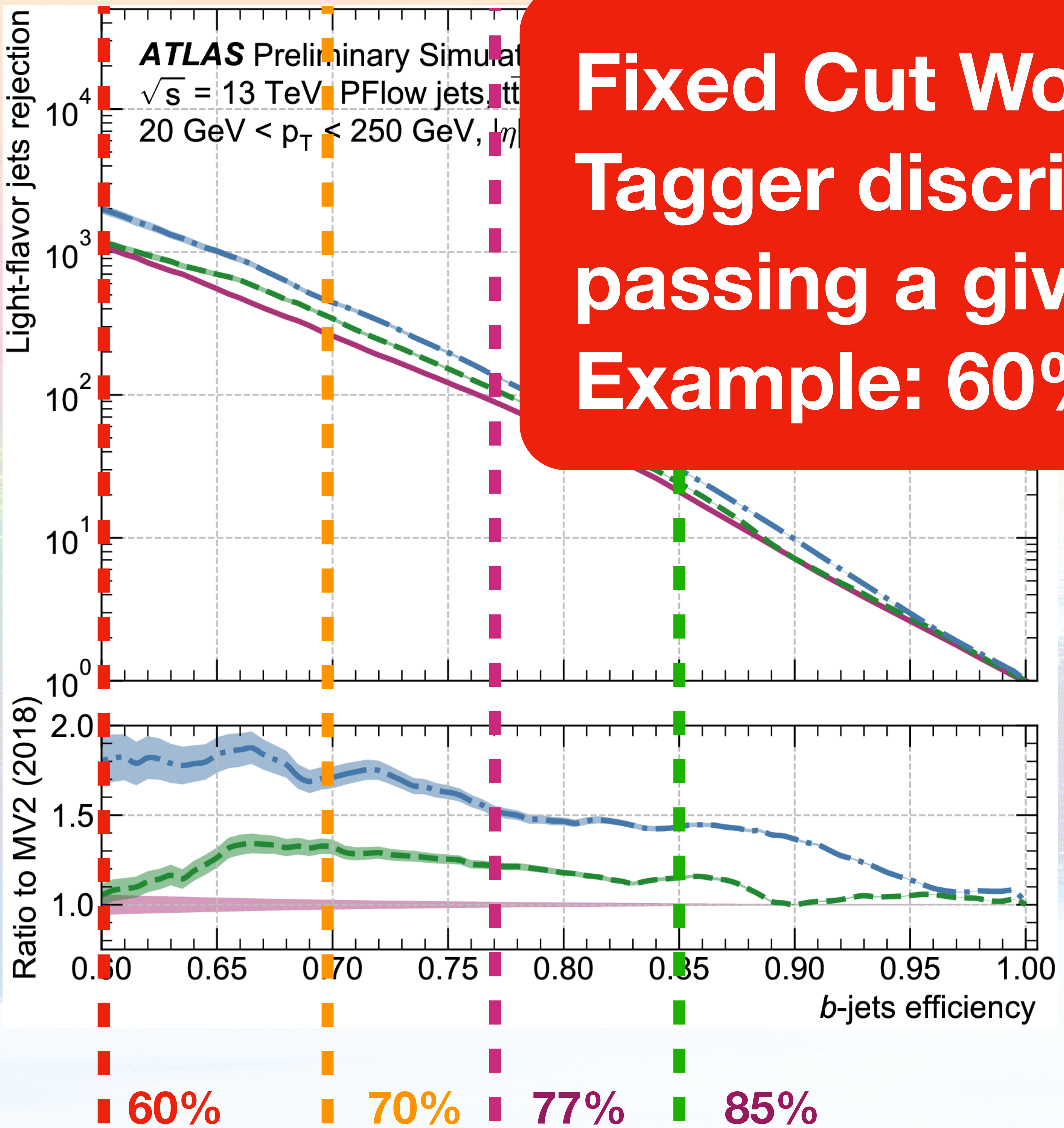
Working Points are defined by the expected b-tagging efficiency



Corresponding discriminant output values

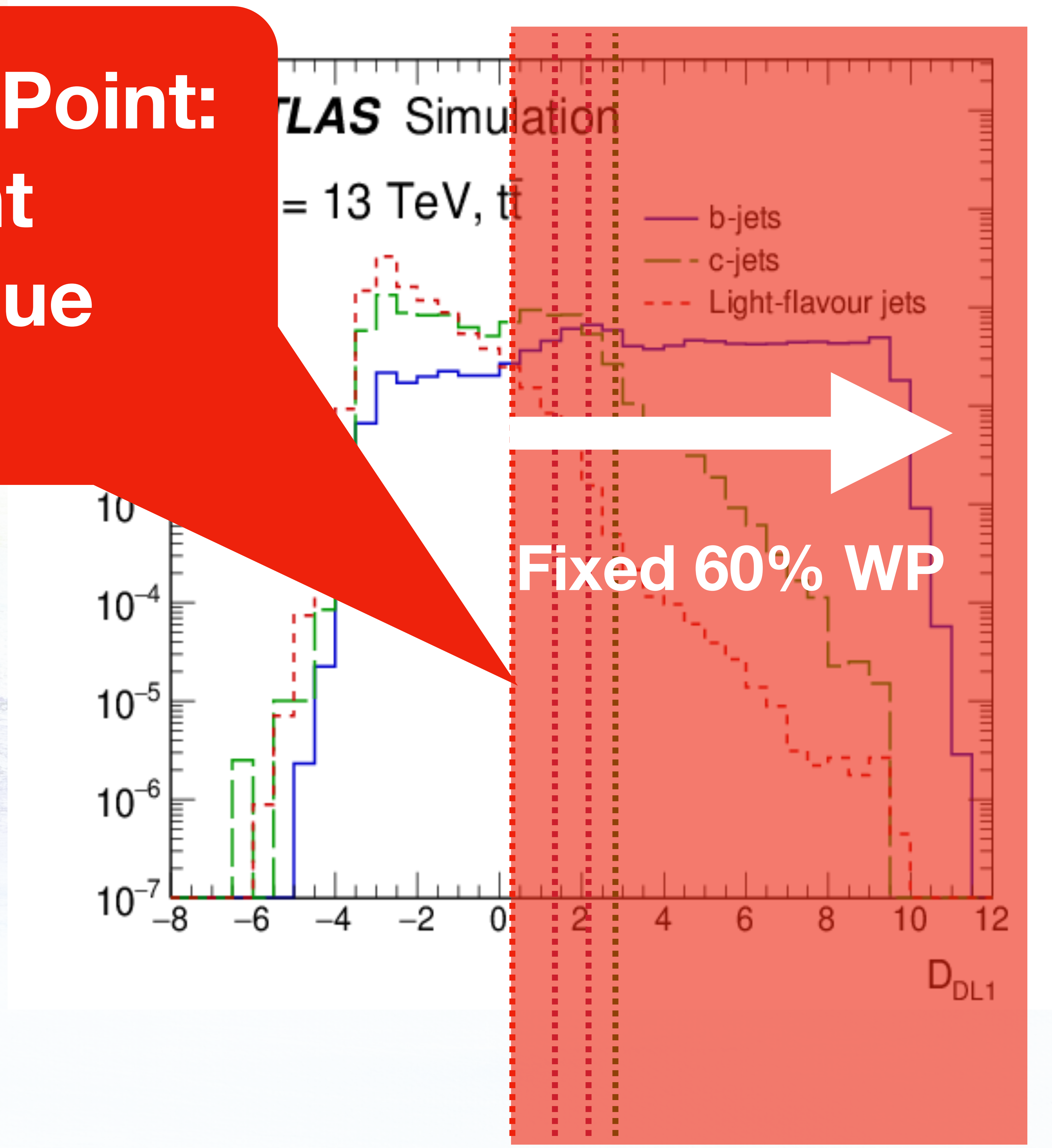
Working Points (WPs)

FTAG-2019-005



Working Points are defined by the expected b-tagging efficiency

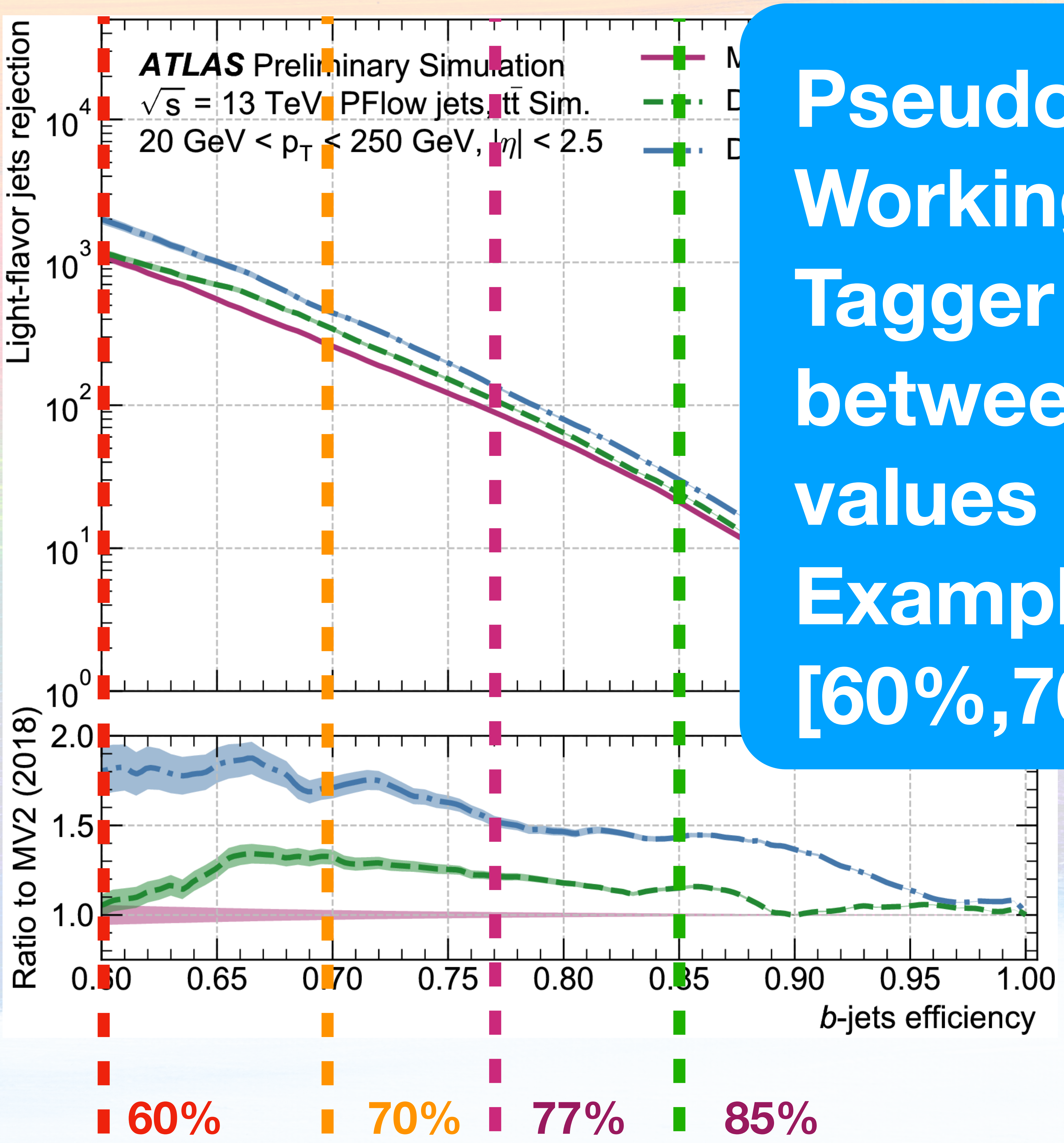
Fixed Cut Working Point: Tagger discriminant passing a given value
Example: 60% WP



Corresponding discriminant output values

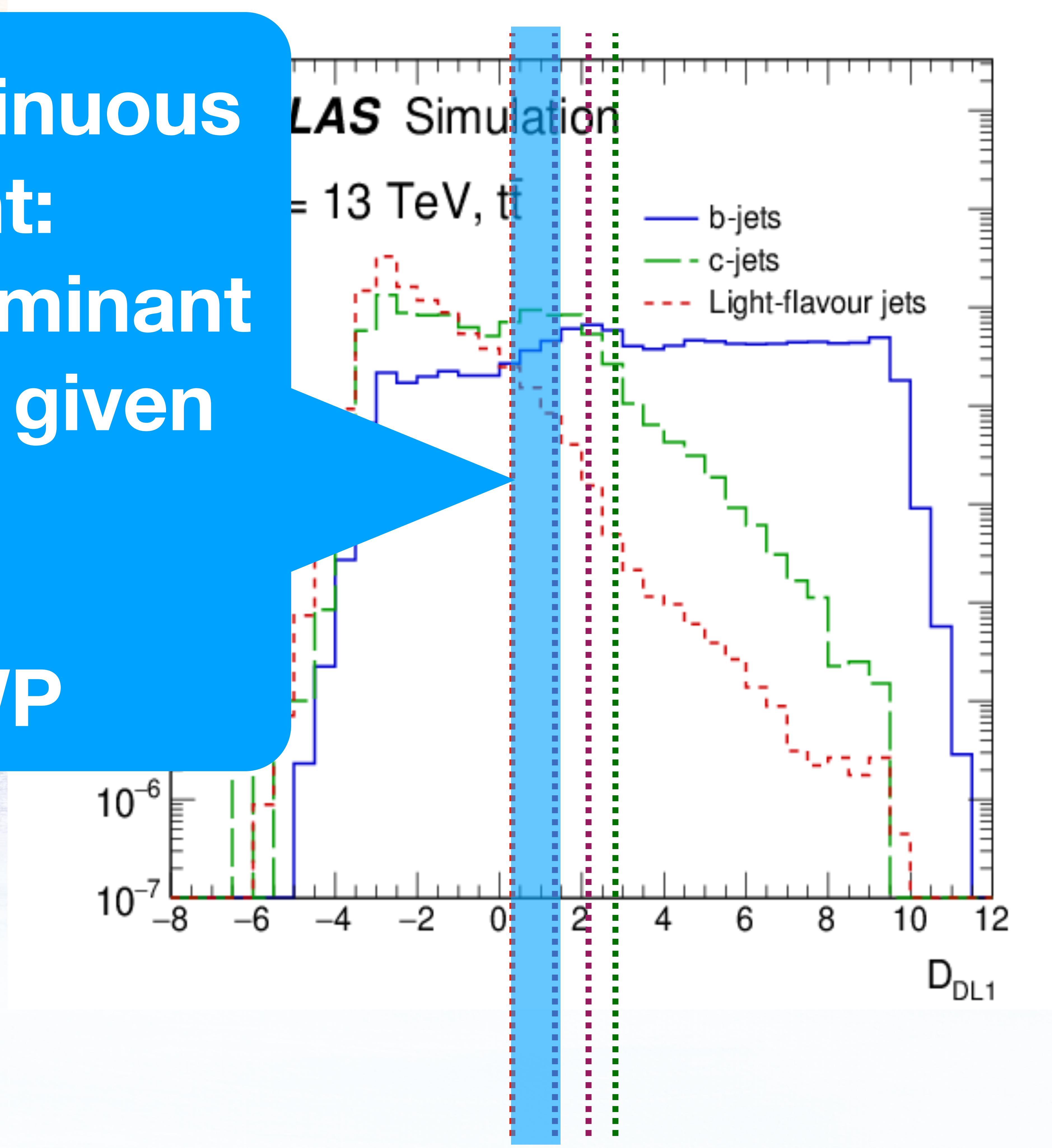
Working Points (WPs)

FTAG-2019-005



Working Points are defined by the expected b-tagging efficiency

Pseudo-continuous Working Point: Tagger discriminant between two given values
Example: [60%,70%] WP



Corresponding discriminant output values

Flavor Tagging Calibration

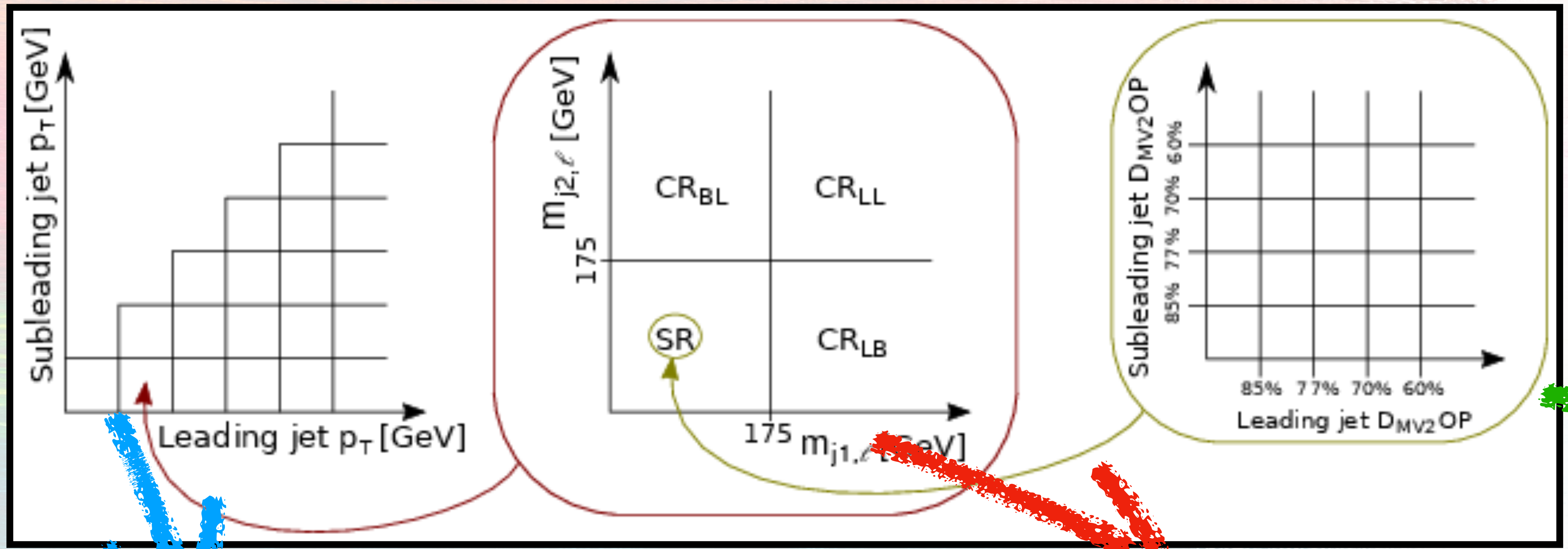
- The performance of b-tagging in MC is different from that in data
  - Mis-modeling of the input variables used by the algorithms
- Need to correct the performance in MC
  - Ideally one can correct all input variables
  - Practically we correct the resulting tagging performance
- Basic idea
  - Measure the b-tagging efficiency/mis-tag rate in data and MC binned in jet p_T, and correct the performance in MC to match the data
- The mainstream calibrations are done in $t\bar{t}$ and Z + jets events
- The expanding physics programs now demand more versatile calibrations
  - To cover different kinematic regions (Di-b-jet resonance)
  - To avoid circular dependence (Top decay branching ratio measurement)

