Search for Z’ production in 4 b-tagged jet final states in proton-proton collisions

Andrea Delgado

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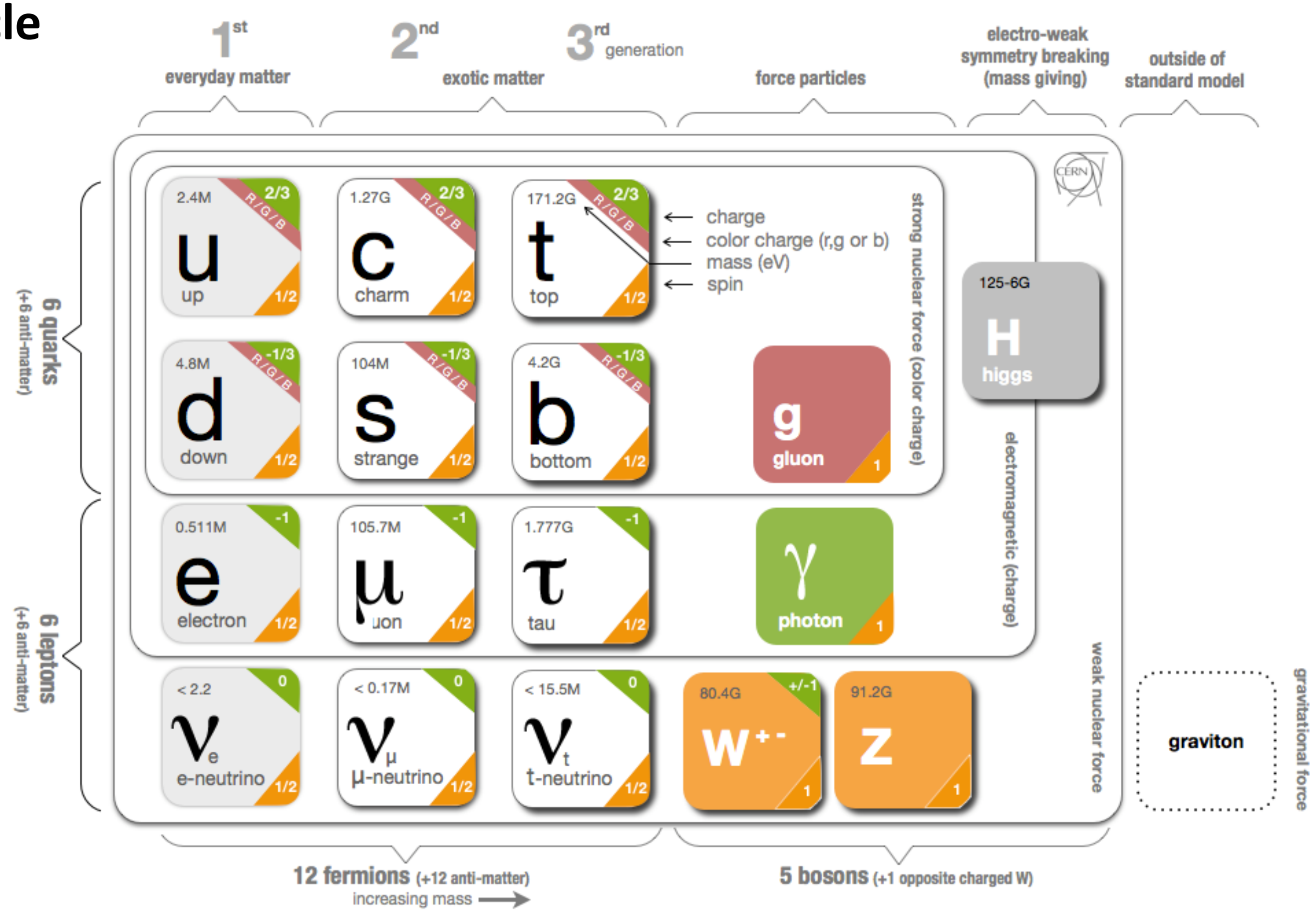
- Introduction - Standard Model Overview
- Search for Z' production
- Analysis Strategy Overview
- Experimental Tools
    - LHC and CMS
- Jets
    - B-tagging
- Event Selection and Methodology
- MC Corrections
- Trigger
- Systematic Uncertanties

The Standard Model

The best theoretical framework we have for particle physics today!

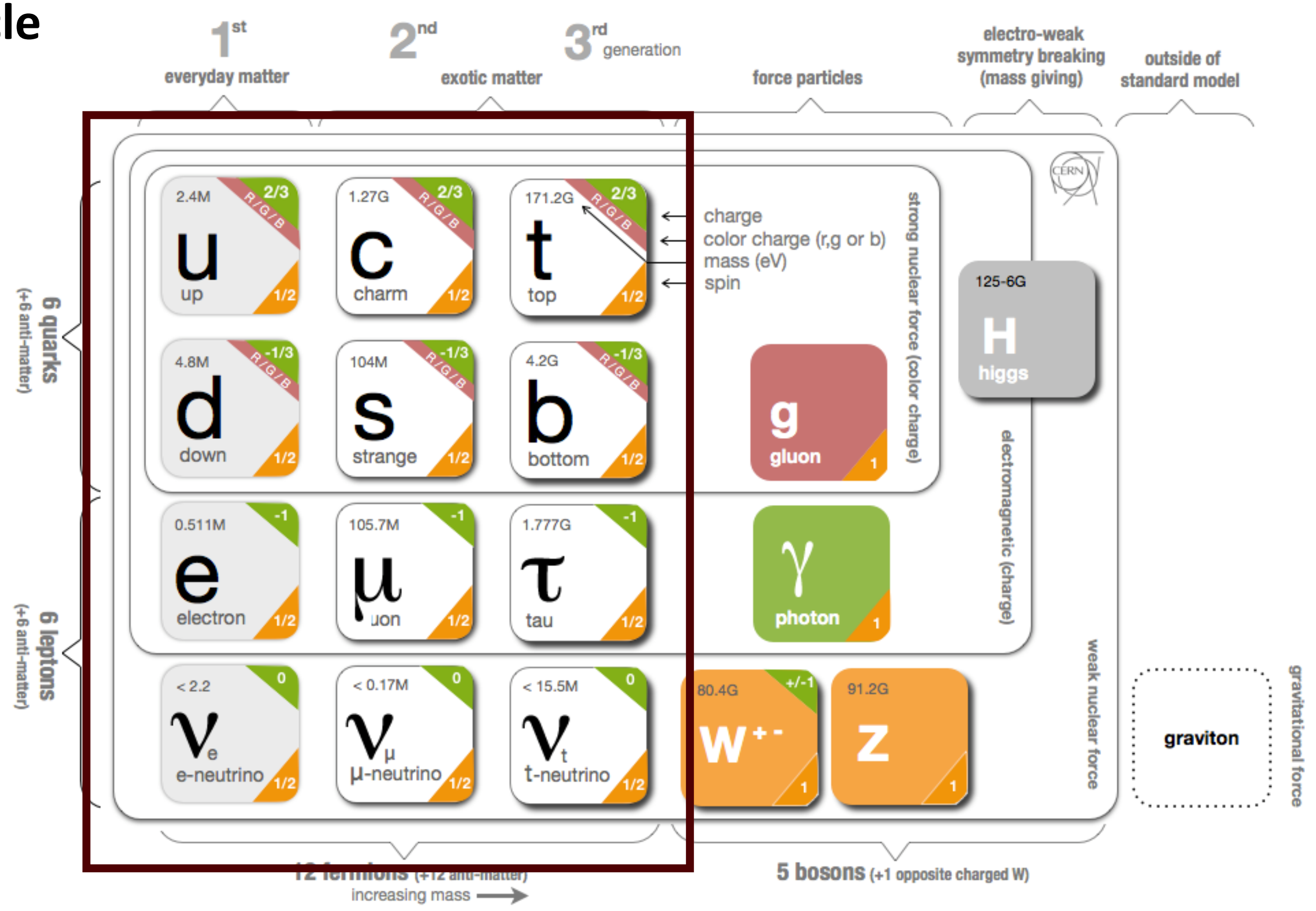


The Standard Model

The best theoretical framework we have for particle physics today!

A description of the interaction between fundamental particles (**fermions**)

- Spin ½
- Further divided into quarks and leptons
- Make up everyday matter
- Grouped into families according to their mass