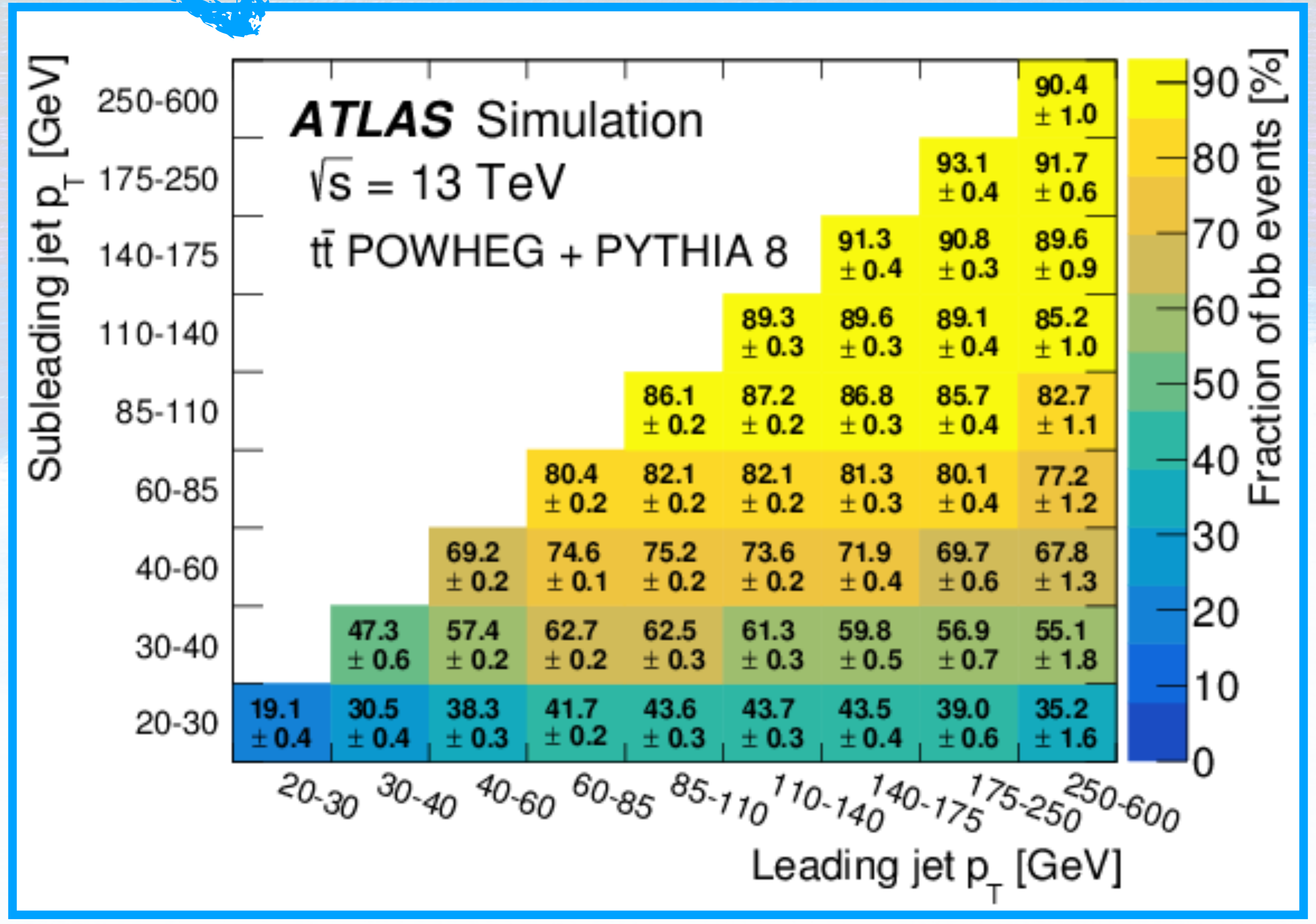
Mainstream Calibrations

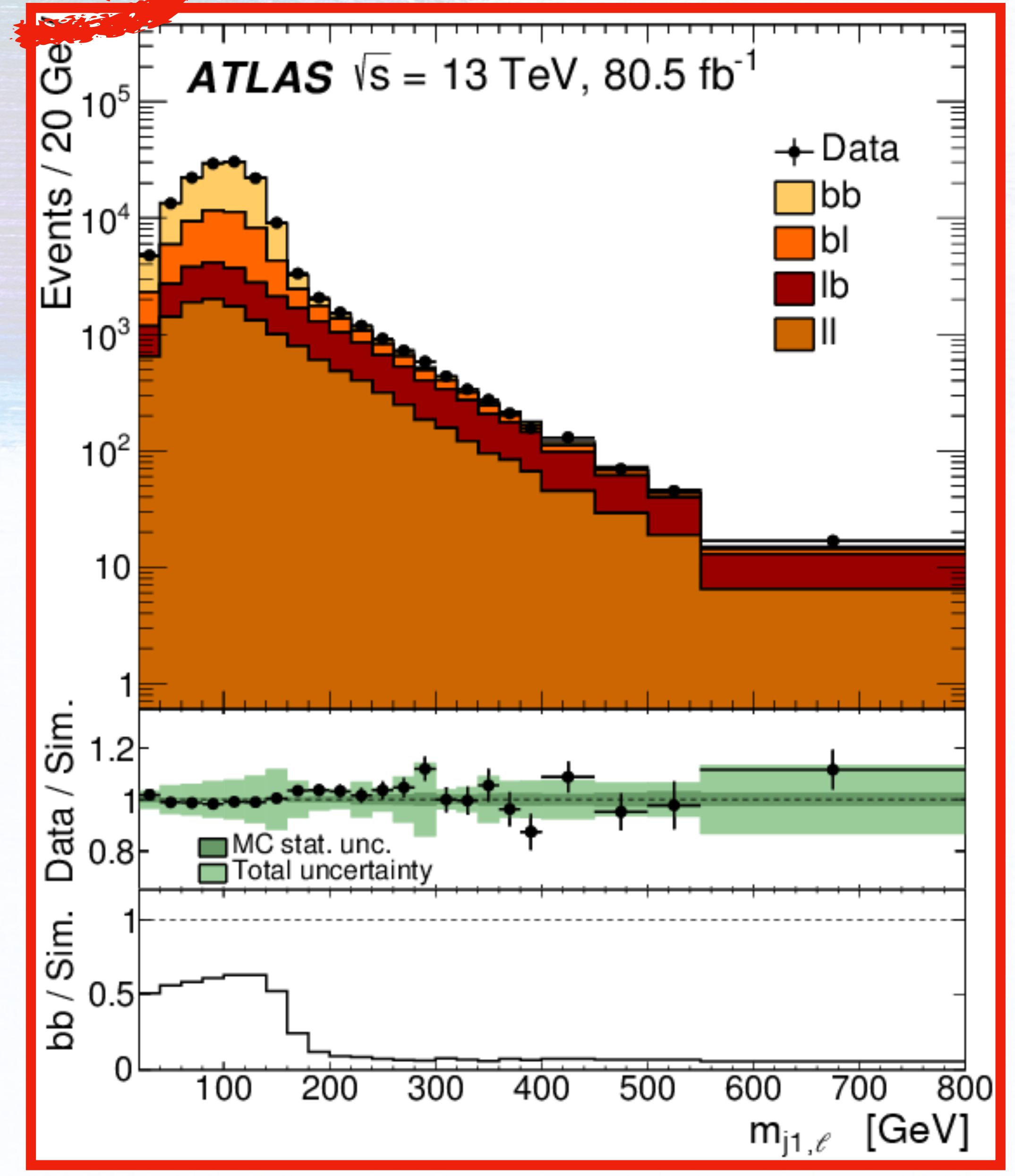
B-tagging Efficiency Calibration

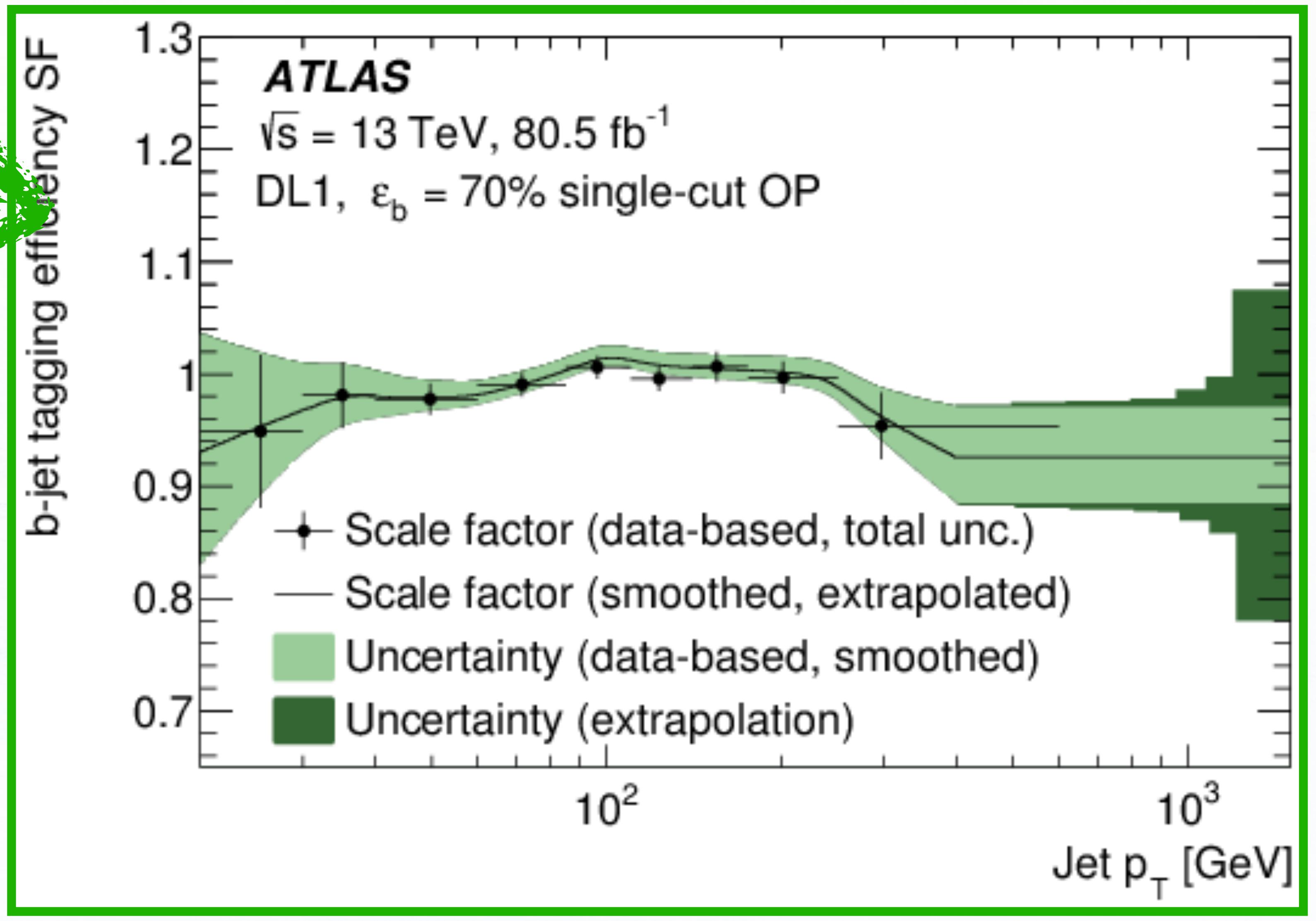
Eur. Phys. J. C 79 (2019) 970

- Method: Select di-lepton $t\bar{t}$ events, construct CR/SR based on the $m_{j,l}$ distribution and perform a combined log-likelihood fit







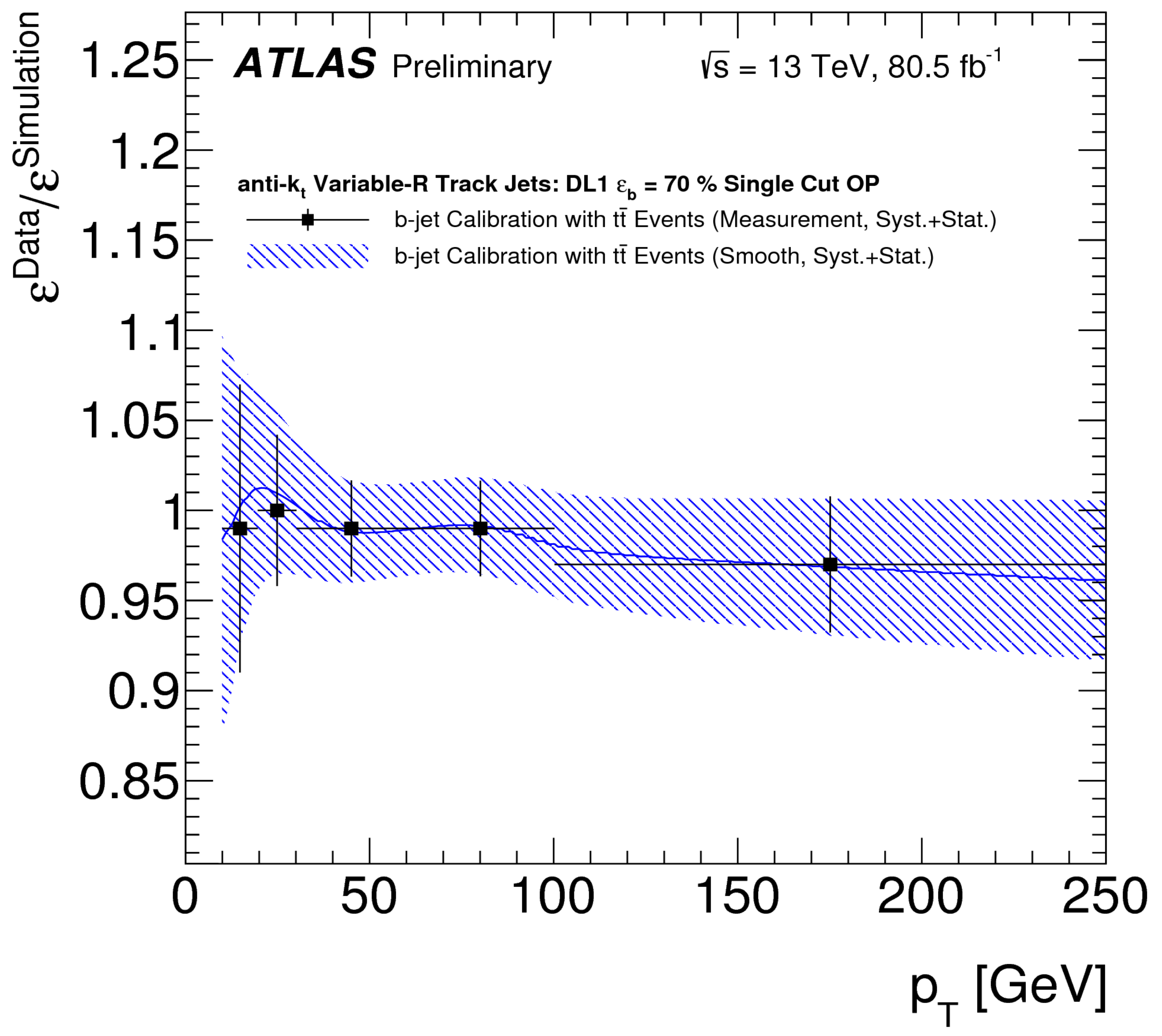


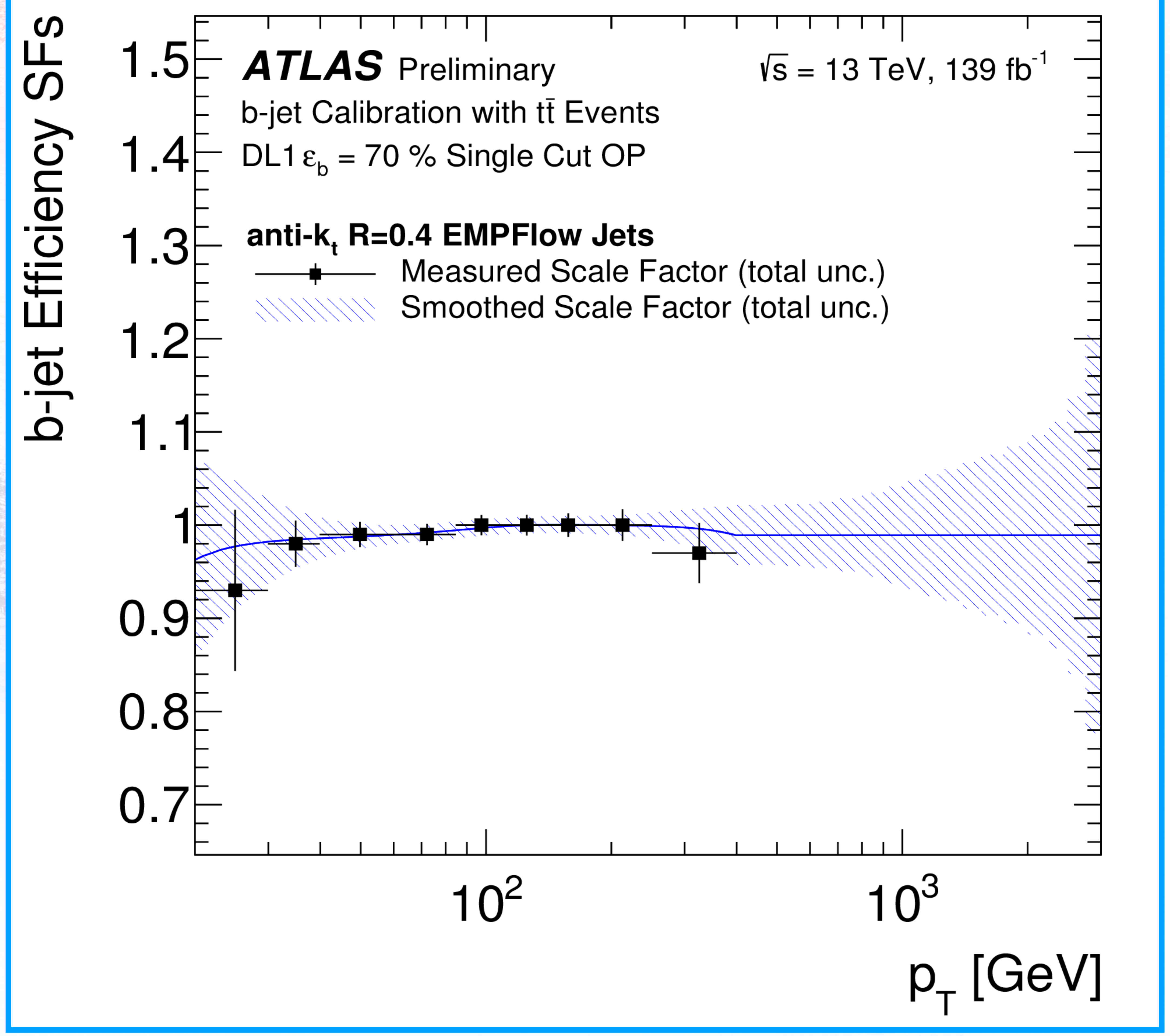
B-tagging Efficiency Calibration

FTAG-2019-003

FTAG-2019-004

- Latest results for VRTrack Jets and EMPFlow Jets

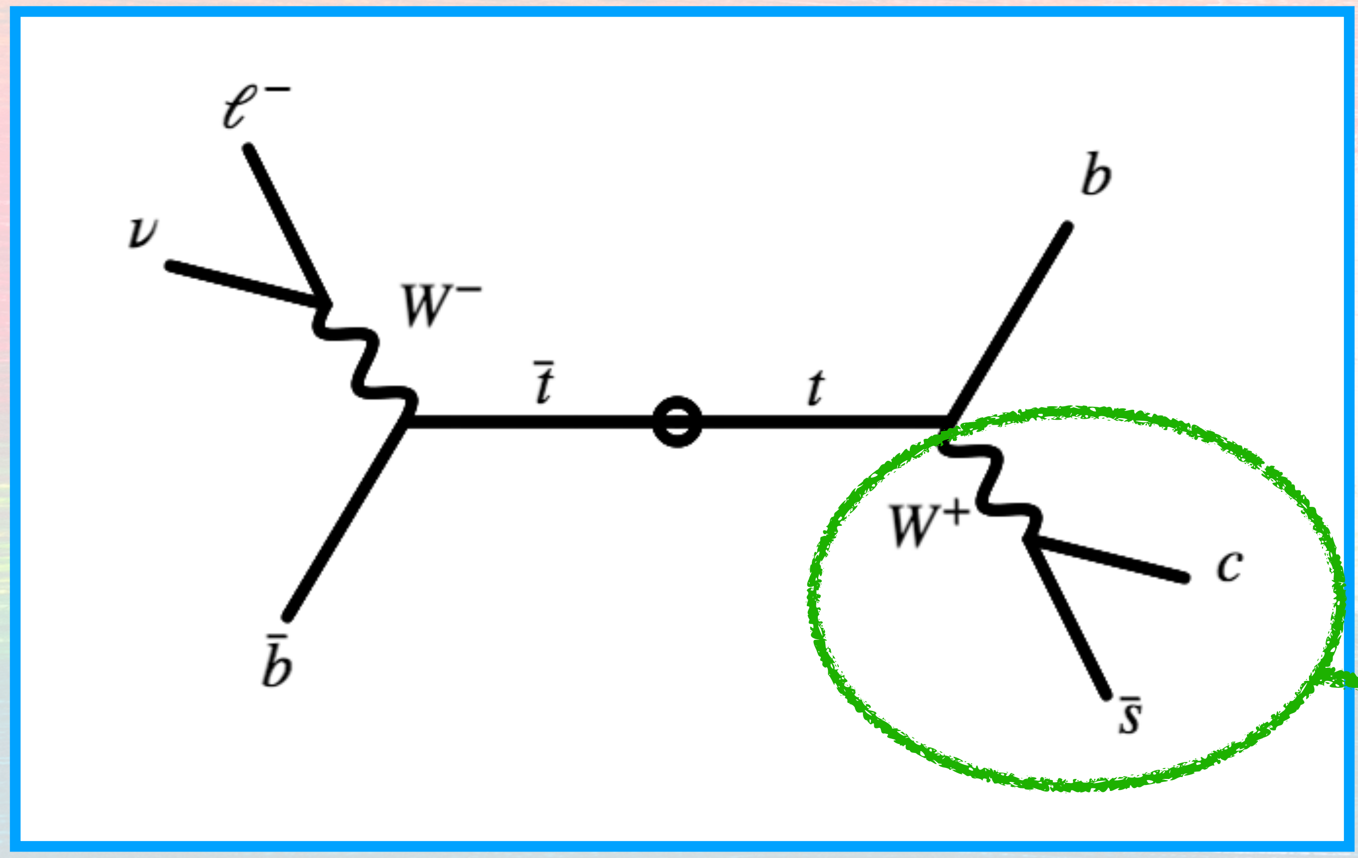




C-mistag Rate Calibration

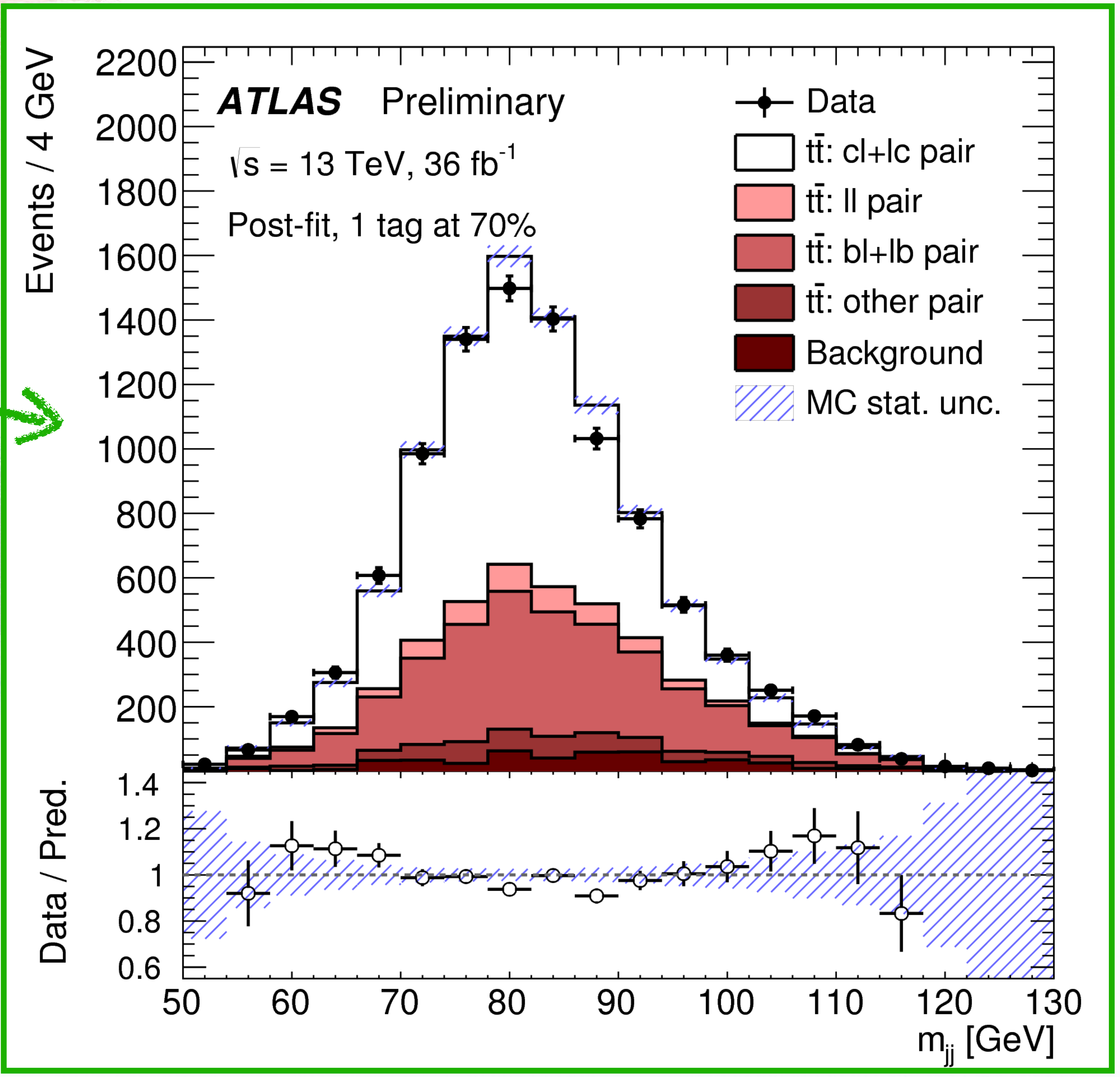
ATLAS-CONF-2018-001

- Method: Select semi-leptonic $t\bar{t}$ events, associated jets with W boson via a kinematic fit and perform a likelihood fit to extract the mis-tag rate



ATLAS Simulation Preliminary — f_{cl} (%)

leading jet p_T [GeV] \ subleading jet p_T [GeV]	[25,40]	[40,65]	[65,140]
[65,140]	26.6 ± 0.1	24.2 ± 0.1	27.3 ± 0.1
[40,65]	21.8 ± 0.1	20.8 ± 0.1	
[25,40]	20.0 ± 0.1		