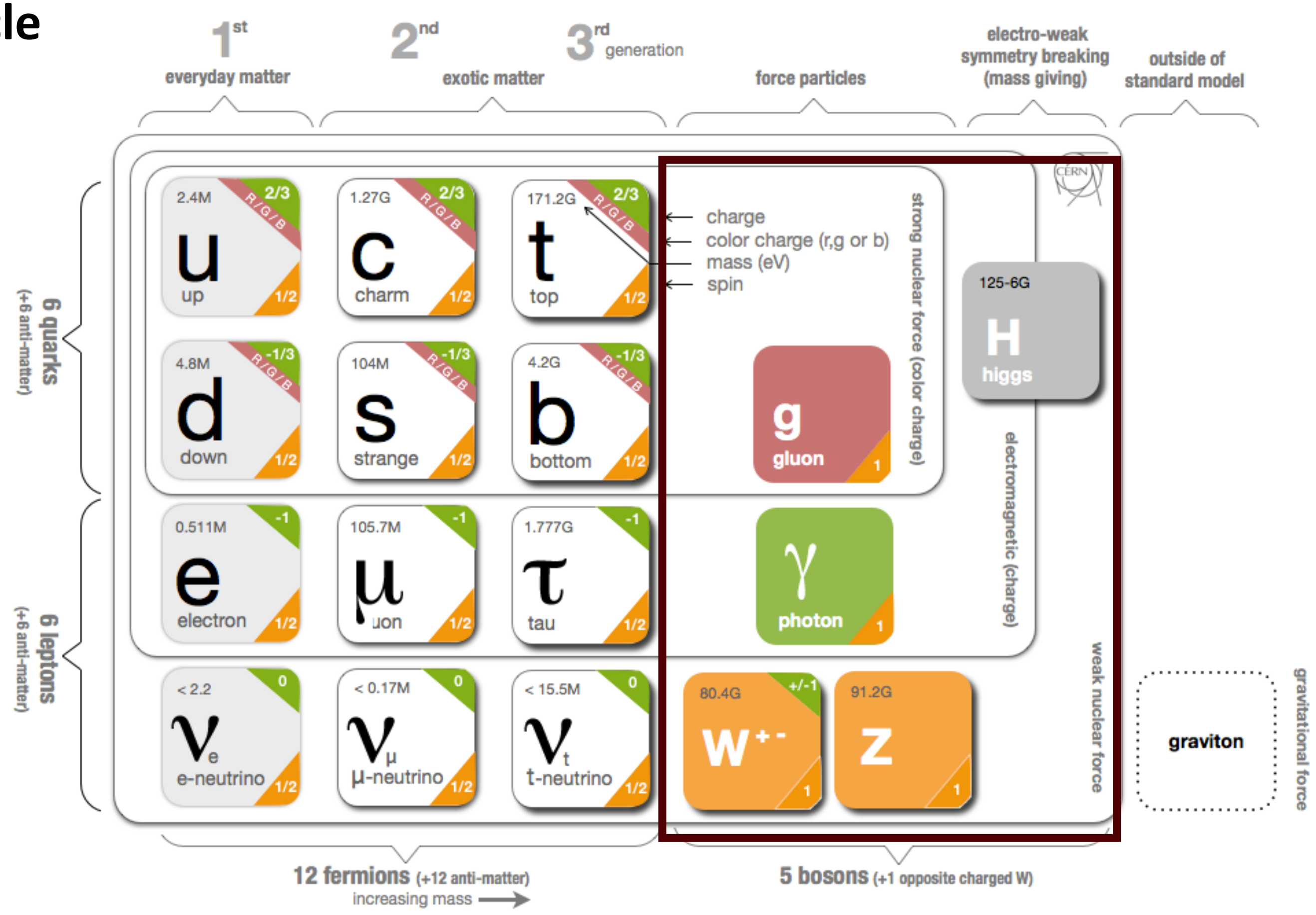
The Standard Model

The best theoretical framework we have for particle physics today!

A description of the interaction between fundamental particles (**fermions**)

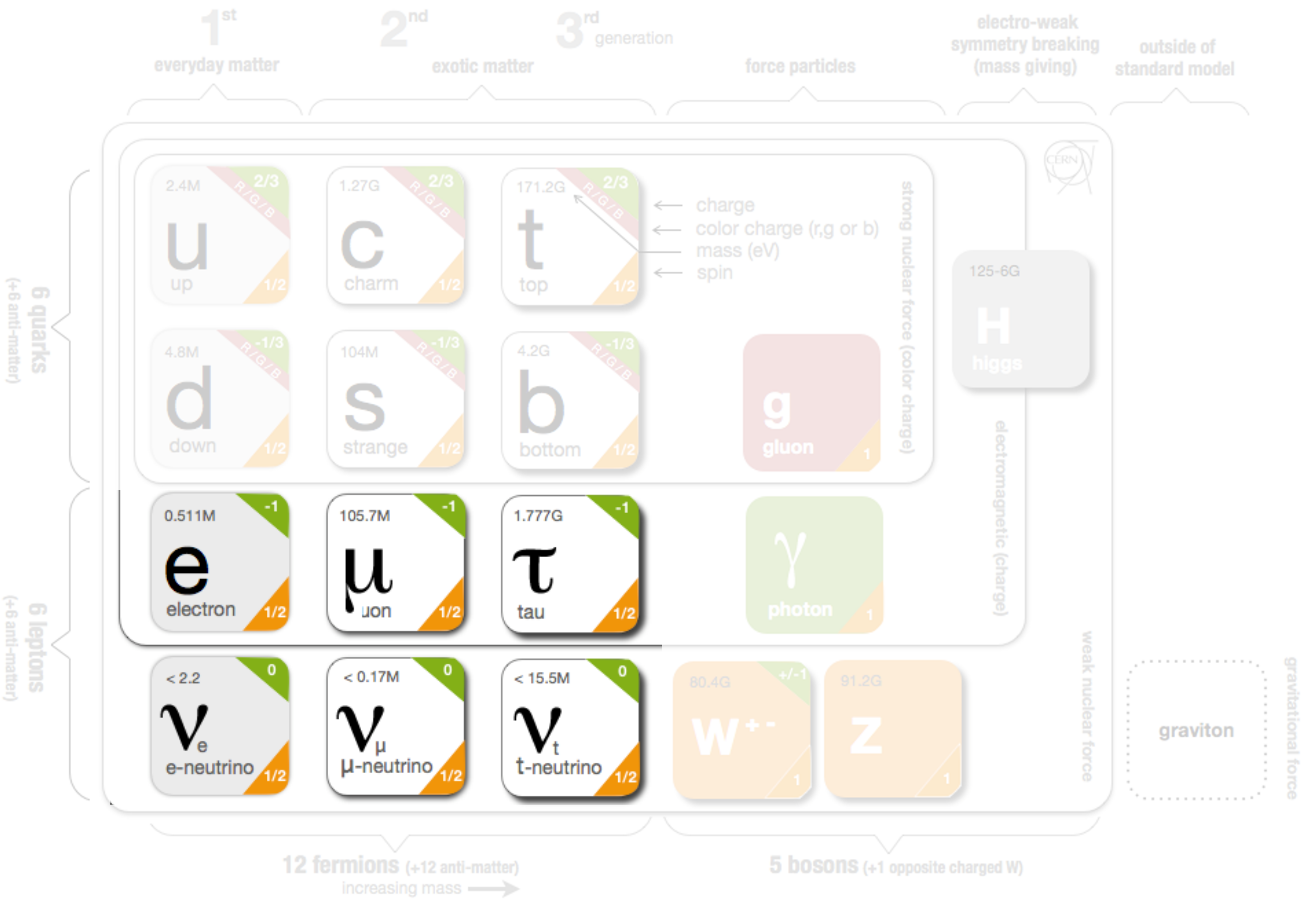
mediated by integer-spin particles (**bosons**)

- Gauge(spin-1) bosons act as 'force carriers' *gluon, photon, W/Z*
- Spin-0 – mass giving boson *Higgs*



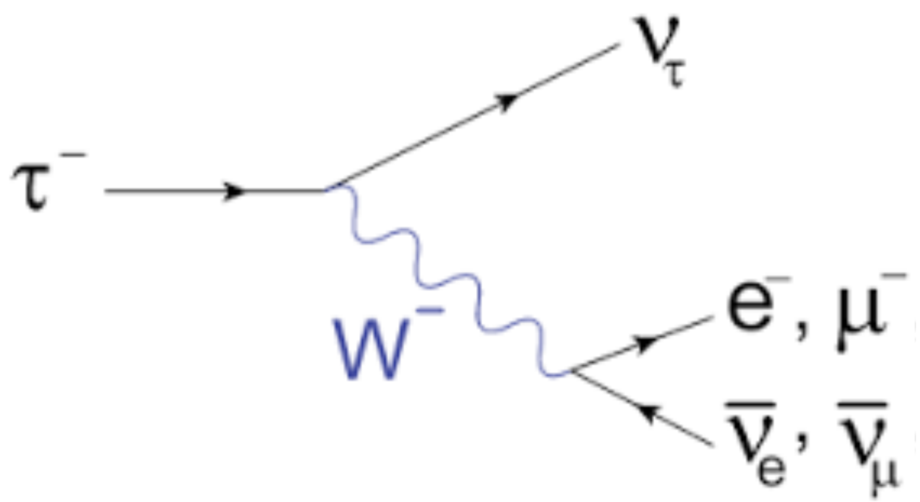
The Standard Model
Lepton Universality

- Experimental data are consistent with **lepton universality** assumptions.
  - Muon/tau/electron interactions are identical in the weak sector.



Lepton Universality

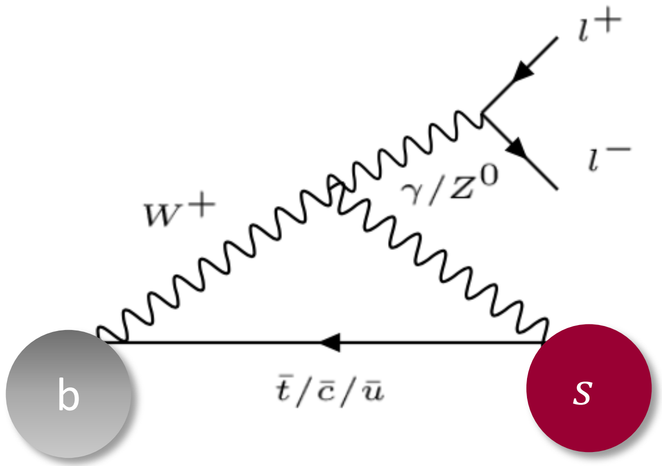
- Experimental data are consistent with **lepton universality** assumptions.
  - Muon/tau/electron interactions are ***identical*** in the weak sector.
- Full theoretical calculation of the ratio of the BR of the muon and electron decay modes yields a value 0f **0.973**.
- Current experimental value is **0.976 $\pm$0.003**. *(According to current PDG values.)*

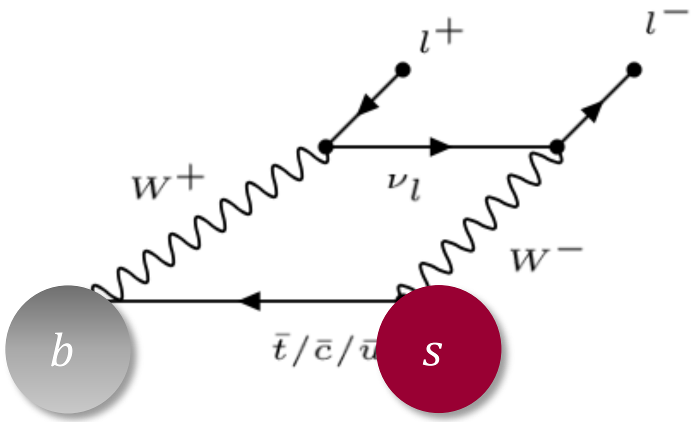


SM Expectation:

$$\Gamma(\tau^- \to e^- + \overline{\upsilon_e} + \upsilon_\tau) = \Gamma(\tau^- \to \mu^- + \overline{\upsilon_\mu} + \upsilon_\tau)$$

A Test To Lepton Universality
Flavor-Changing Neutral Currents

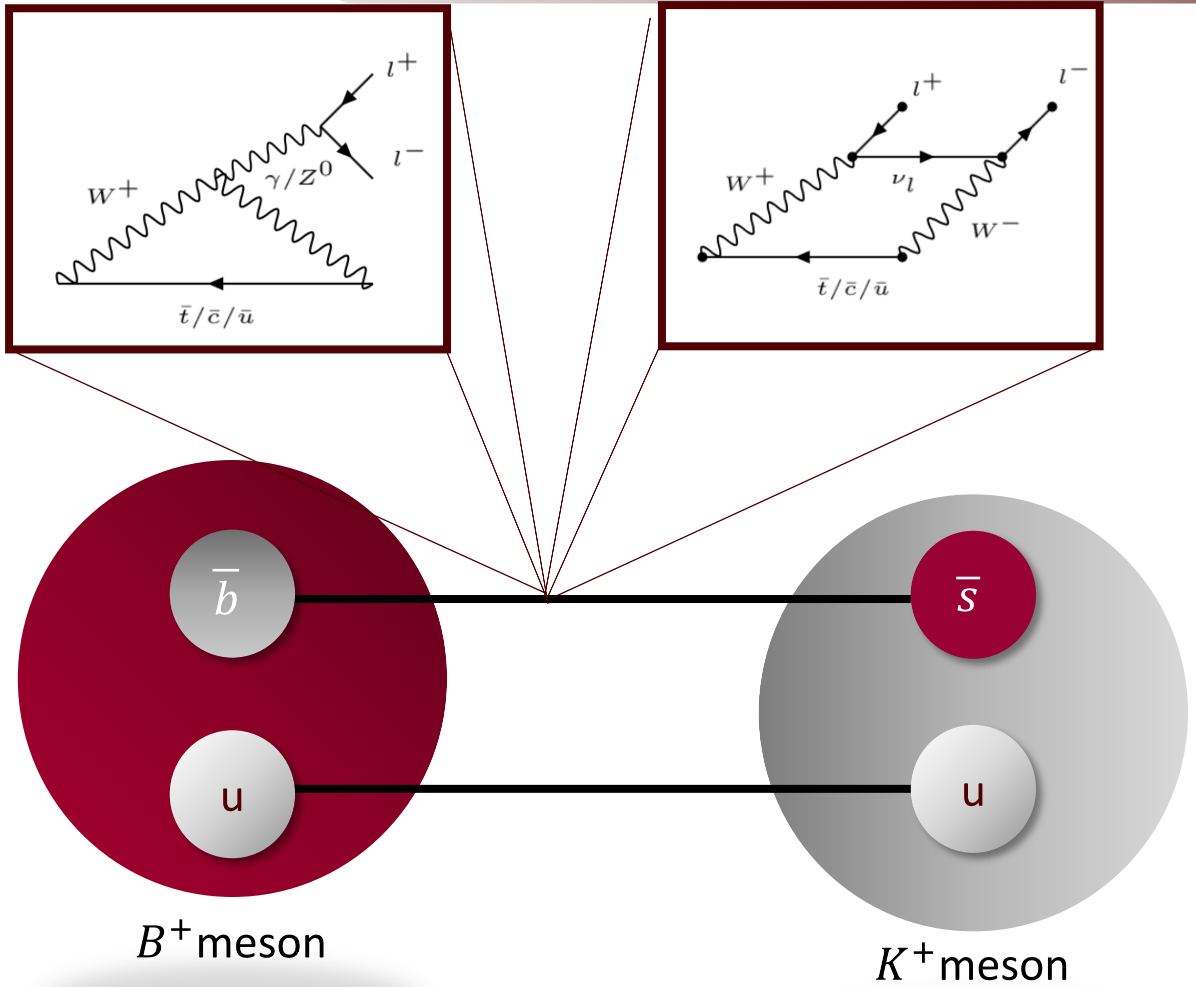




- ❑ $b \to sl^+l^-$ transitions are mediated by flavor-changing neutral currents.
- ❑ Very suppressed in the SM.
- ❑ Sensitive to new physics.

Recent results by the LHCb experiment hint that e^+e^- pair might be produced at a greater rate than $\mu^+\mu^-$ pairs in B-meson decays involving $b \to sl^+l^-$ transitions

B-hadron anomalies



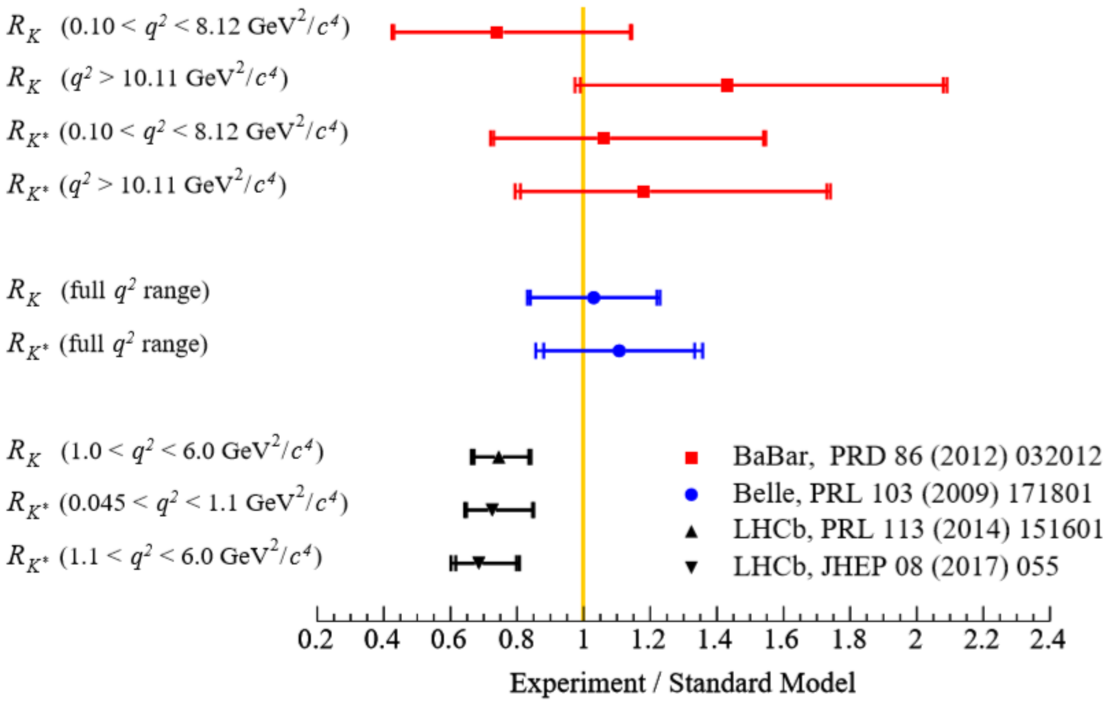
- B-mesons are sensitive to BSM physics due to rare decays such as $b \rightarrow sll$
- Hints to deviations from SM predictions in lepton flavor universality ratios such as

$$R_K = \frac{BR(B^+ \rightarrow K^+\mu^+\mu^-)}{BR(B^+ \rightarrow K^+e^+e^-)}$$

$$R_{K^*} = \frac{BR(B^+ \rightarrow K^*\mu^+\mu^-)}{BR(B^+ \rightarrow K^*e^+e^-)}$$