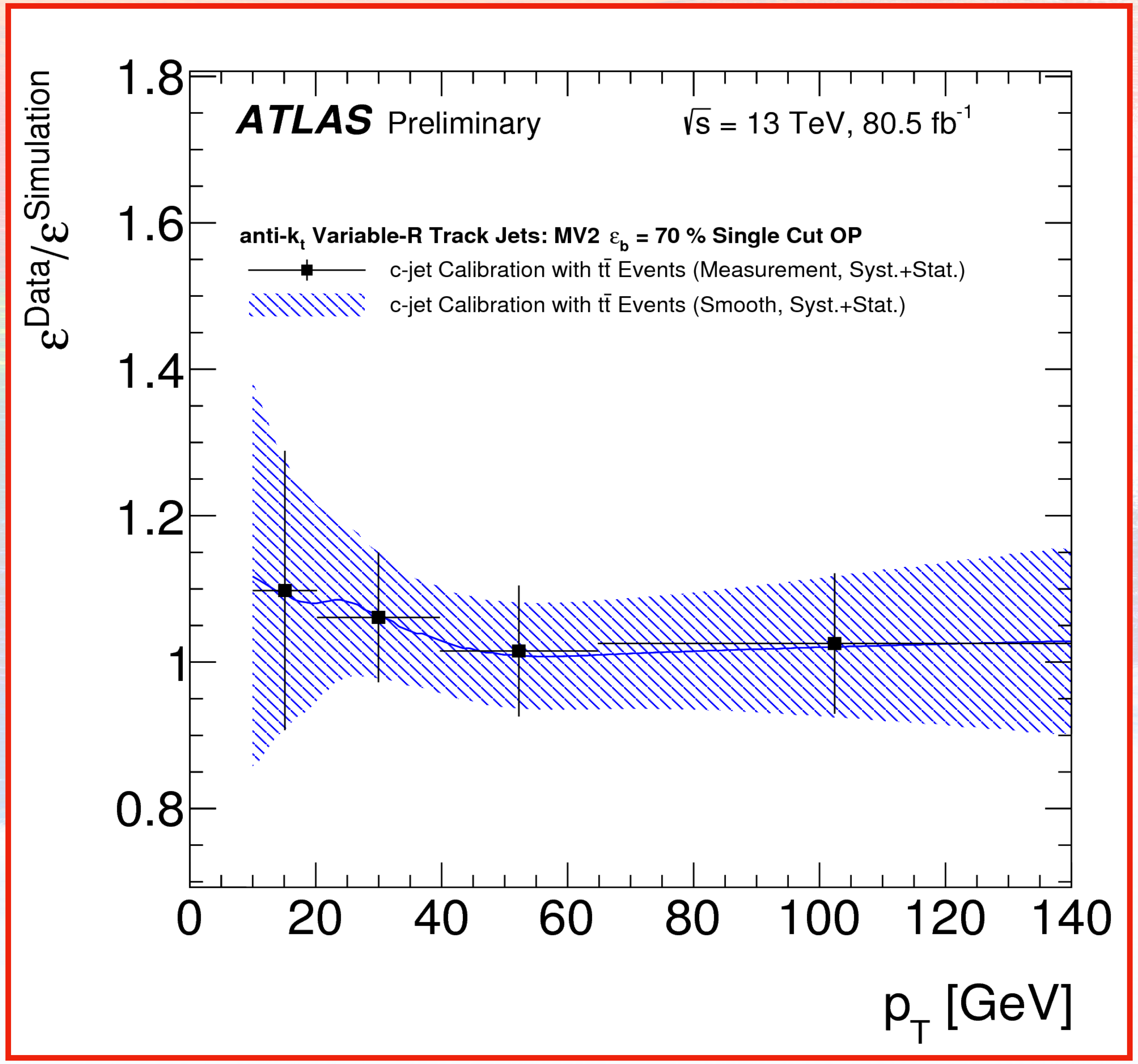
Bingxuan Liu

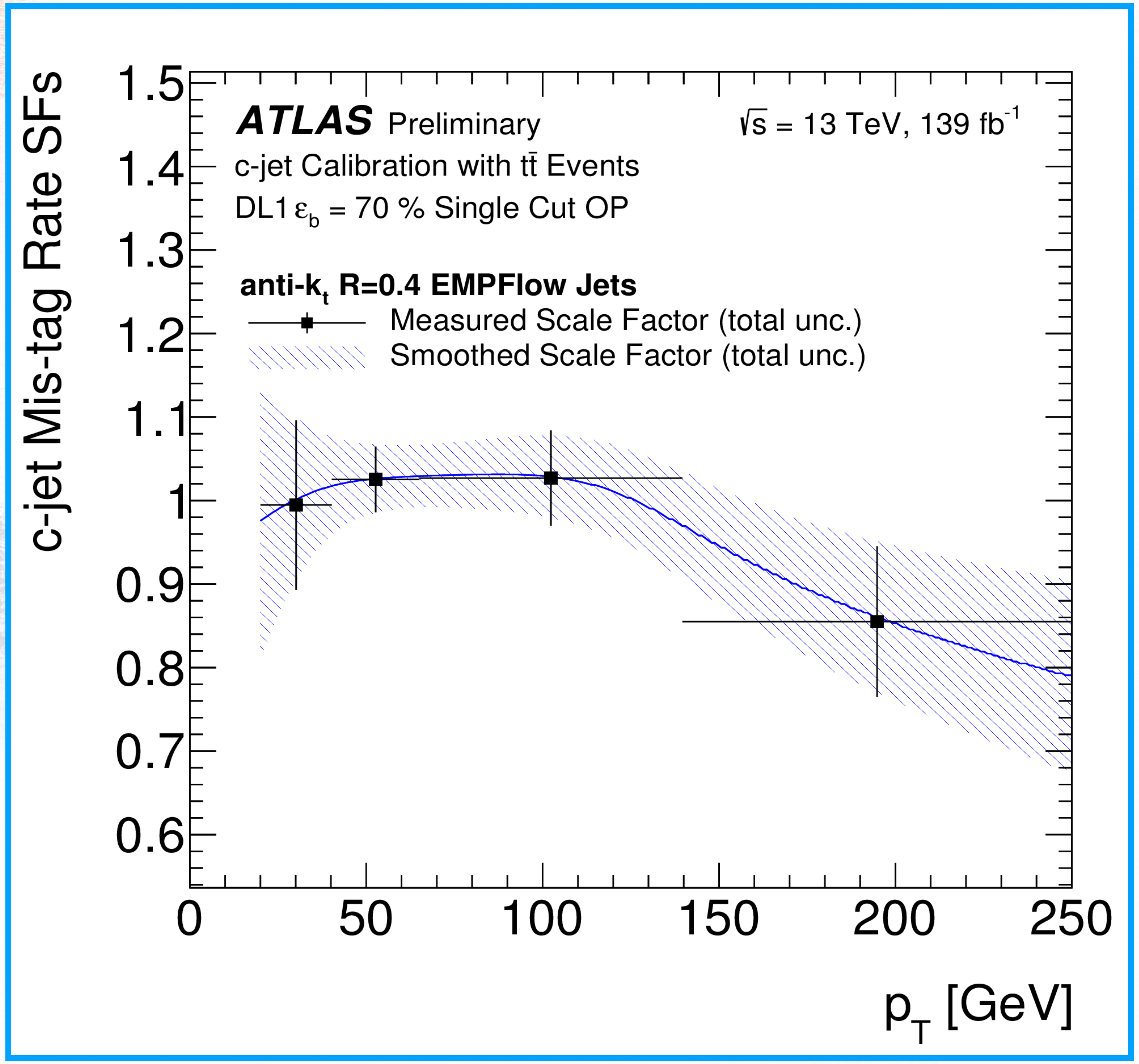
C-mistag Rate Calibration

FTAG-2019-003

FTAG-2019-004

- Latest results for VRTrack Jets and EMPFlow Jets

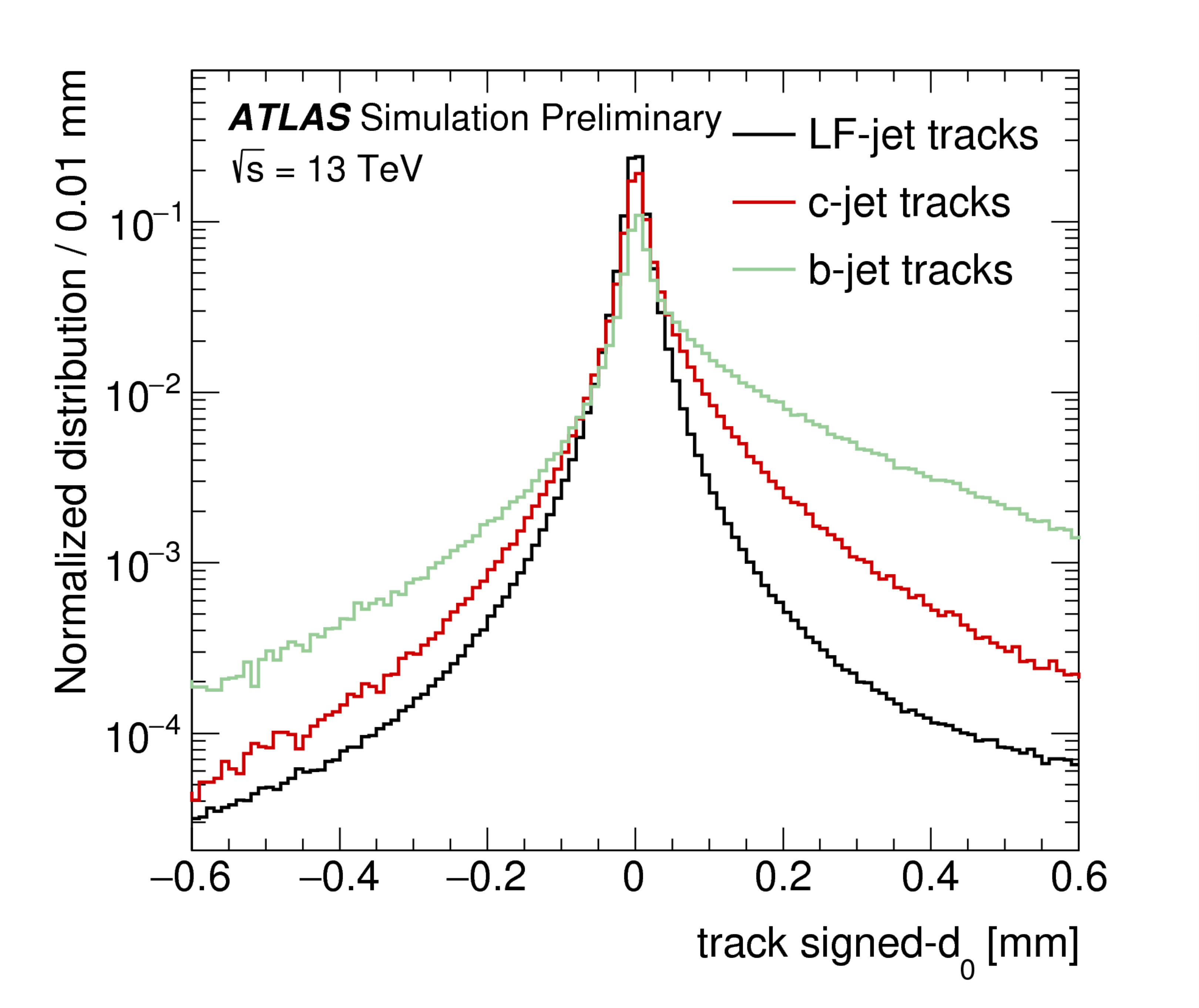




L-mistag Rate Calibration

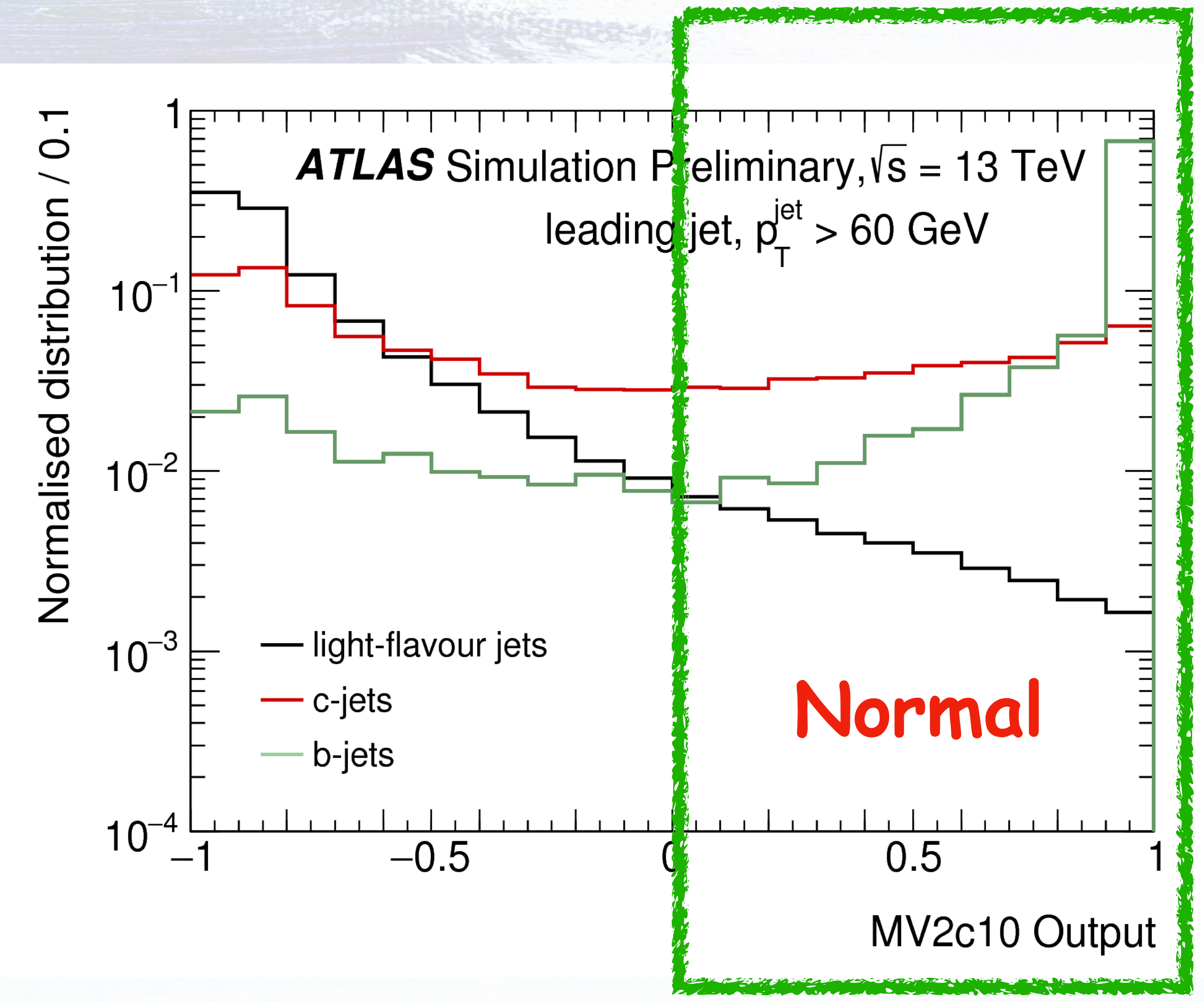
ATLAS-CONF-2018-006

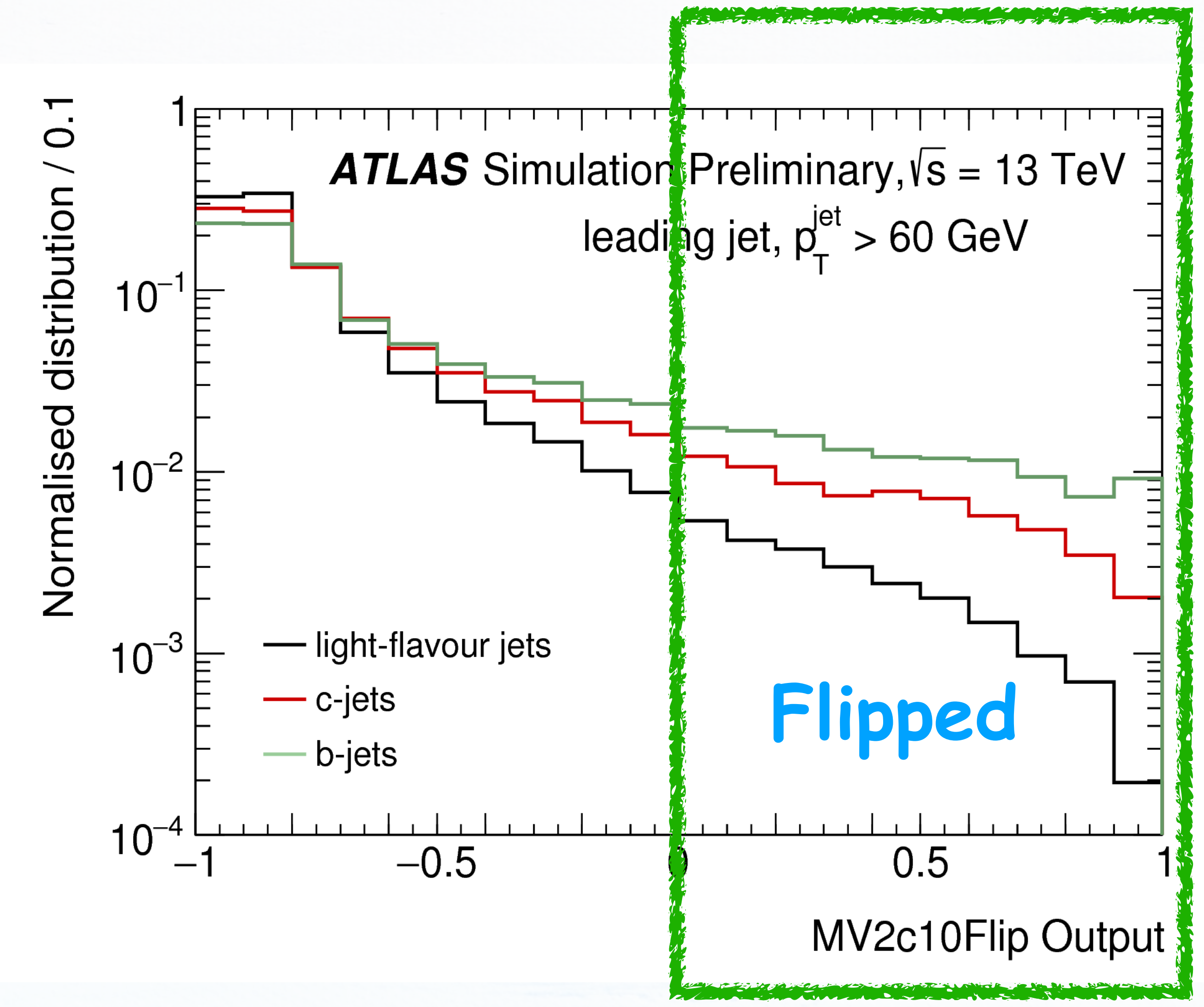
- Method: Enrich the light jet fraction via "flipped" taggers, select Z + jets events, fit the secondary vertex mass to obtain flavor fractions and perform a likelihood fit to extract light jet mistag rate



- Light-flavor jets have a ~symmetric signed d_0 distribution
- Charm- and bottom-flavor jets have much longer positive tails

- Flipped Tagger
  - Negate the sign of track IP parameters before b-tagging
  - Tagger output of light jets does not change much while those of bottom or charm are shifted towards lower values
  - The light jet fractions are significantly enhanced in the target regions