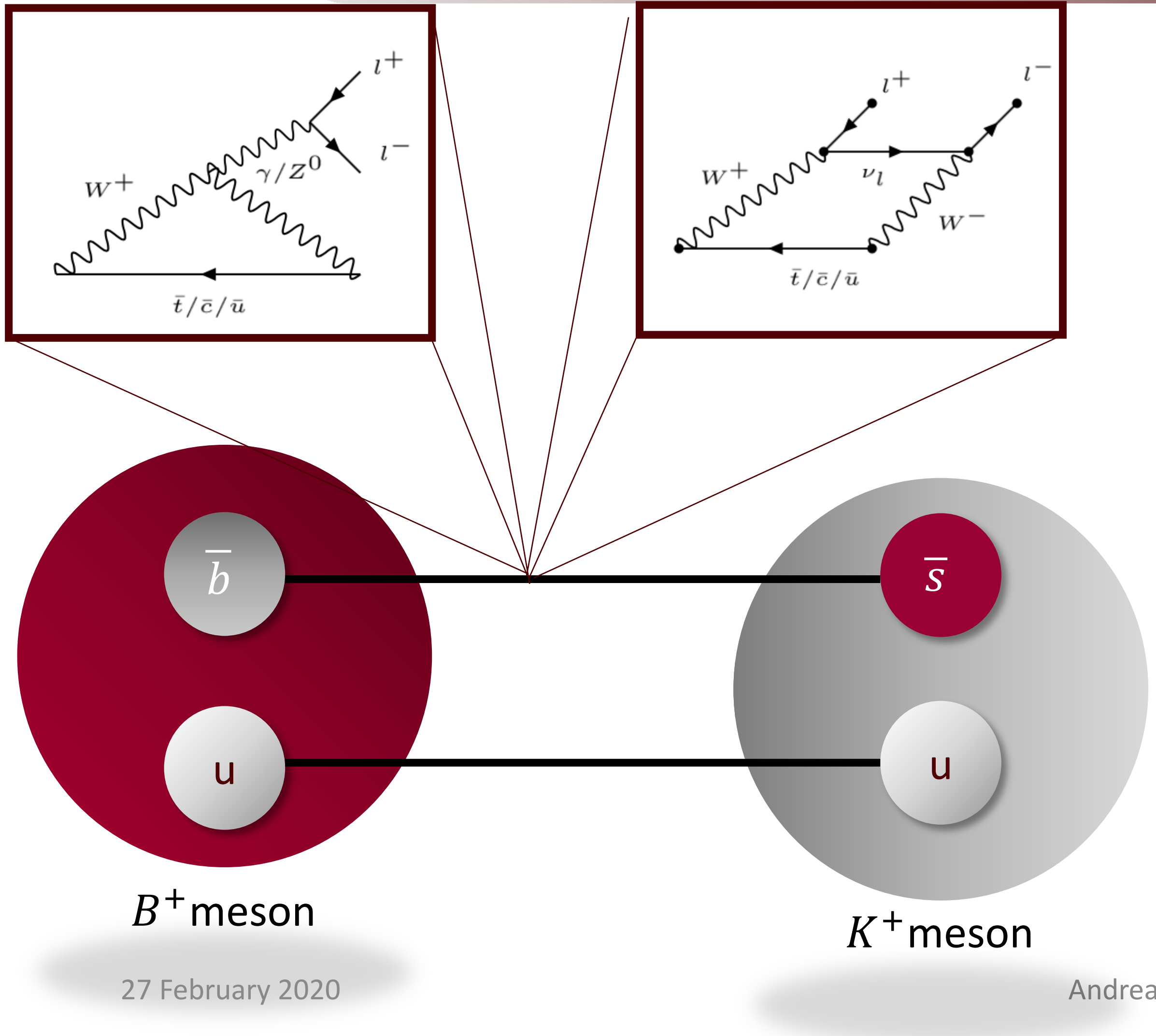
B-hadron anomalies

- Theoretical predictions in the SM for R_K and R_{K*} are extremely accurate!
- Measurements performed by the LHCb collaboration are found to be 2.6 and 2.1-2.5 lower than the SM expectation



Bifani, Descotes-Genon, Romero-Vidal, Schune. arXiv:1809.06229 (2019)

B-hadron anomalies
A Closer Look



B-hadron anomalies
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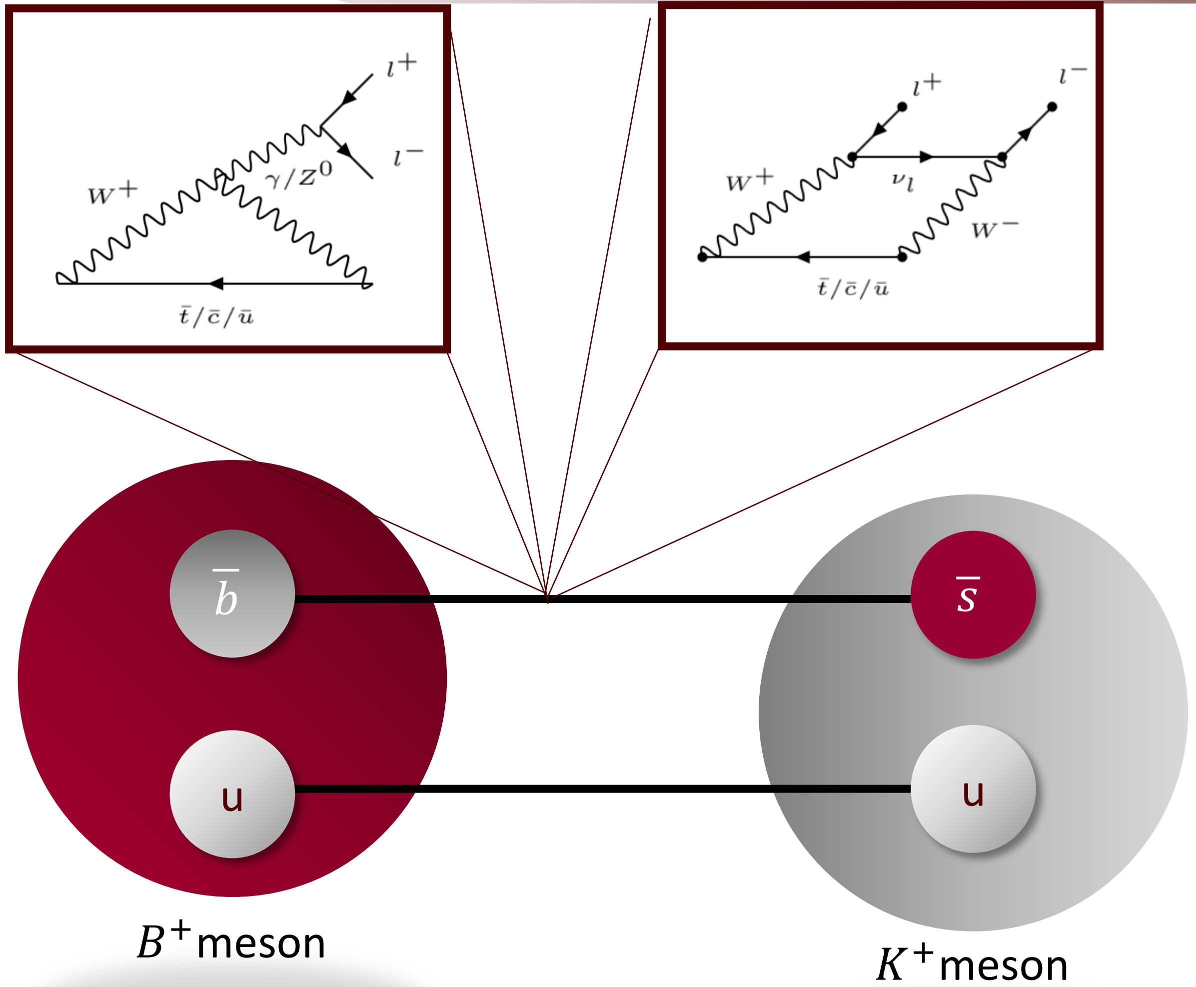
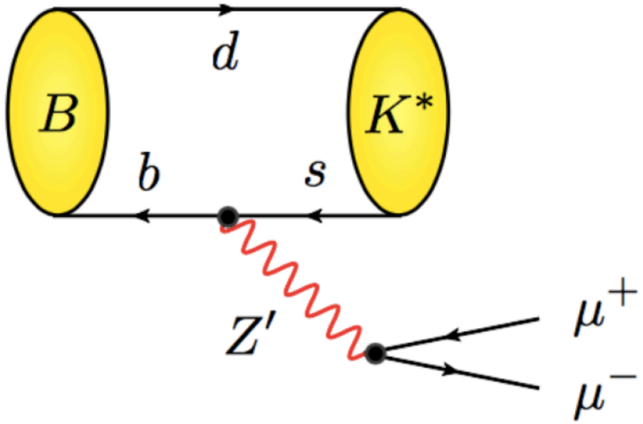


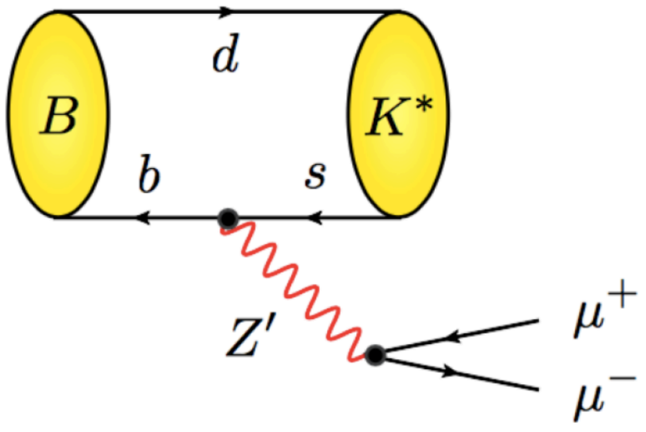
or



A new particle!

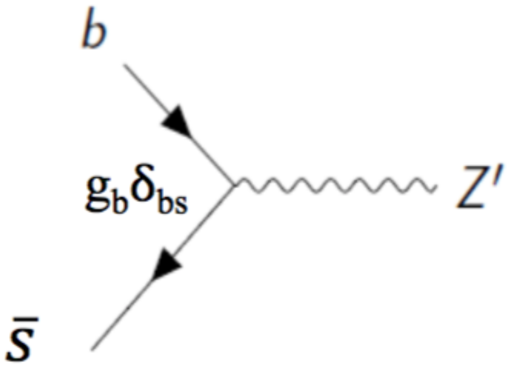
The Z'

- An extension to the SM could explain SM deviations in B-meson decays.
  - An extra U(1) gauge group resulting in a new gauge boson, the Z'.