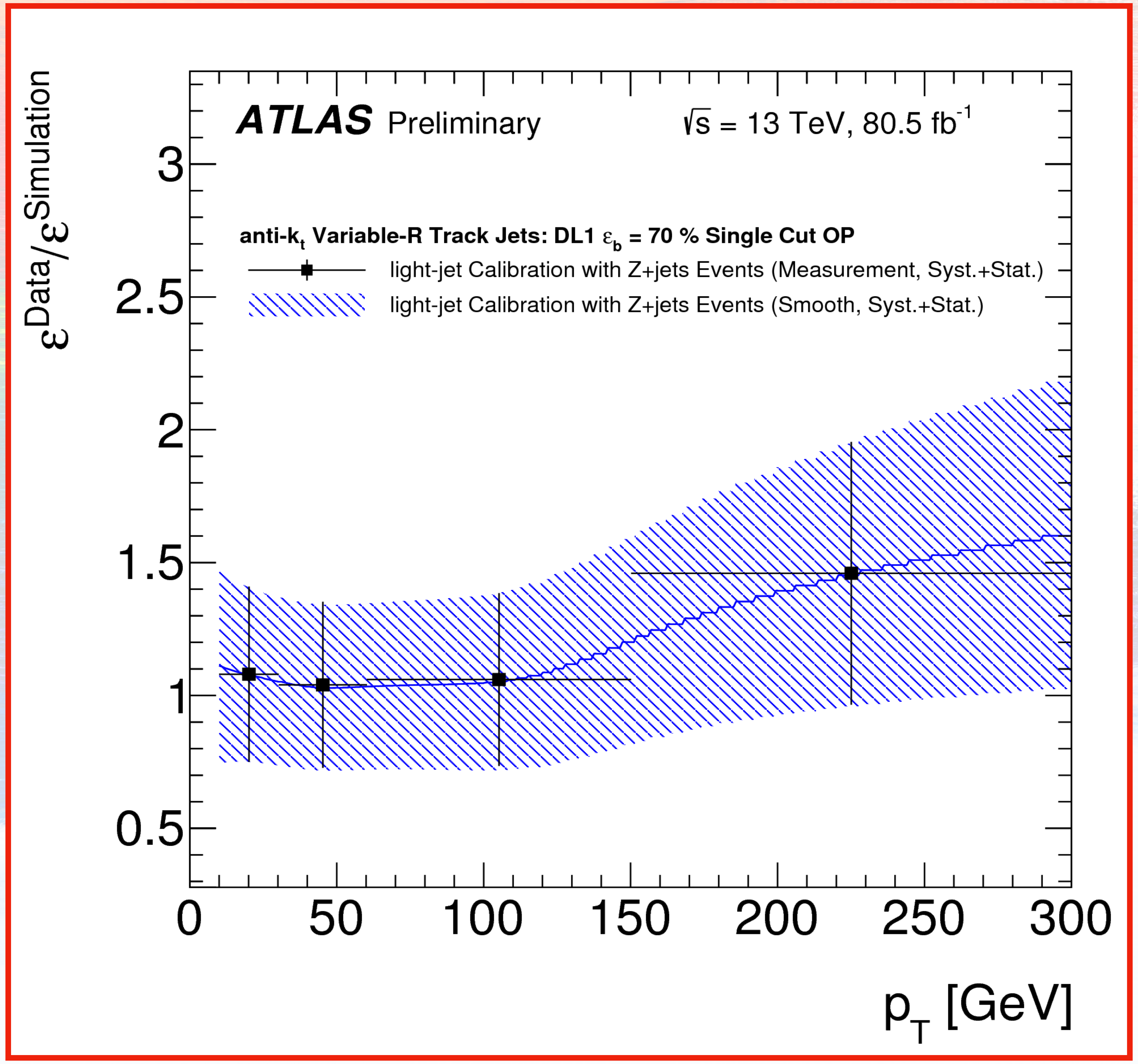


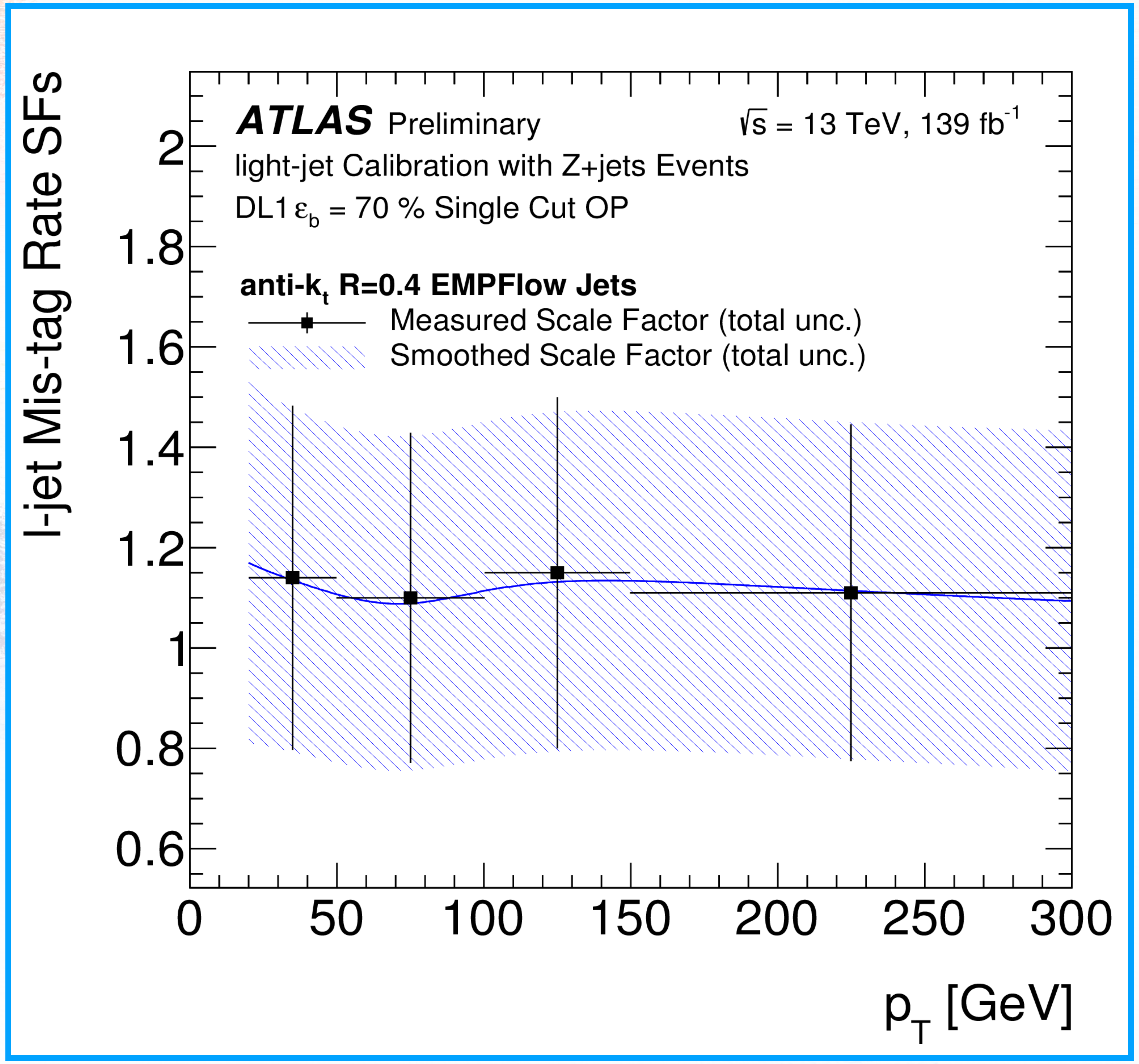
L-mistag Rate Calibration

FTAG-2019-003

FTAG-2019-004

- Latest results for VRTrack Jets and EMPFlow Jets

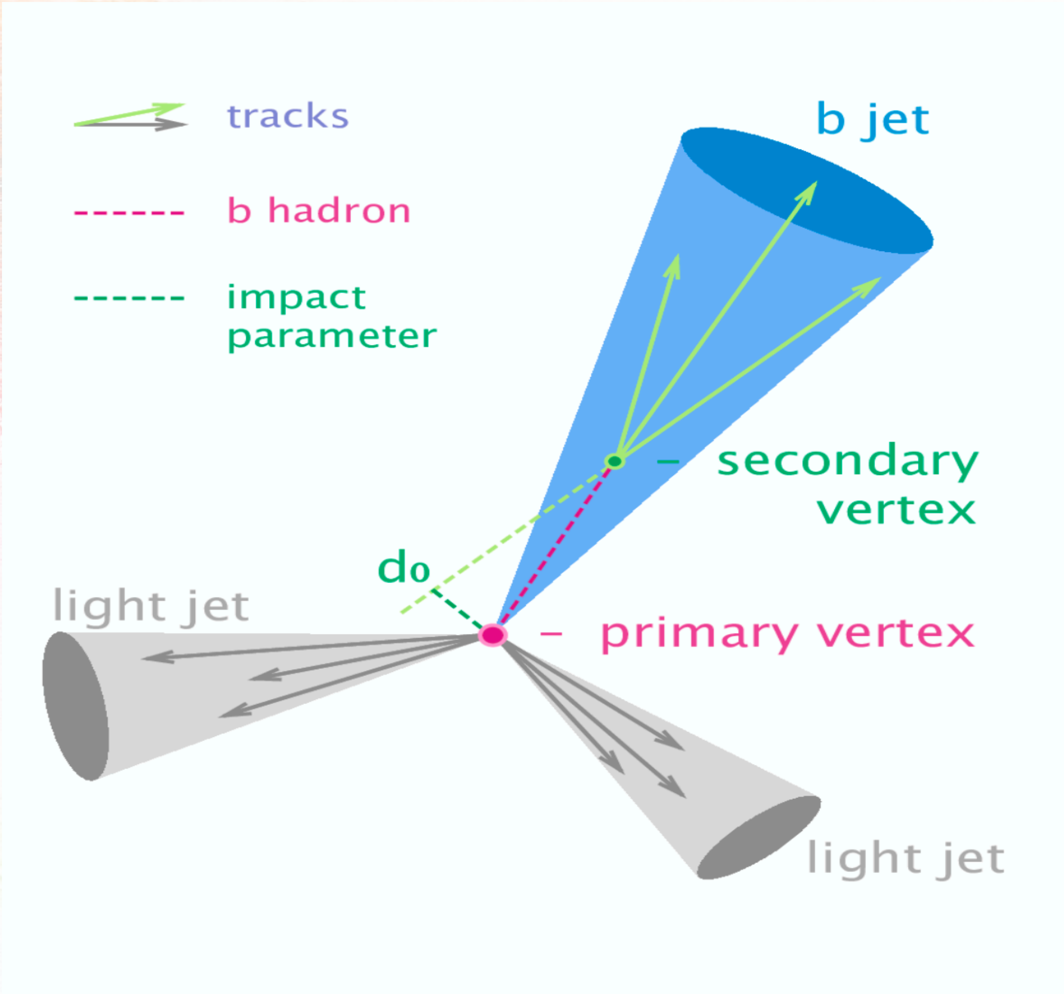




Calibrations In Multi-jet

Calibrations Using Multi-jet Events

- Multi-jet events provide an abundance source of b-jets
  - A large number of b-jets populated in a broader kinematic region
- More challenging
  - There is also more background
  - Simulation is not sufficient
- The calibrations apply template fits
  - Two discriminant variables can be used
    - S_{d_0} and p_T^{rel}

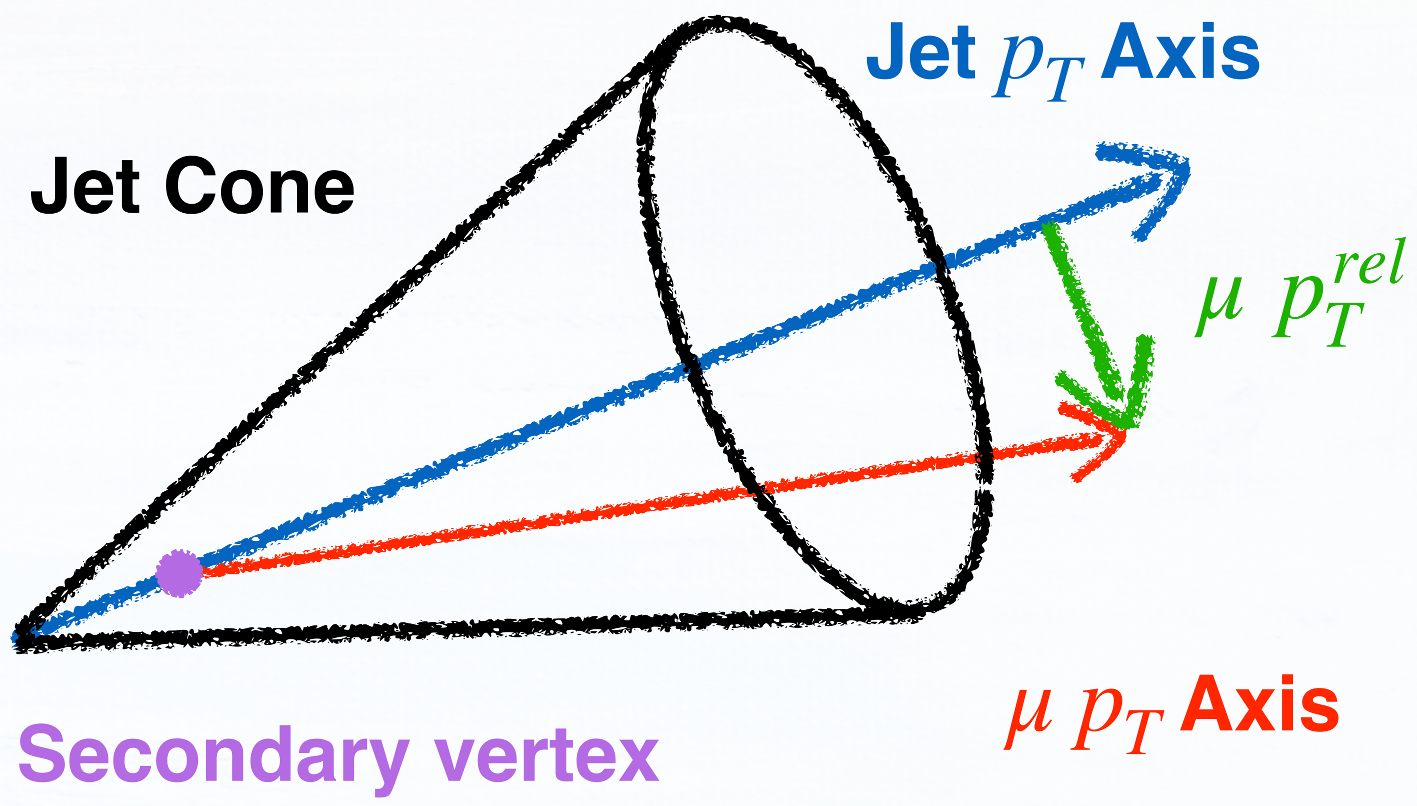


$$S_{d_0} = \left|\frac{d_0}{\sigma_{d_0}}\right| \cdot s_j$$

$$s_j = \text{sign}\left[\sin\left(\arctan\left(\frac{p_y(j)}{p_x(j)}\right) - \phi(t)\right) \cdot d_0\right]$$

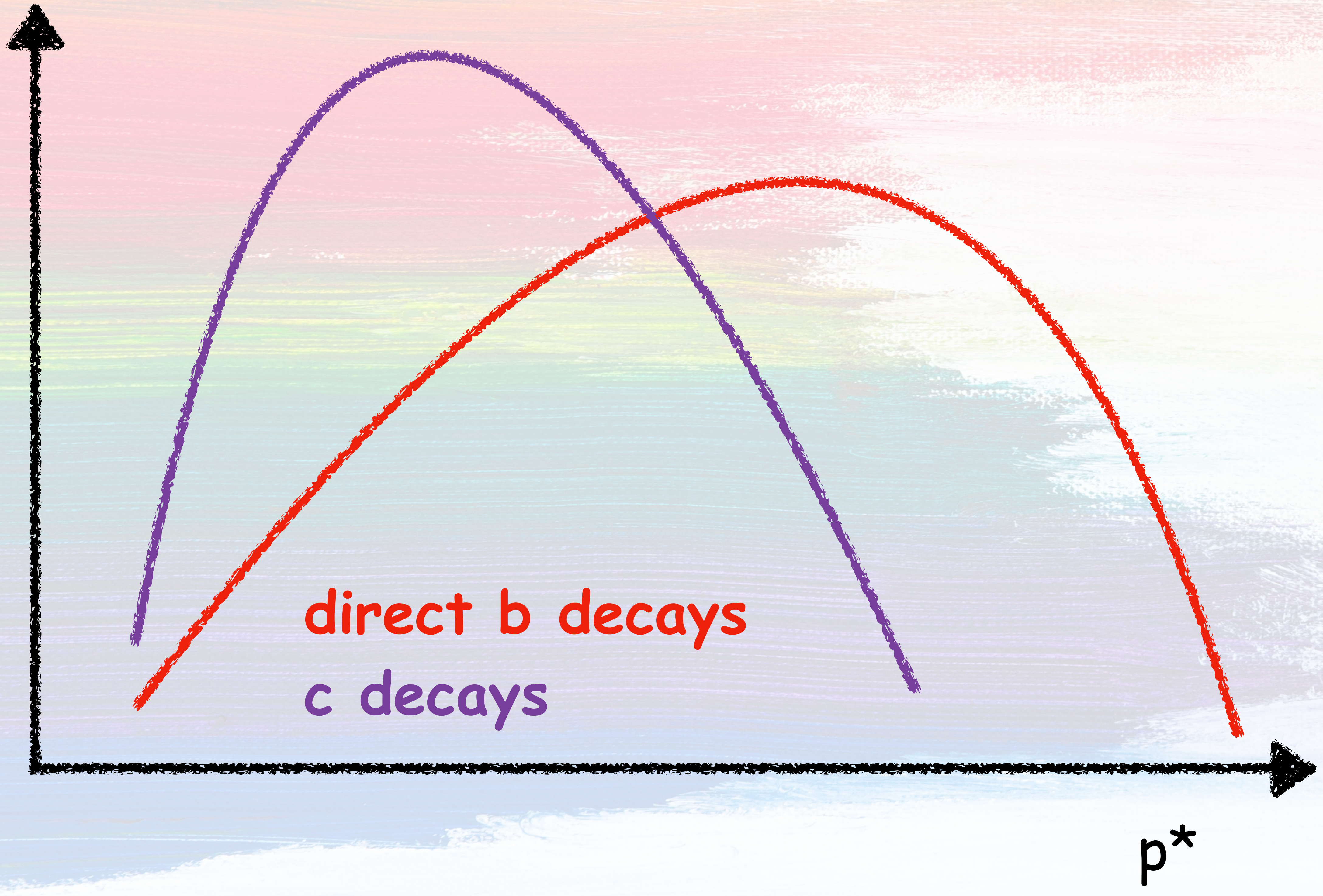
S_{d_0}: b-hadrons have longer lifetimes

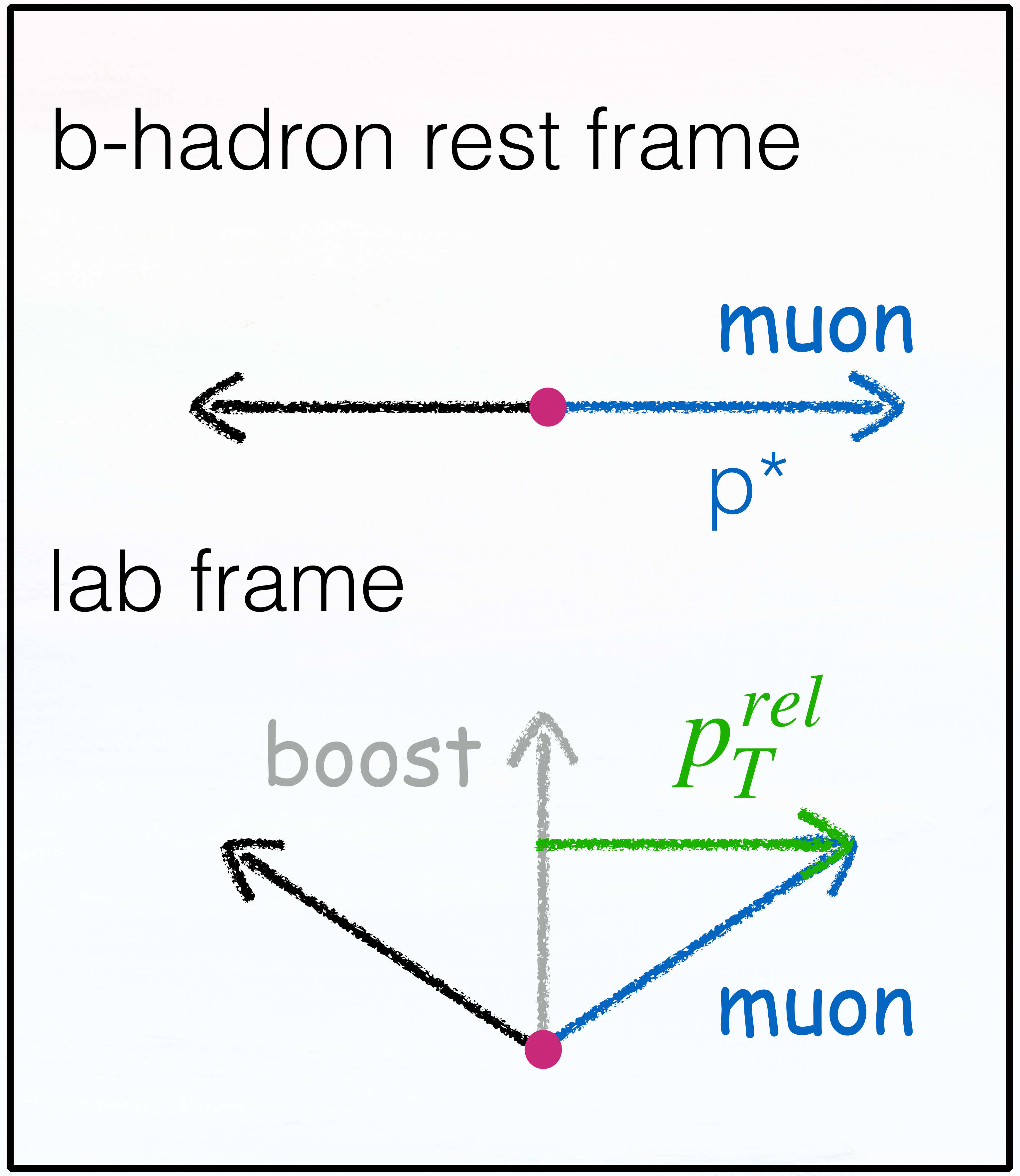
p_T^{rel}: b-hadrons have heavier masses



p_T^{rel} Calibration: Discriminant Variable

- Muons from direct bottom decays have harder p_T in the rest frame of b-hadron (p*) than that from charm or cascade bottom decays





Consider a massless two-day decay:

$$(P, \overrightarrow{P}) + (P, \overrightarrow{P}) = M_{b/c}$$

$$P = \frac{1}{2} M_{b/c}$$

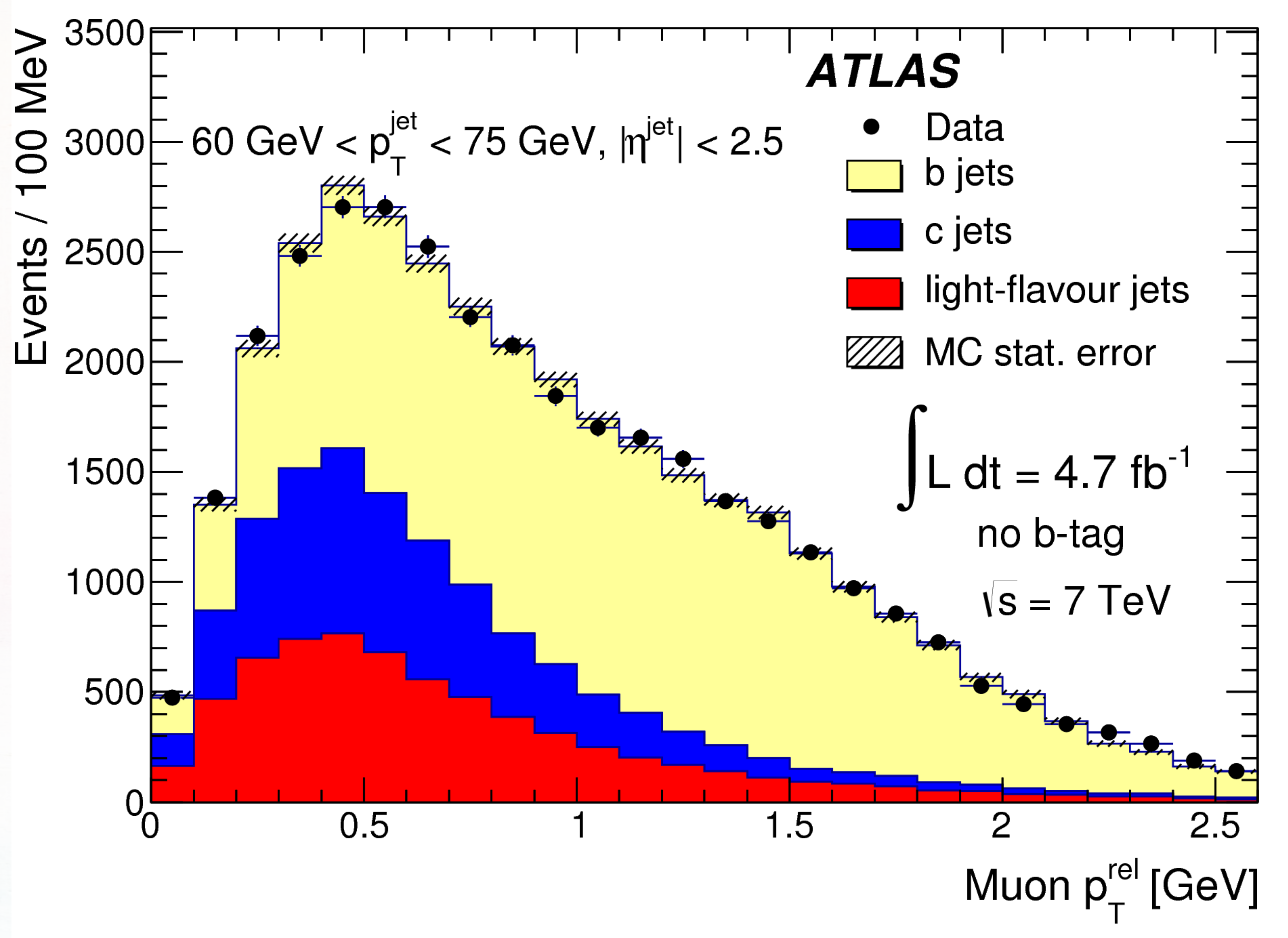
p_T^{rel} Calibration: Method

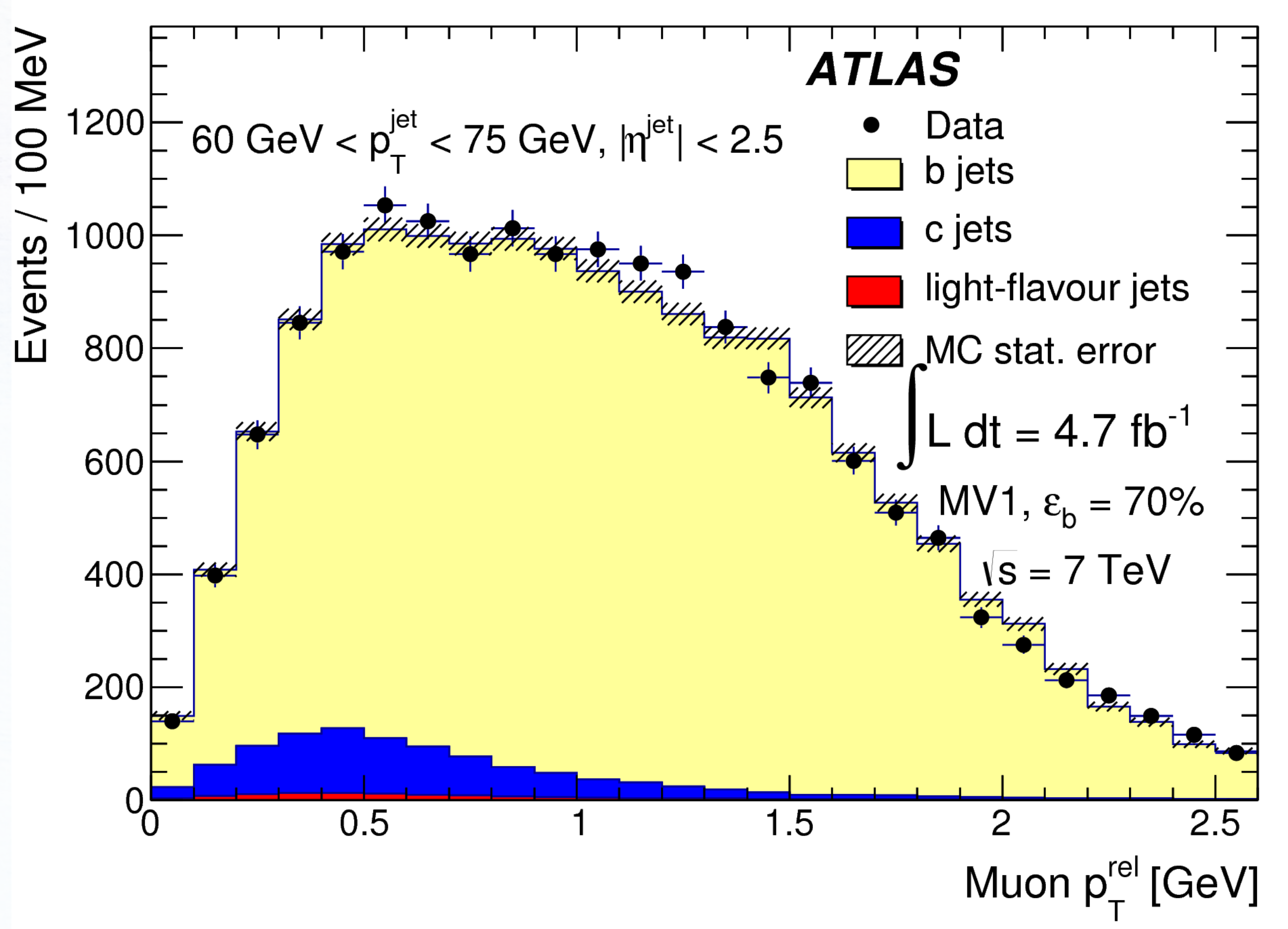
2016 JINST 11 P04008

- Calibration strategy:
  - Define a discriminating variable — p_T^{rel}
  - Produce p_T^{rel} templates for jets with different flavors, bottom (b), charm (c) and light (l)
  - Apply the b-enhanced selections in data
  - Perform a template fit to tagged data and un-tagged data to obtain the fraction of b's

$$\varepsilon_b^{data} = \frac{f_b^{tagged} N_{data}^{tagged}}{f_b^{tagged} N_{data}^{tagged} + f_b^{untagged} N_{data}^{untagged}}$$

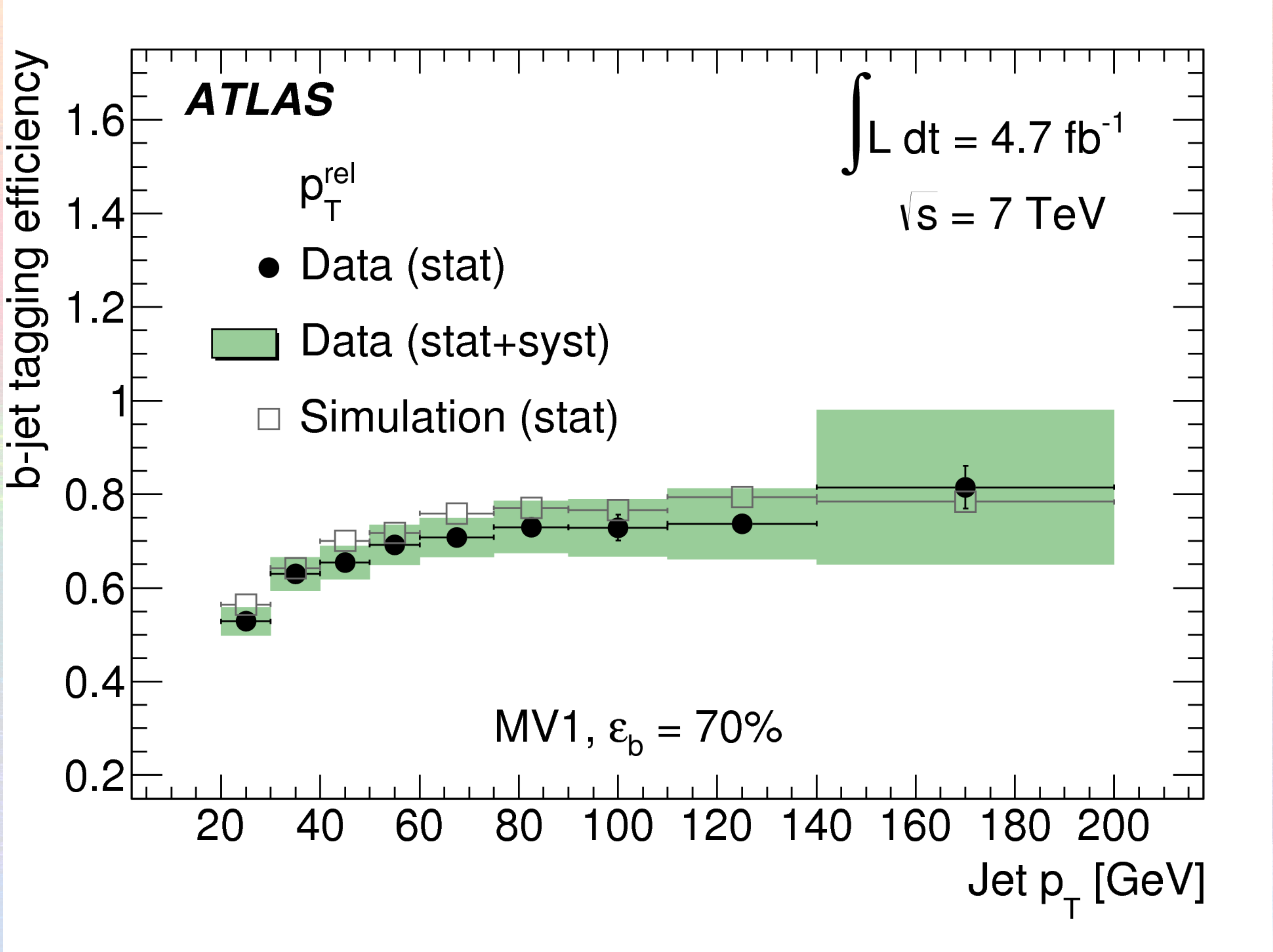
  - Extract the b-tagging efficiency using number of events and the fractions
  - Compare the efficiencies measured in data with the those in MC to derive corrections