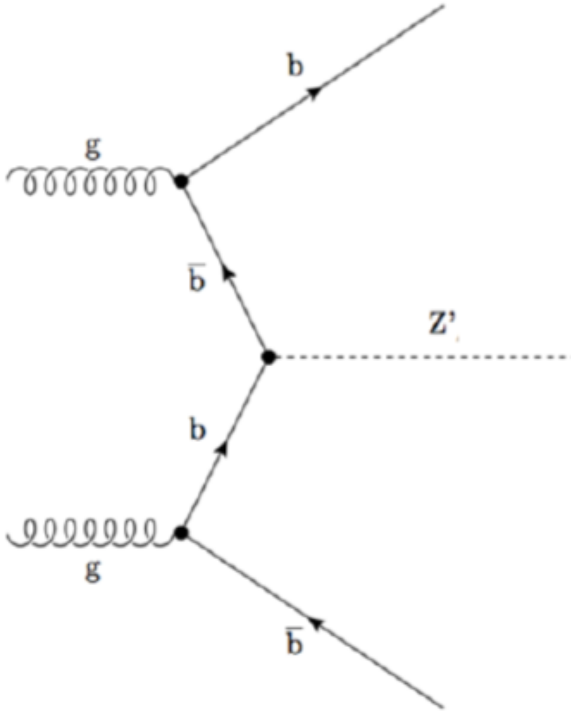


$$\mathcal{L} \supset Z'_{\mu}[g_{\mu}\bar{\mu}\gamma^{\mu}\mu + g_{\mu}\overline{\nu_{\mu}}\gamma^{\mu}P_L\nu_{\mu} + g_b\sum_{q=t,b}\bar{q}\,\gamma^{\mu}P_L q(g_b\delta_{bs}\bar{s}\gamma^{\mu}P_L b + h.c.)]$$

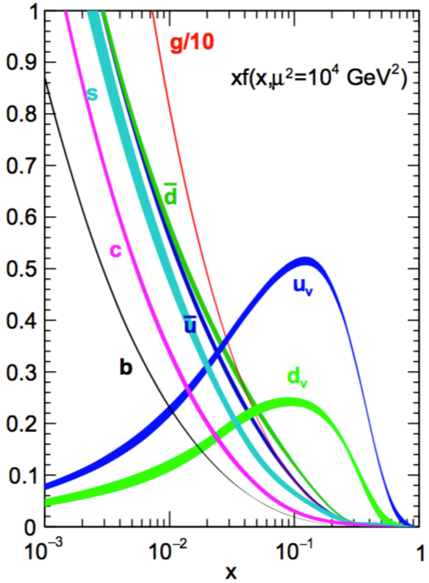
- Current constraints:
  - Heavier than SM Z.
  - Non-universal coupling to leptons.
  - Flavor-changing coupling δ_{bs}.



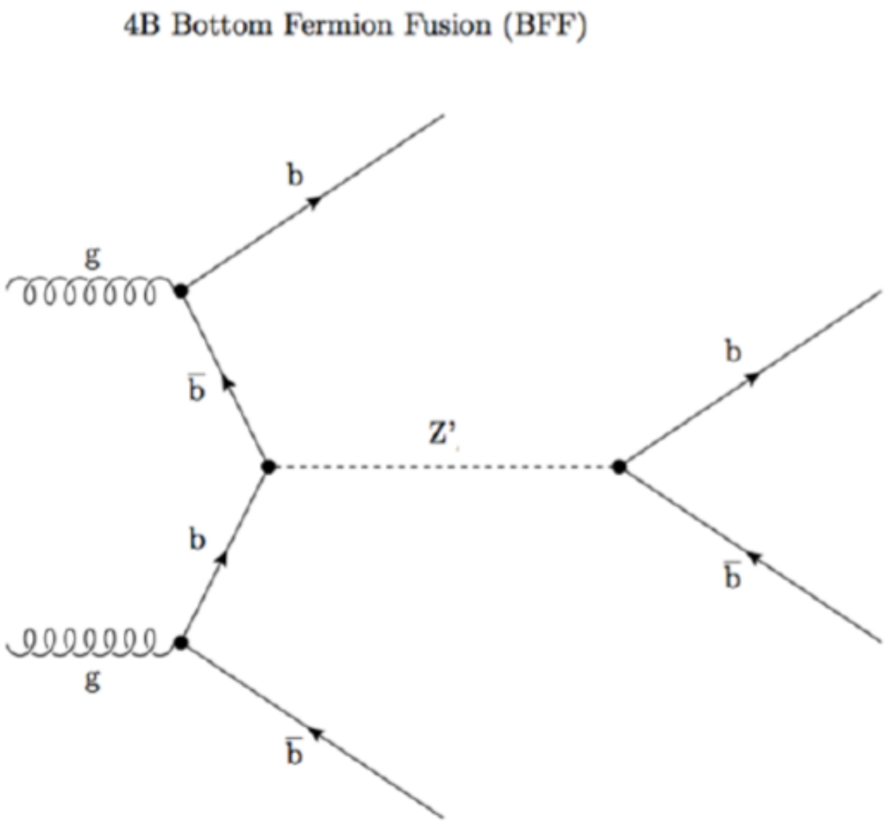
The Z'
Bottom Fermion Fusion



- Z' can be produced through its couplings to b-quarks
  - Take advantage of gluon-splitting!
  - Z' production from b-quark fusion (**Bottom Fermion Fusion**)

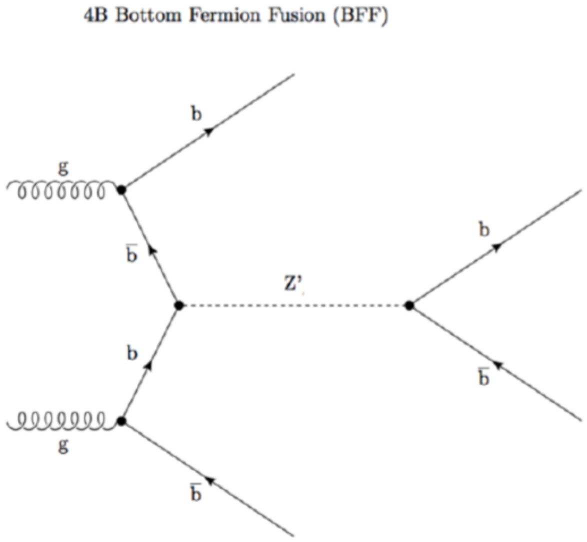


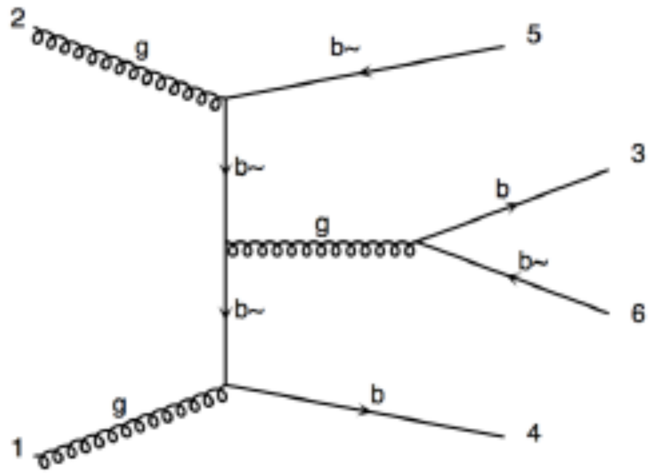
The Z'
4b - Bottom Fermion Fusion



- Z' can be produced through its couplings to b-quarks
  - Take advantage of gluon-splitting!
  - Z' production from b-quark fusion (Bottom Fermion Fusion)
- Z' can decay into pairs of b-quarks, muons, muon neutrinos, and top quarks
  - Look at di-b jet final state.
  - 4 b quarks in final state

General Analysis Strategy





❑ Signal:

- **Associated jets** have low or moderate energy.
- Energy of all 4 jets in final states ~ Z' mass.
- Immense rate of QCD multi-jet events

❑ Background:

- **Any process with 4 b jets in the final state**
- Immense rate of QCD multi-jet events

CMS Detector and Object Reconstruction

The Large Hadron Collider (LHC)

- World's largest **particle accelerator**.
- A 27-km ring of superconducting magnets and accelerating structures.
- Designed to operate at a center of mass energy of 14 TeV.
- Particle **collisions** at 4 points (CMS, ATLAS, ALICE, and LHCb).
  - **Compact Muon Solenoid** (CMS): One of the two general-purpose particle detectors at the LHC.

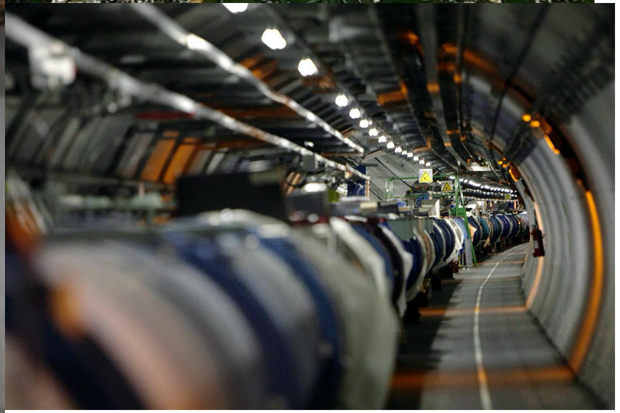



Image Credit: home.cern

Compact Muon Solenoid

- ❑ High magnetic field
- ❑ High granularity tracker
- ❑ Excellent electromagnetic calorimeter resolution
- ❑ Good particle ID due to particle flow (PF) algorithm

Silicon Tracker:

$$\frac{\sigma}{p_T} \sim 1.5 \cdot 10^{-4} p_T(GeV) \oplus 0.005$$

Electromagnetic Calorimeter:

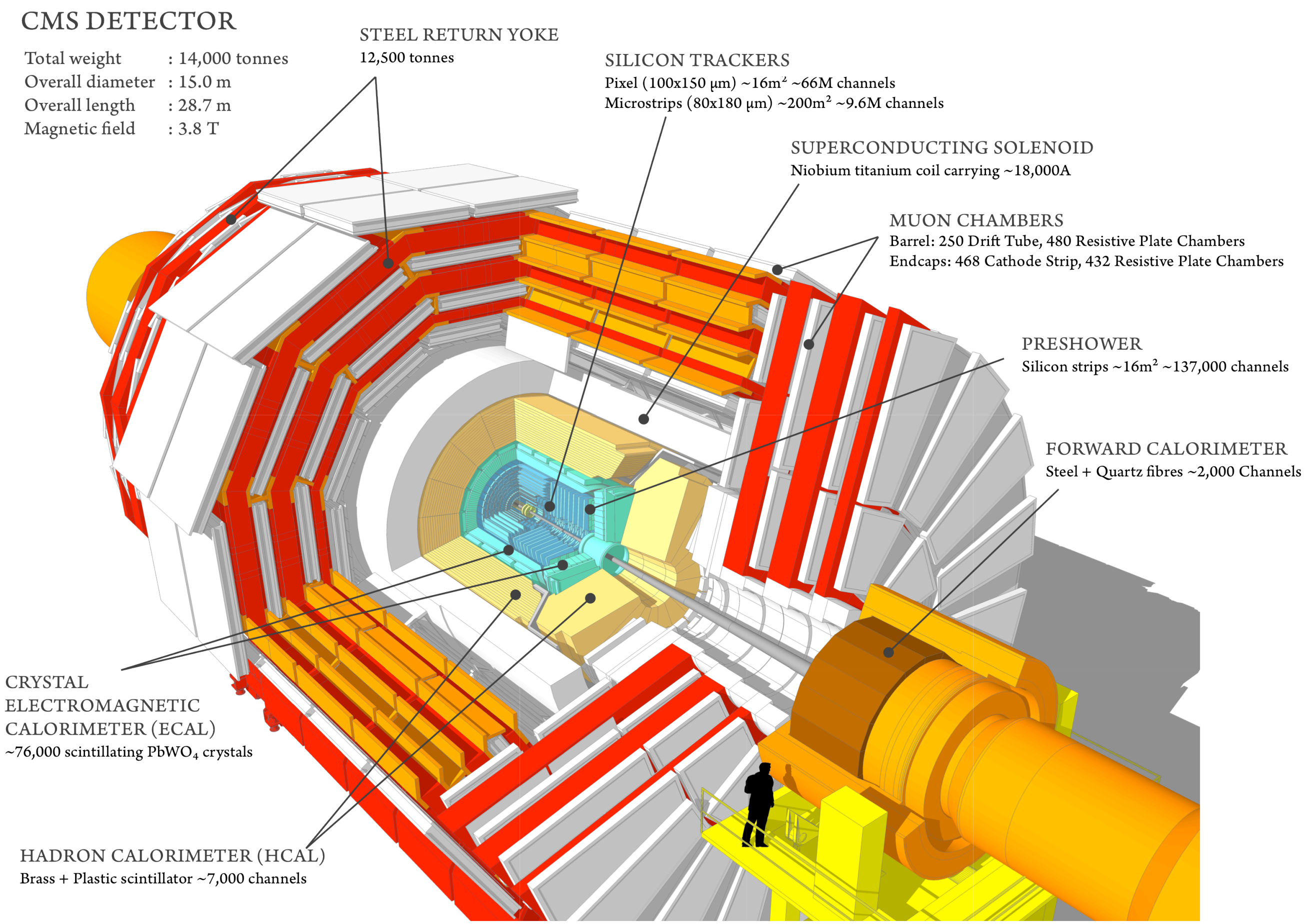
$$\frac{\sigma_E}{E} \approx \frac{2.9\%}{\sqrt{E(GeV)}} \oplus 0.5\% \oplus \frac{0.13}{E(GeV)}$$

Hadronic Calorimeter:

$$\frac{\sigma_E}{E} \approx \frac{120\%}{\sqrt{E(GeV)}} \oplus 6.9\%$$

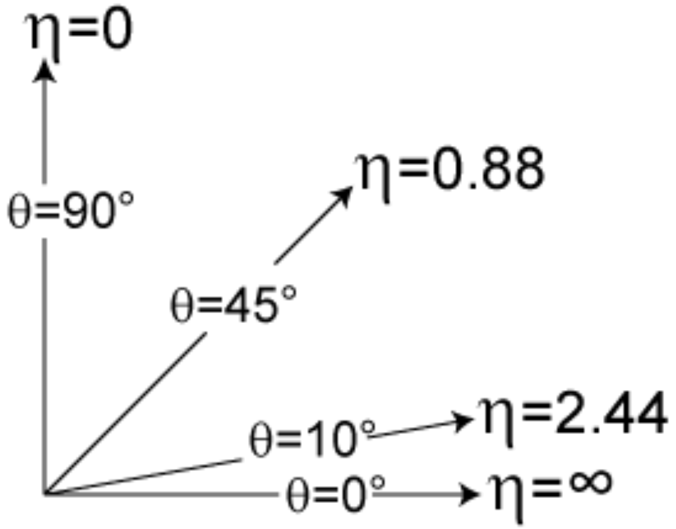
Muon Spectrometer:

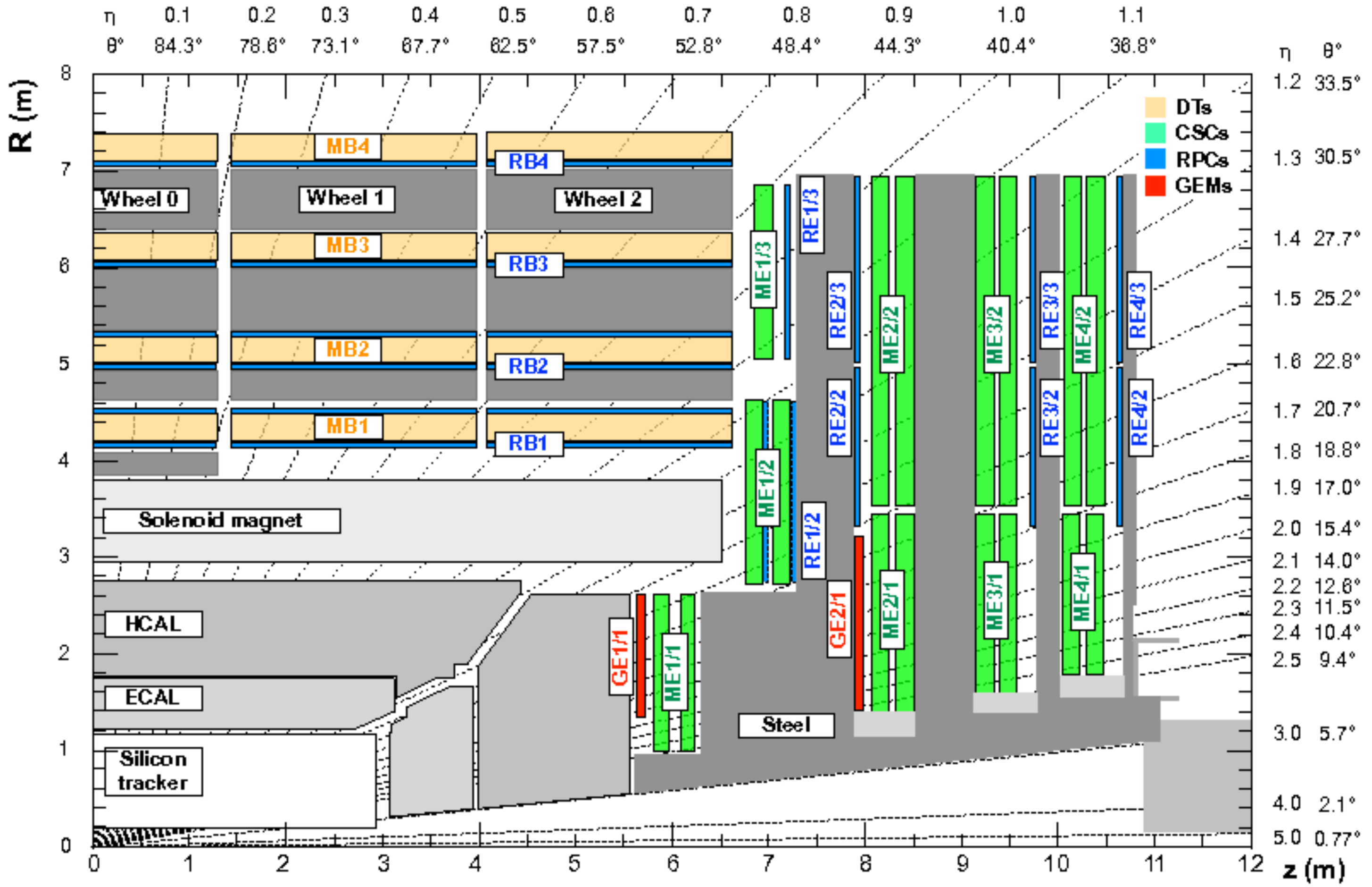
$\frac{\sigma_{p_T}}{p_T} \approx 1(5)\%$ for low (high) p_T muons