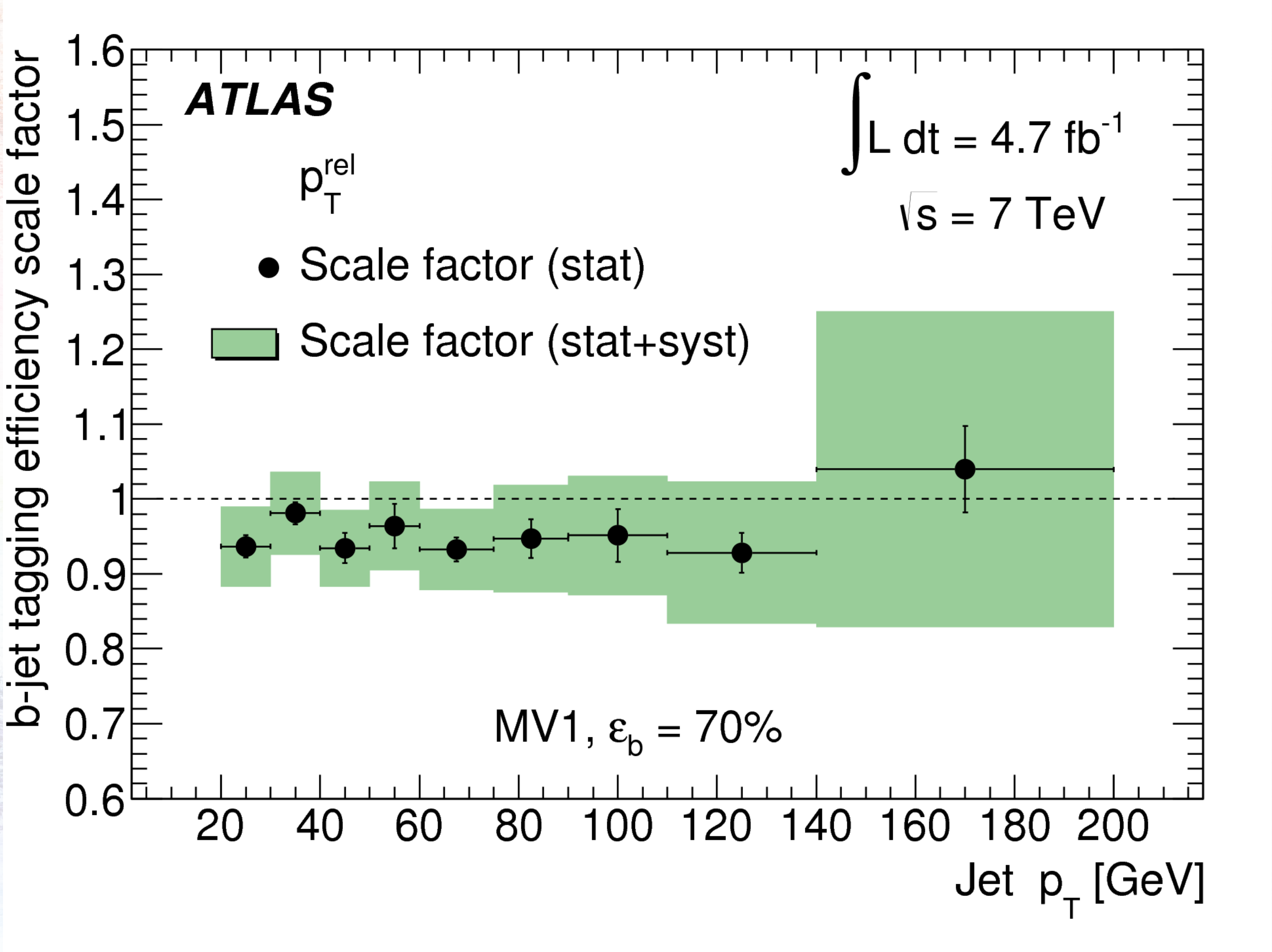


p_T^{rel} Calibration: Results

2016 JINST 11 P04008



Efficiencies



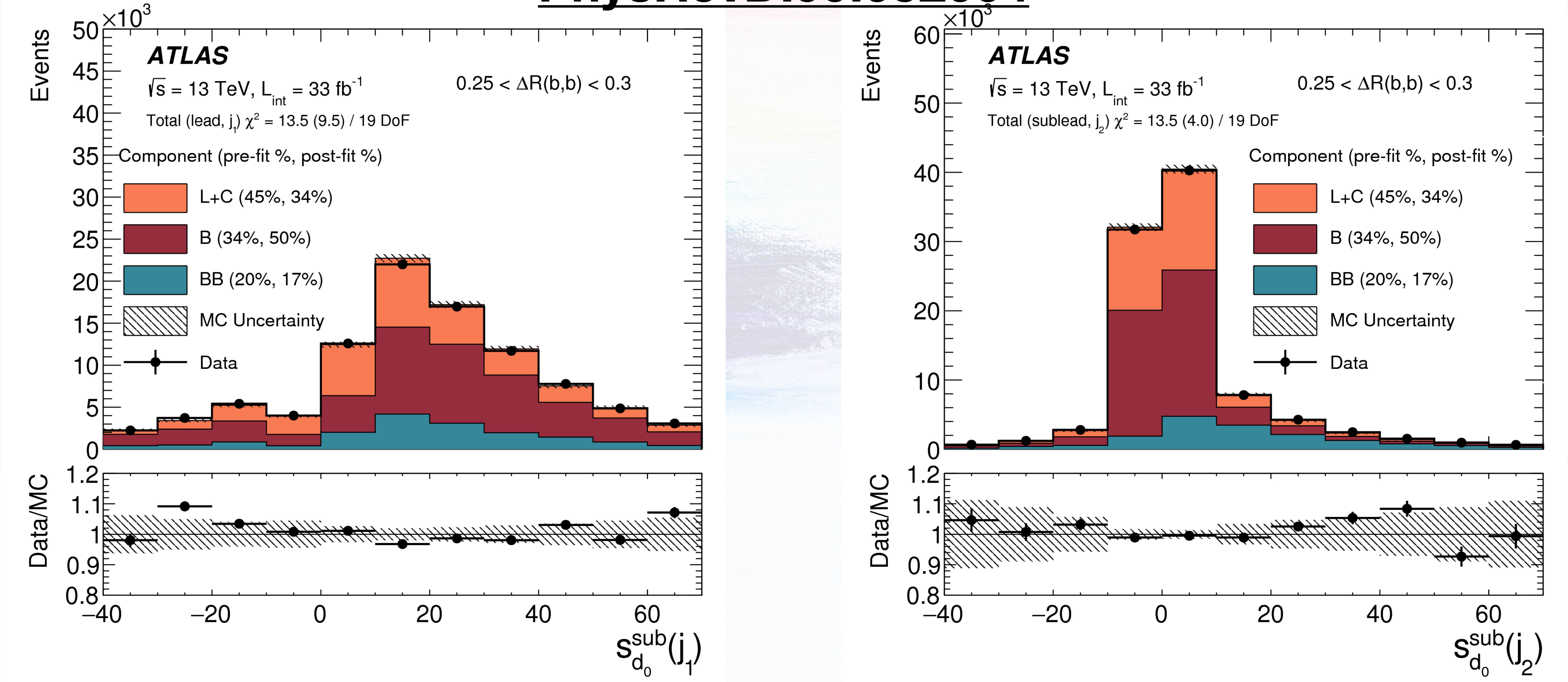
Scale Factors

- Full Run2 calibration is going with much improved strategies
  - Better precision is expected

High p_T Calibration: Discriminant Variable

- Similar strategy as the p_T^{rel} calibration
  - No public results are available yet. Show example distributions from $g \rightarrow bb$ measurement

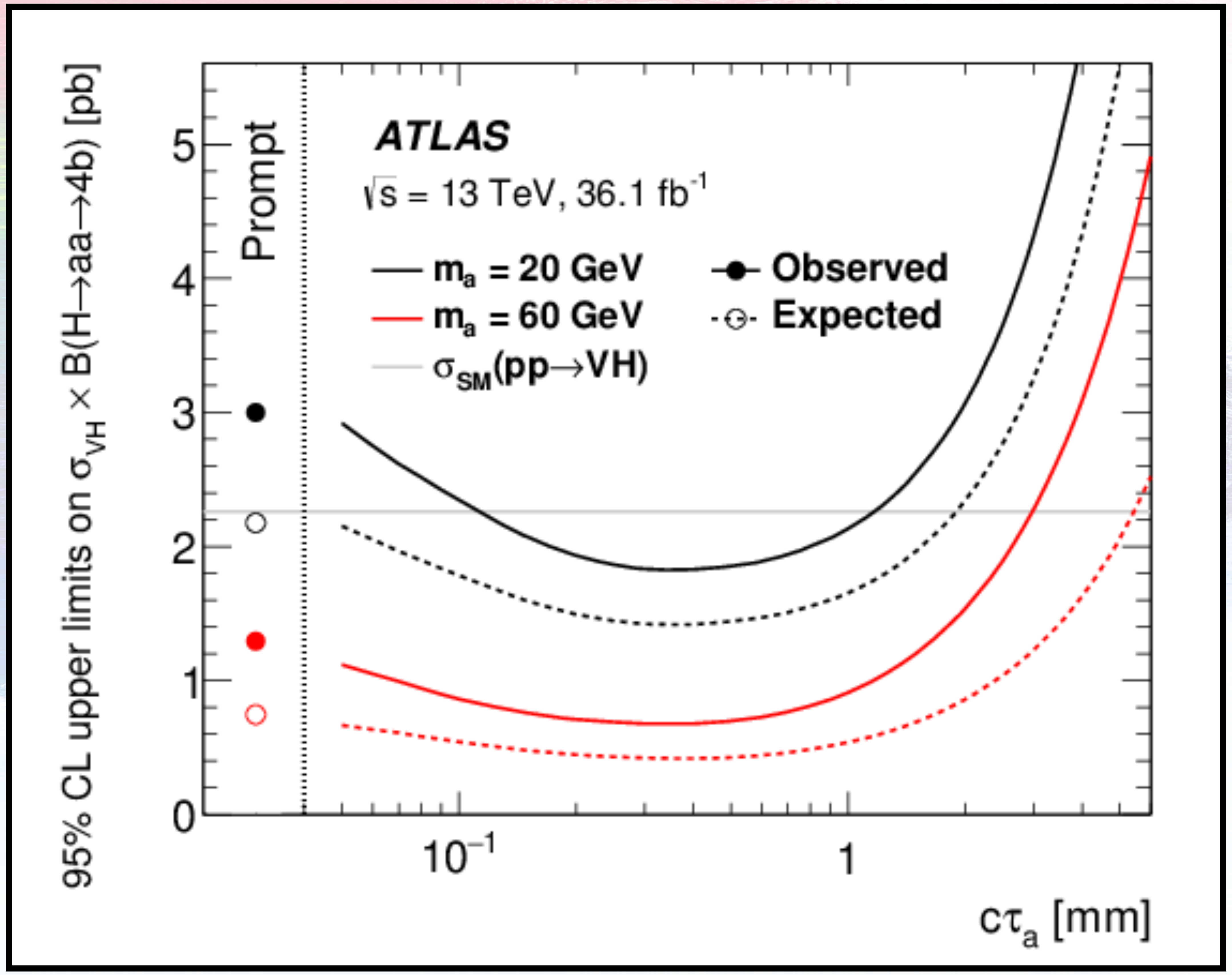
PhysRevD.99.052004



Even Longer Lifetimes…

B-tagging and LLP Tagging

- Long-lived particles can have lifetimes similar as b-hadrons
  - Can be b-tagged
  - Standard searches with b-tagging have sensitivities to such LLPs



- We performed a re-interpretation of the $VH(H \rightarrow aa \rightarrow bbbb)$ search
- Without changing analysis strategy, the search is sensitive to $c\tau_a$ up to 1mm
- Very exciting to see the potential of dedicated taggers targeting intermediate lifetimes

Future of b-tagging

Low Level Taggers

- Explore new strategies to improve performance at high p_T
- Optimize the existing low taggers

High Level Taggers

- Proving ground for new Machine Learning techniques

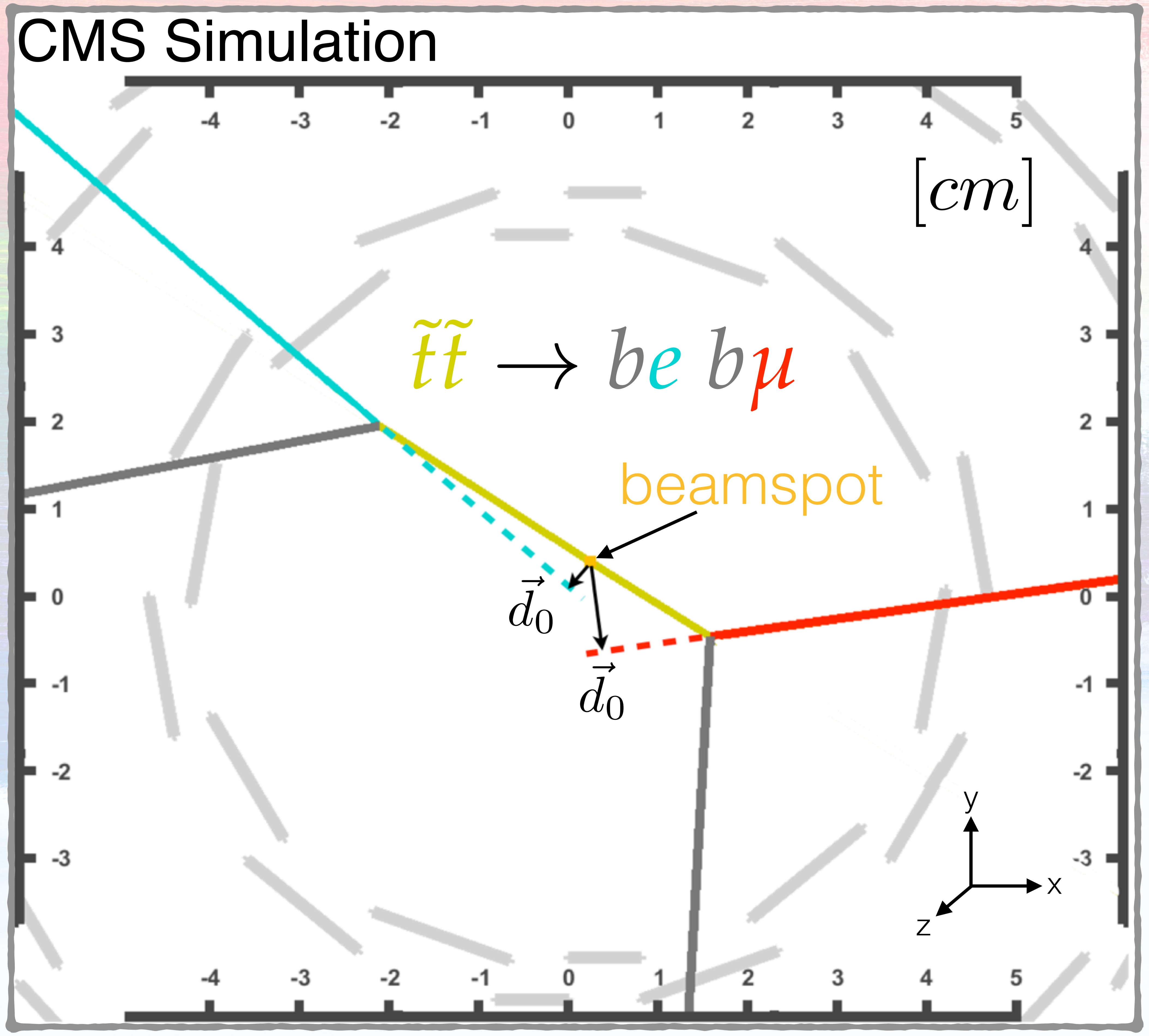
Training

- More efficient and unbiased training samples?
- Training for charm/strange tagging
- Training for LLP tagging?

A Flashback…Displaced
Lepton In CMS

Displaced Lepton Search

- R-parity Violating Supersymmetry can yield leptons with large impact parameters

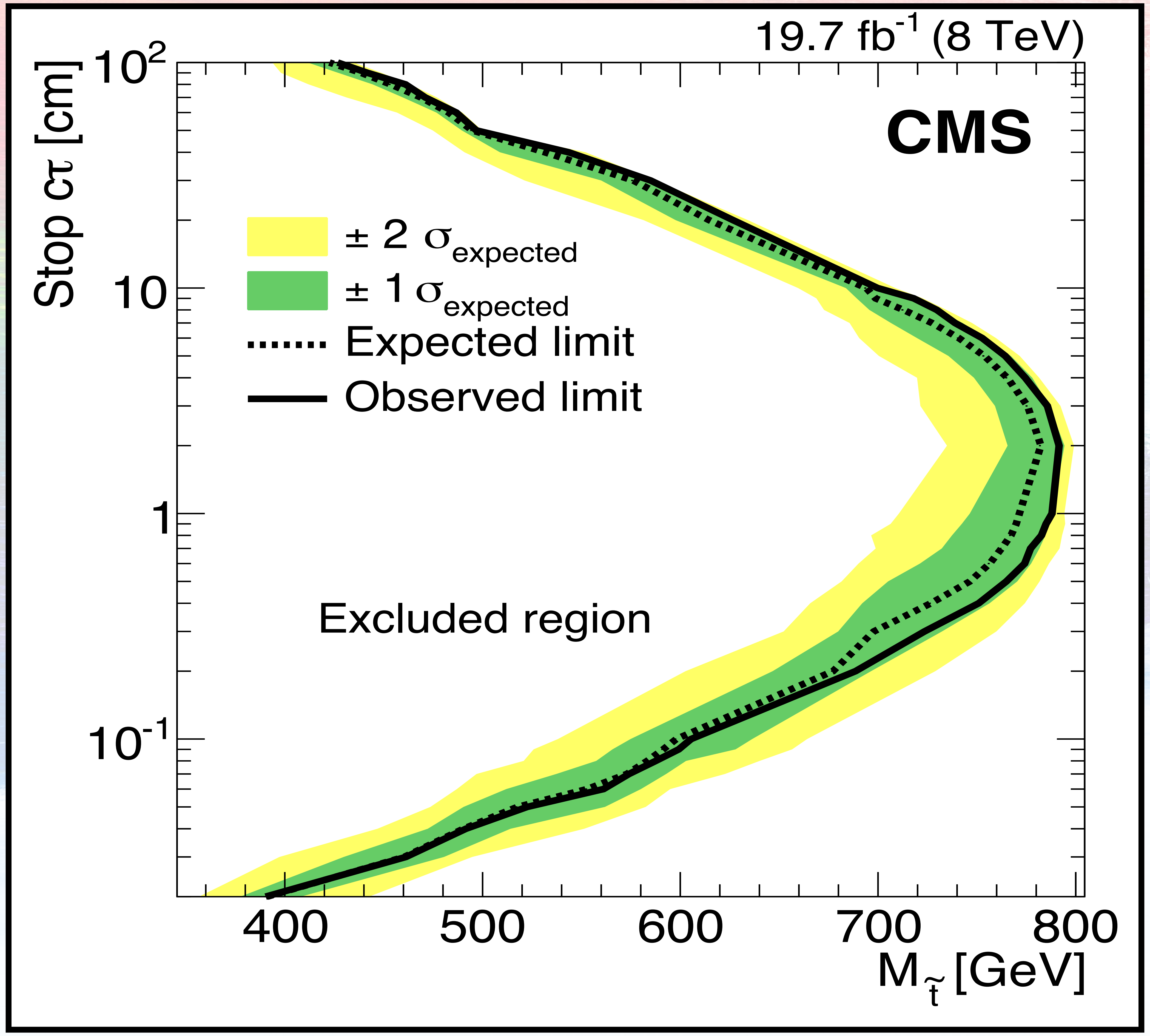


- A search was done by simply requiring a displaced e - μ lepton pair
  - Large impact parameter d_0
- Main backgrounds come from heavy flavor multi-jet and events $Z \to \tau\bar{\tau}$
- Estimate multi-jet via a data-driven method and the rest in simulation

Displaced Lepton Search

PhysRevLett.114.061801

- R-parity Violating Supersymmetry can yield leptons with large impact parameters