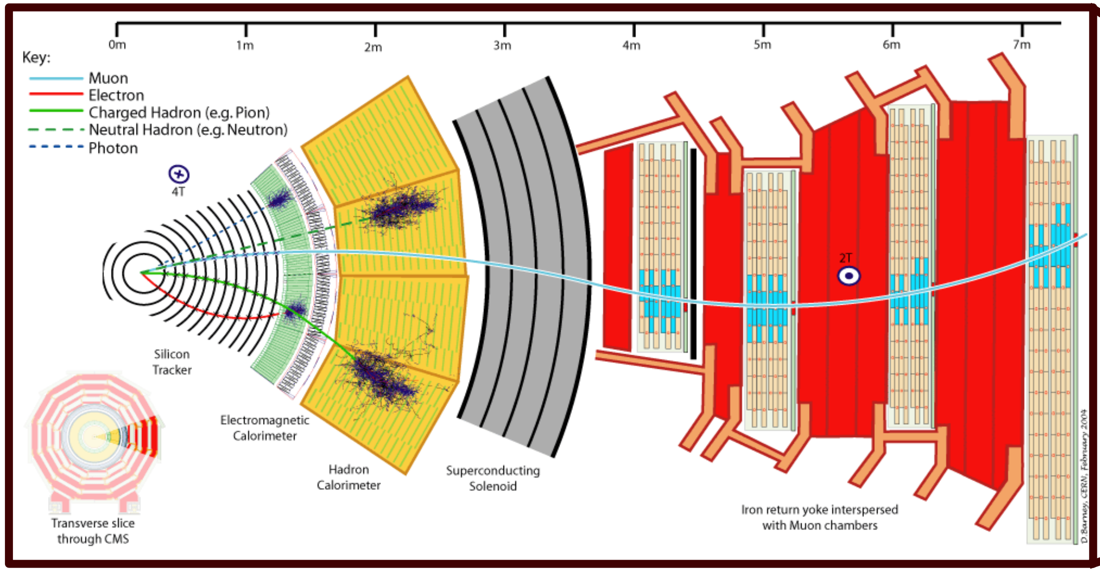
Compact Muon Solenoid
Coordinate System

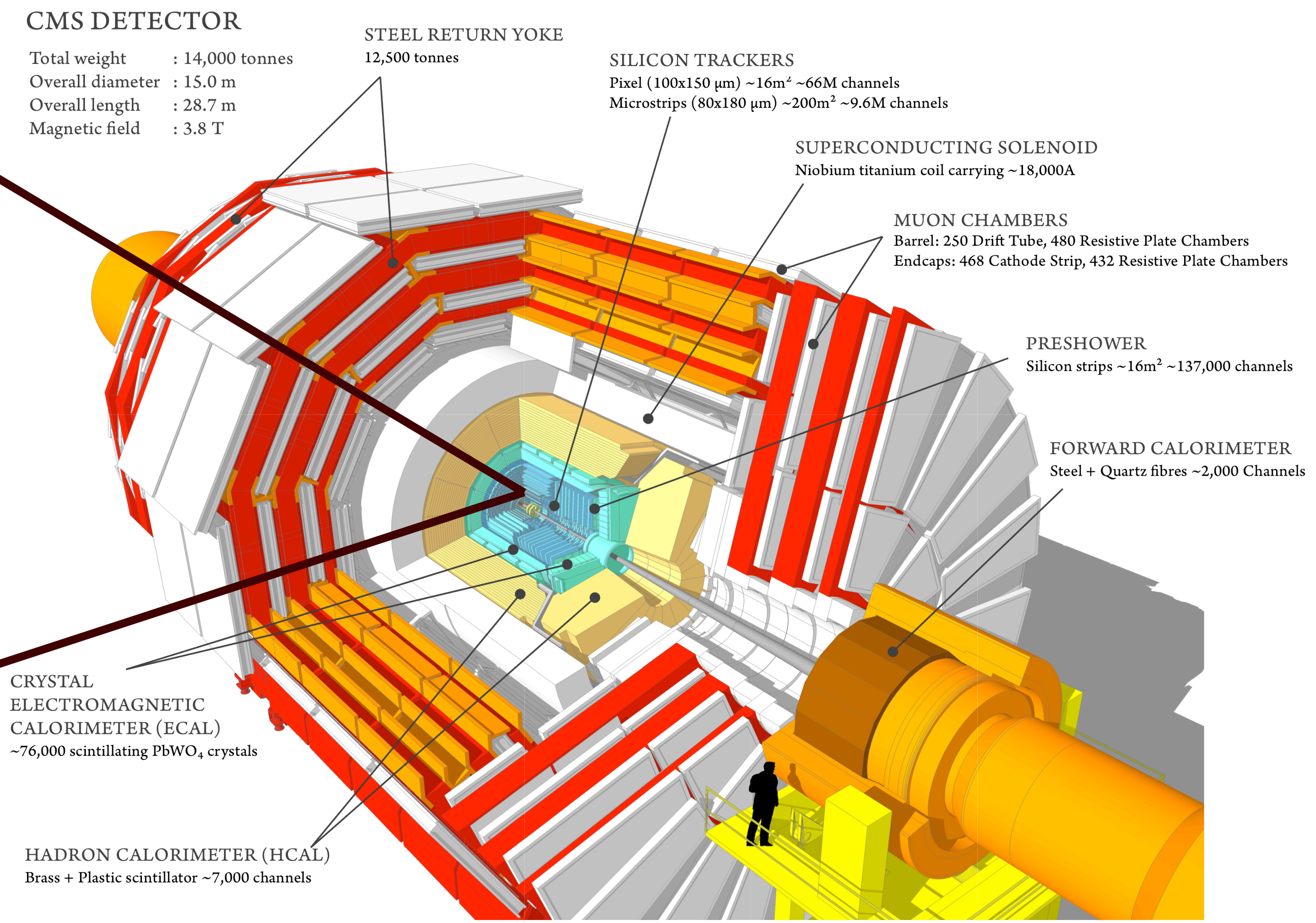
- Z-axis – Along the beam pipe
- ∅ - Azimuthal angle
- $\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$ – Pseudorapidity
- p_T - Transverse momentum (x-y plane)





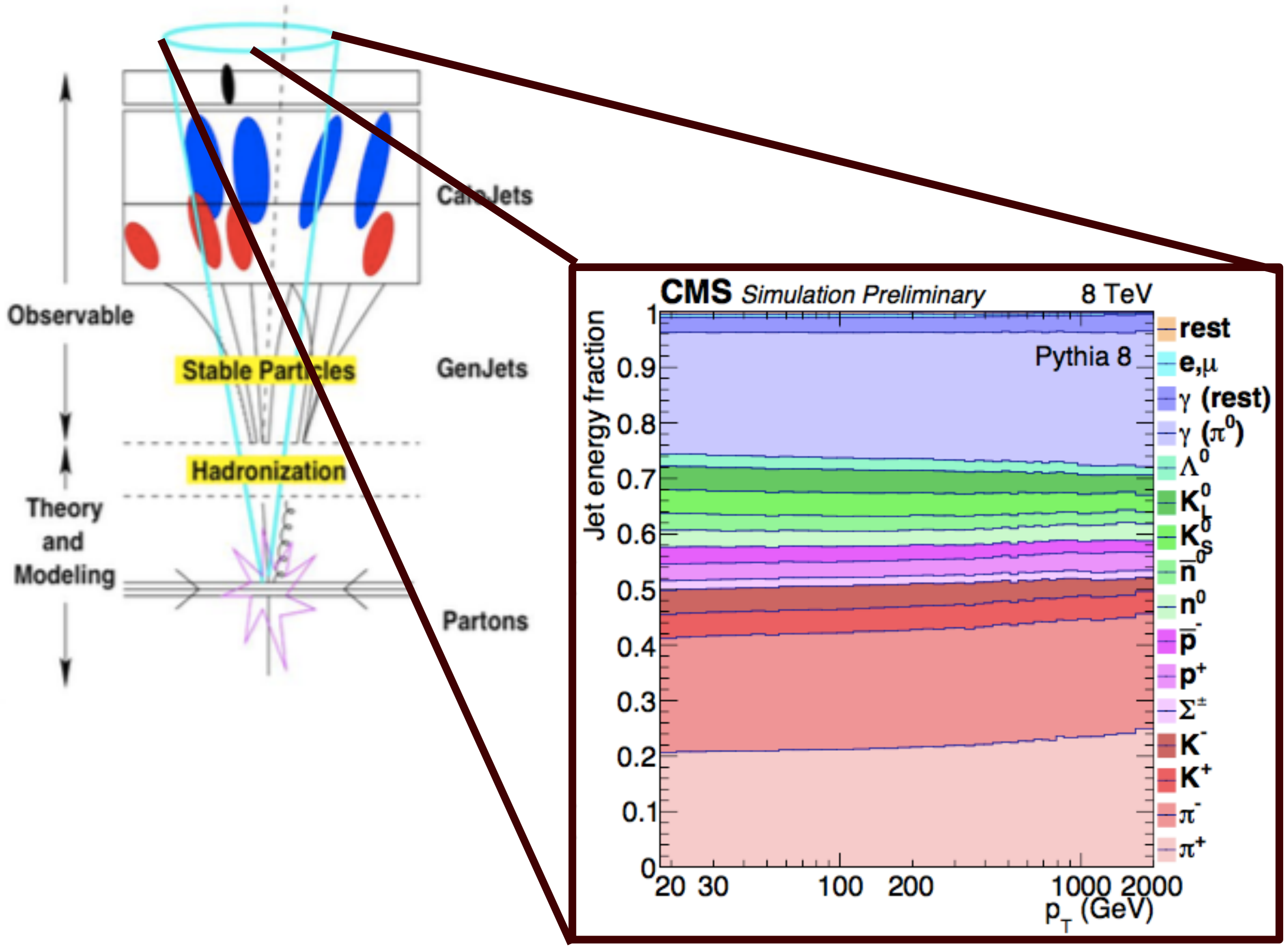
Compact Muon Solenoid





Each layer of the detector is designed to exploit particle properties to measure either its position or momentum

Physics Objects
Jets

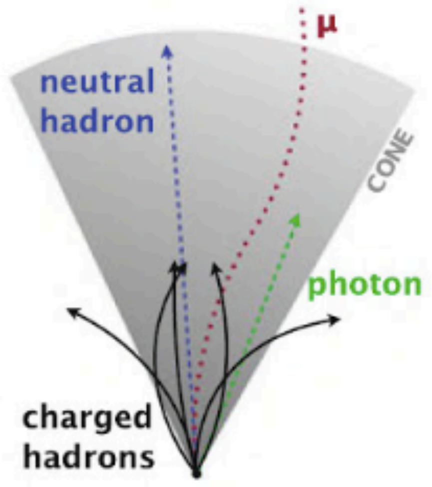


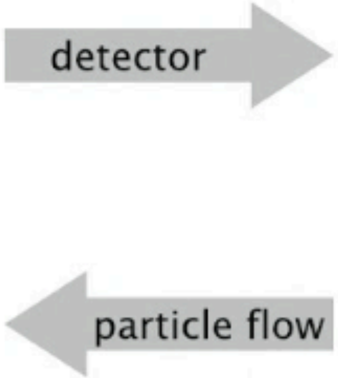
- A **jet** is a collimated spray of particles, resulting from the hadronization of quarks and gluons after a p-p collision.
- This collection of particles can provide information about the properties of the original parton.