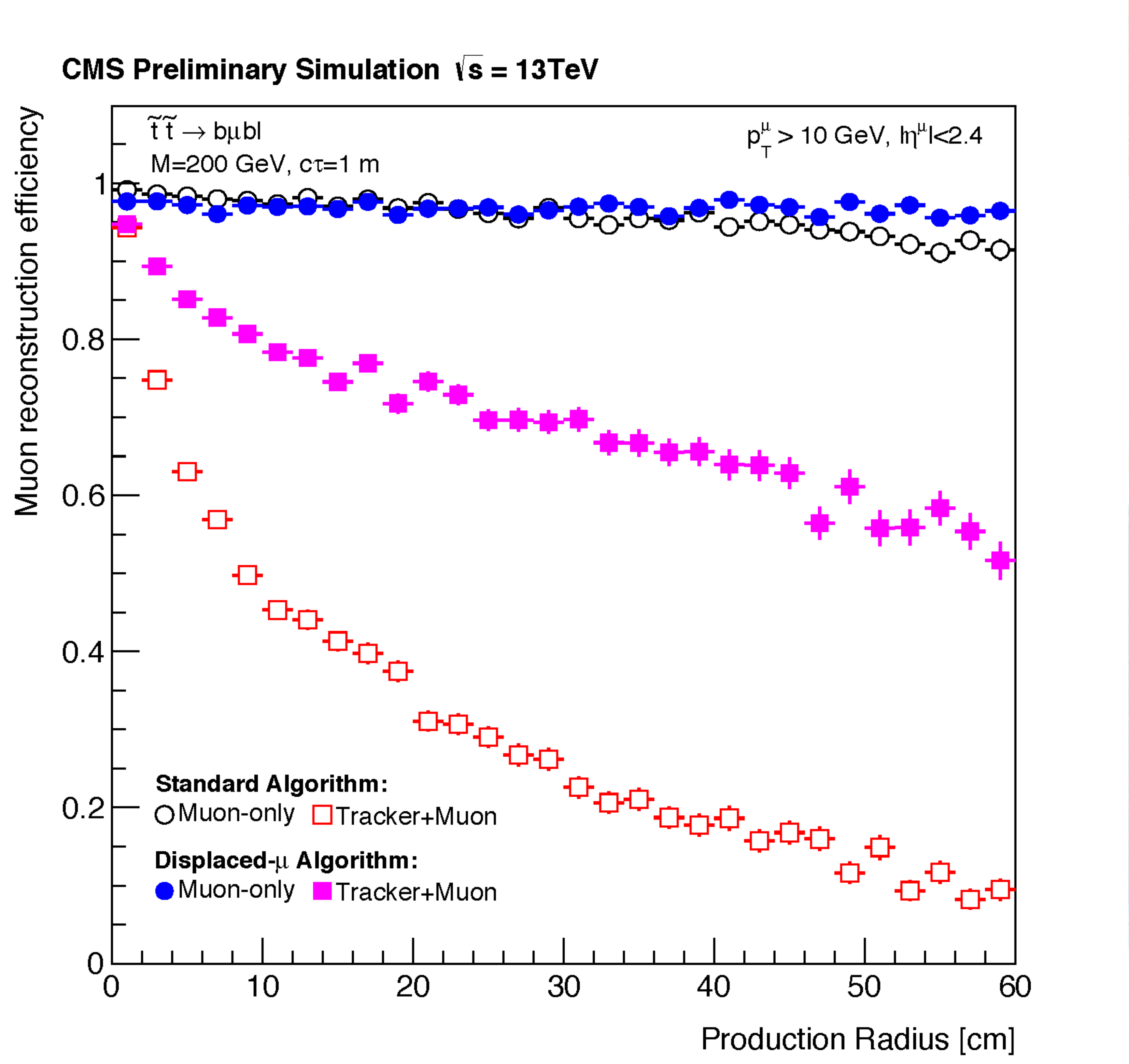


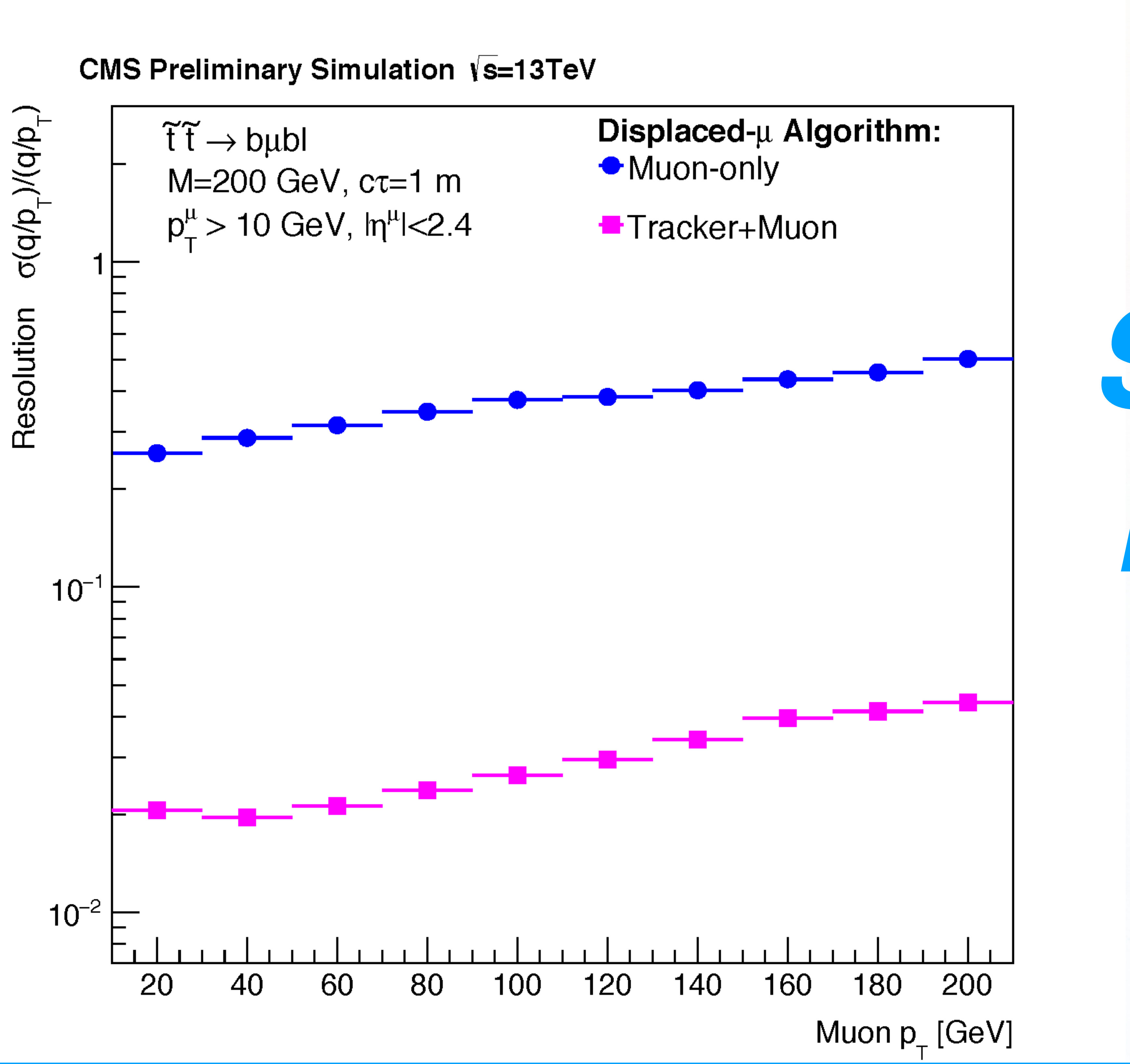
- Applying standard algorithms with the analysis strategies optimized for long-lived signatures, top squark mass up to 790 GeV with $c\tau$ of 2 cm is excluded.
- However it was found sensitivities to longer lifetimes were constrained by standard algorithms

Displaced Muon Reconstruction

CMS-DP-2015-015

- During LS1 I developed a set of new algorithms for displaced muons





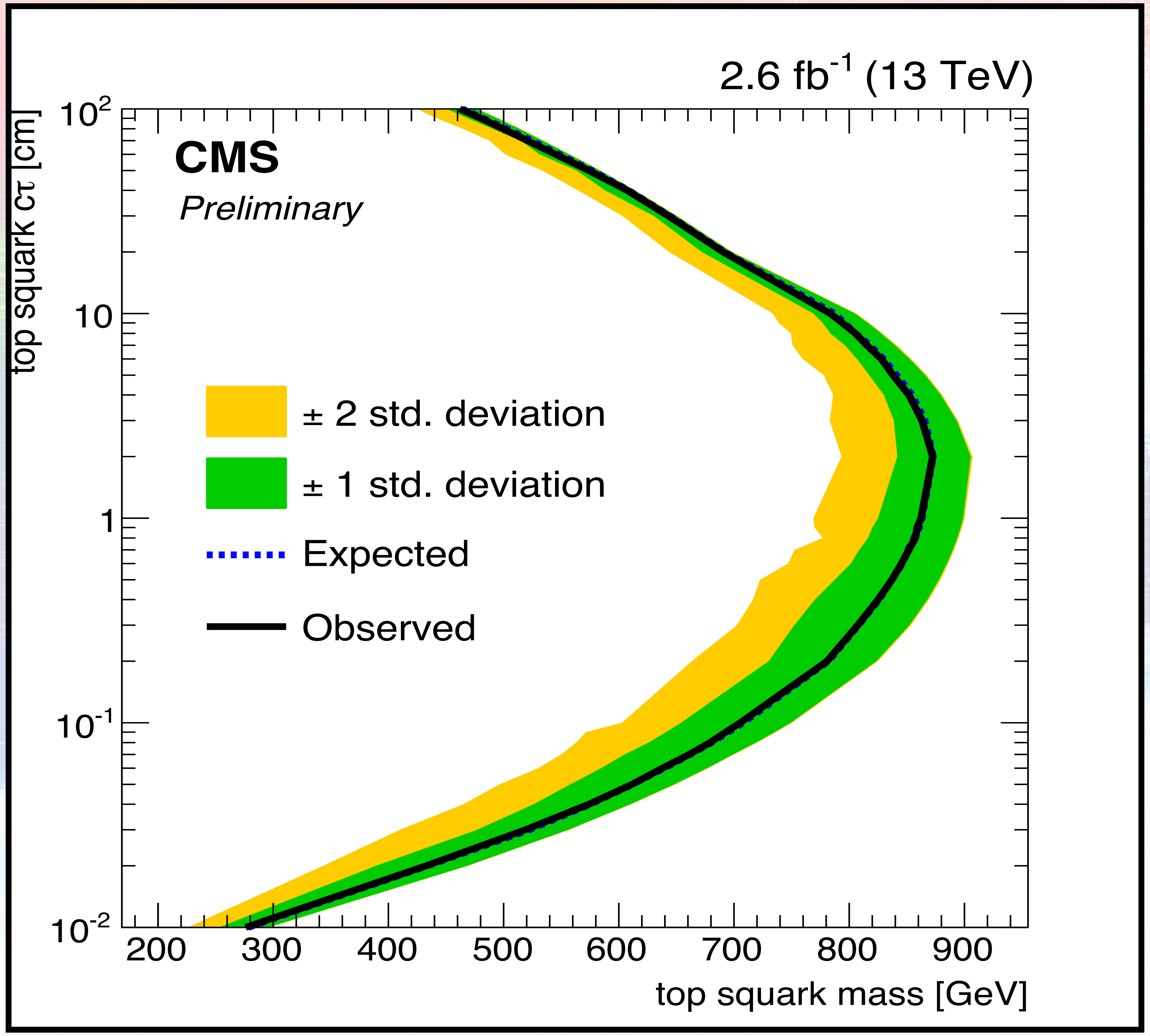
Still the best fo far!

- The special algorithms (Displaced Muon-only and Displaced Muon + Tracker) have much better performance at large production radius compared with standard ones (Muon-only and Track + Muon)

Displaced Lepton Search

CMS-PAS-EXO-16-022

- Applying some of the improvements, I performed the first displaced lepton search in CMS using 13 TeV data

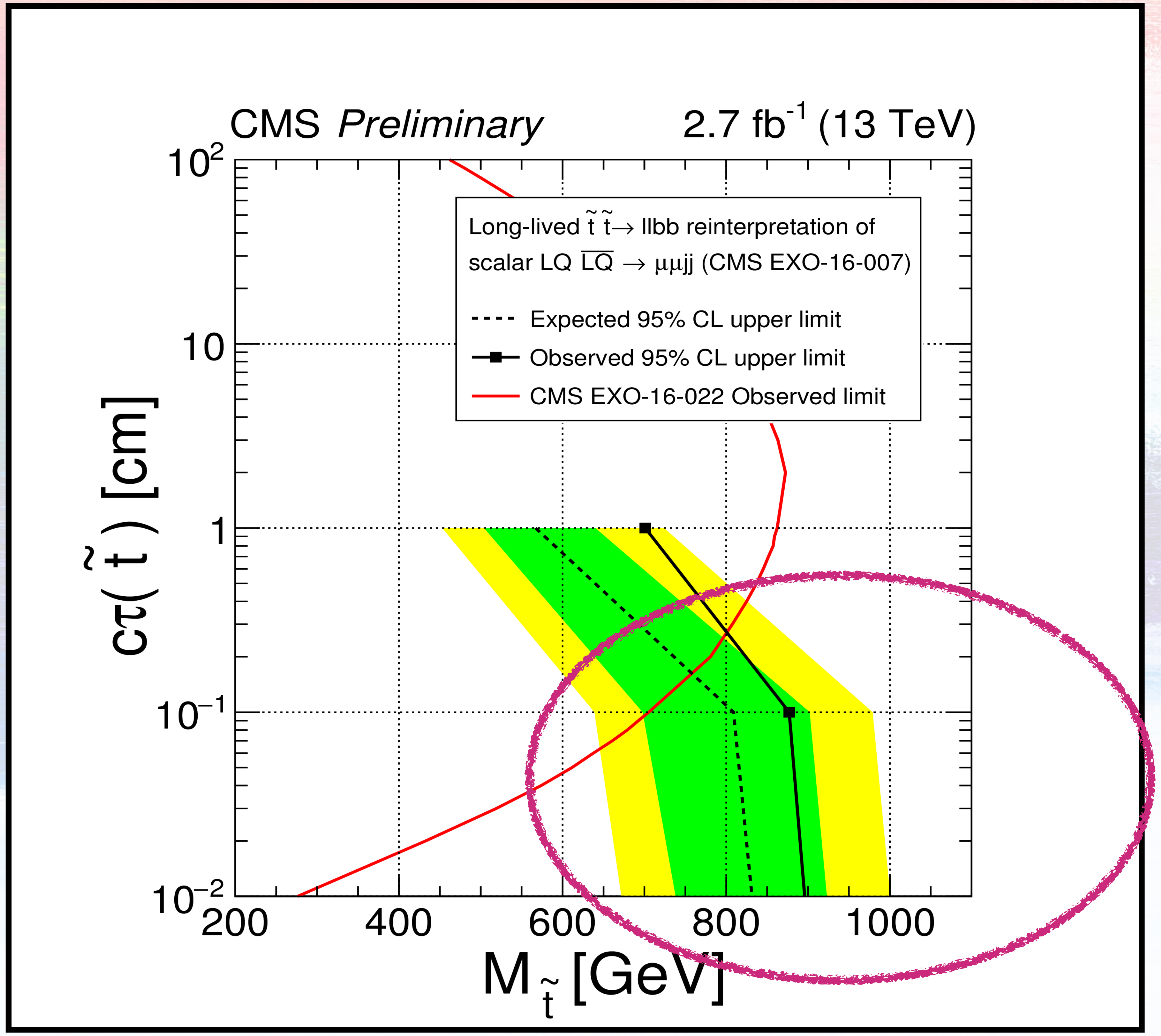


- Top squark mass up to 870 GeV with $c\tau$ of 2 cm is excluded with 2015 data
- **My thesis!**
- Full Run2 results should be on its way

Displaced Lepton Reinterpretation

CMS-PAS-EXO-16-007

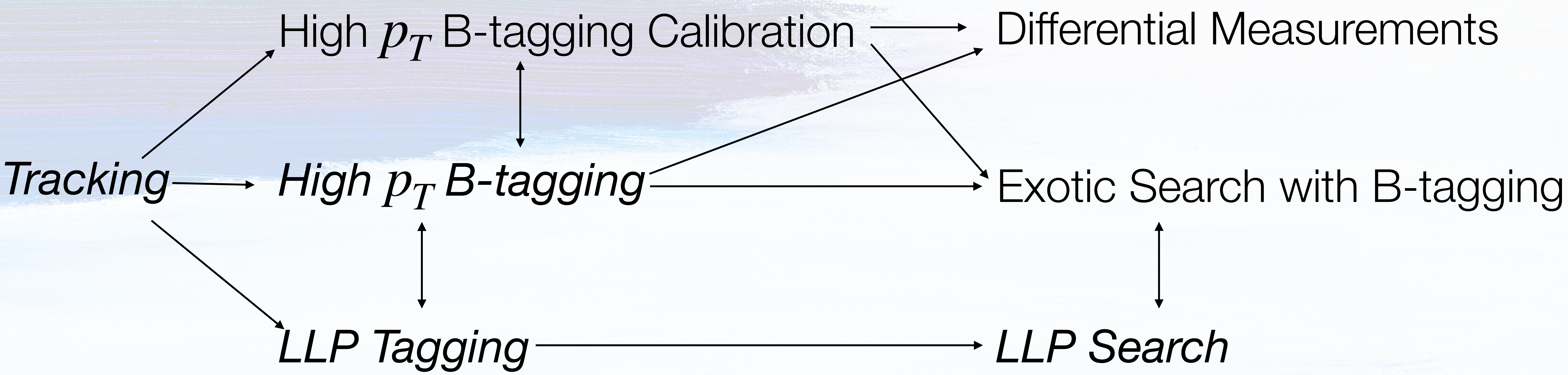
- A similar re-interpretation work was done



- A search for $L\bar{Q} \rightarrow \mu\mu jj$ suing standard techniques can probe shorter lifetimes
- Again it demonstrates the power standard algorithms
- It also shows us where the gap is

Summary and Outlook

- We have seen that traditional methods such as b-tagging and lepton reconstruction are already sensitive to certain long-lived signatures
- The corner of the parameter space for traditional algorithms is already very long-lived (or in general “Exotics”) like
- CP work is crucial and a very comprehensive program can be built during LS2, making us better suited for Run3!



Thank You!