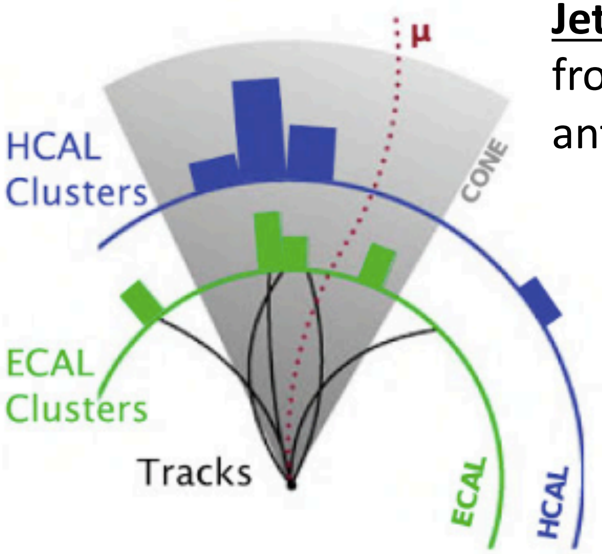
Jet Reconstruction at CMS

Start from the "true" or generated particles

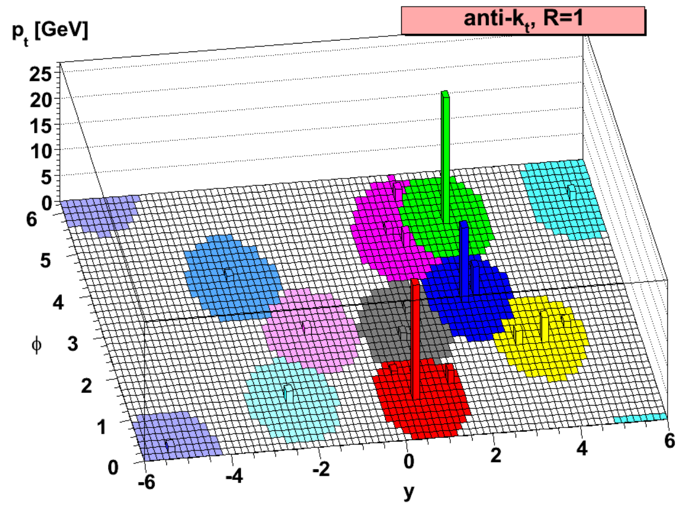
Particle Flow Algorithm: Combines the information from all subdetectors in an optimized way to reconstruct individual particles.





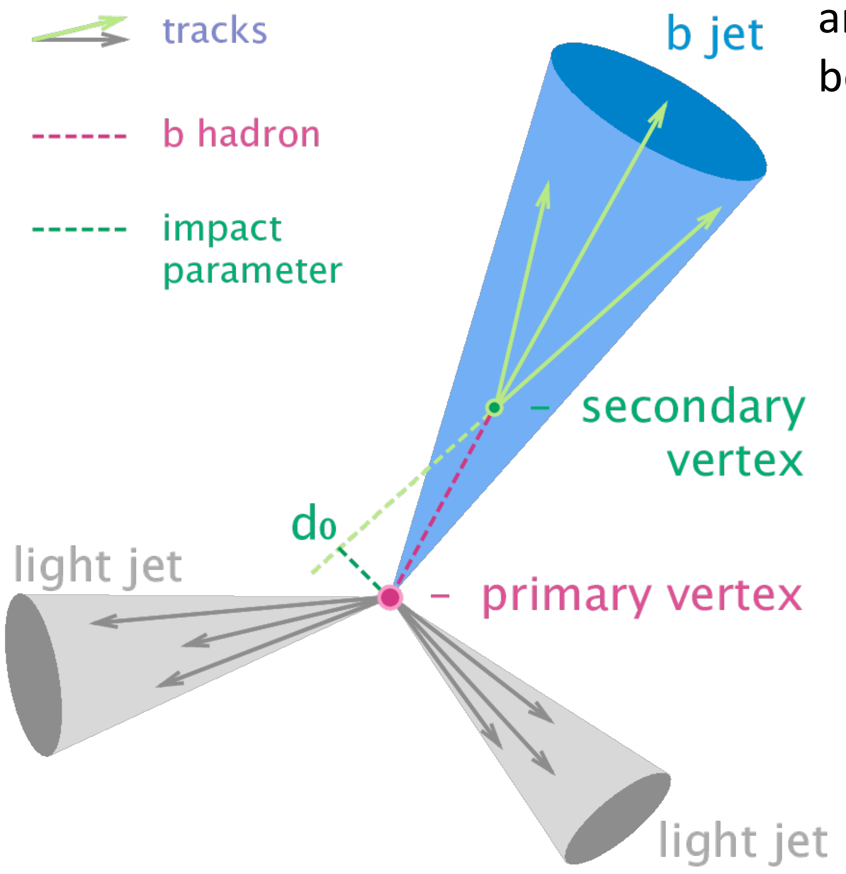


Jet Clustering Algorithm: Cluster particles from PF to form a jet. The CMS standard is anti-kT.



Analysis as if it is done on generator level particles.

B-tagging at CMS



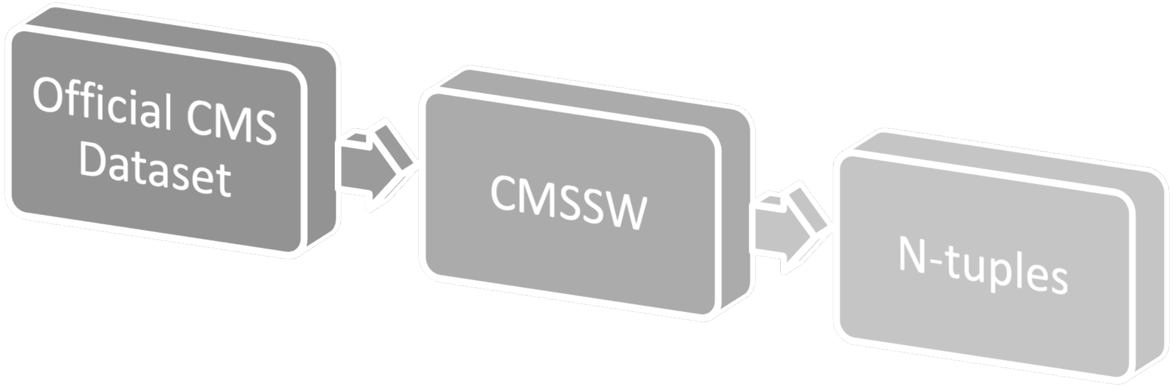
B-meson has large lifetime and travels some distance before decaying.

- B-tagging algorithms identify jets at some confidence level as having decayed from a B meson.
  - Categorizing jets into "Tight" (T), "Medium"(M), or "Loose" working points.
  - WP correspond to 0.1%(T), 1%(M), and 10%(L) misidentification rates.
  - For this analysis, we use DeepCSV tagging algorithm.

Event Selection and Methodology

Data and Simulated Samples
Data

- Data:
  - **BTagCSV/SingleMu** dataset collected at 13 TeV center-of-mass energy.
  - A total of **35.9 fb^{-1}** collected during 2016.



Dataset	Run Range	Integrated Luminosity
/BTagCSV/Run2016B-07Aug17-v*/AOD	272007-275376	5.8
/BTagCSV/Run2016C-07Aug17-v1/AOD	275657-276283	2.5
/BTagCSV/Run2016D-07Aug17-v1/AOD	276315-276811	4.3
/BTagCSV/Run2016E-07Aug17-v1/AOD	276831-277420	4.1
/BTagCSV/Run2016F-07Aug17-v1/AOD	277772-278808	3.1
/BTagCSV/Run2016G-07Aug17-v1/AOD	278820-280385	7.5
/BTagCSV/Run2016H-07Aug17-v1/AOD	280919-284044	8.5
Total BTagCSV	**272007–284044**	**35.9**
/SingleMu/Run2016B-07Aug17-v*/AOD	272007-275376	5.8
/SingleMu/Run2016C-07Aug17-v1/AOD	275657-276283	2.5
/SingleMu/Run2016D-07Aug17-v1/AOD	276315-276811	4.3
/SingleMu/Run2016E-07Aug17-v1/AOD	276831-277420	4.1
/SingleMu/Run2016F-07Aug17-v1/AOD	277772-278808	3.1
/SingleMu/Run2016G-07Aug17-v1/AOD	278820-280385	7.5
/SingleMu/Run2016H-07Aug17-v1/AOD	280919-284044	8.5
Total SingleMu	**272007–284044**	**35.9**

2017/2018 datasets not considered due to changes in the trigger menu

Data and Simulated Samples
Monte Carlo

- MC Simulation:
  - Allow for estimation of hadronic background behavior
  - How would a potential Z’ signal look like in data?

Background

Background Processes		
Process	Dataset Name	Cross Section [pb]
QCD_HT50to100	QCD_HT50to100_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	246300000.0
QCD_HT100to200	QCD_HT100to200_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	28060000.0
QCD_HT200to300	QCD_HT200to300_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	1710000.0
QCD_HT300to500	QCD_HT300to500_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	347500.0
QCD_HT500to700	QCD_HT500to700_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	32060.0
QCD_HT700to1000	QCD_HT700to1000_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	6829.0
QCD_HT1000to1500	QCD_HT1000to1500_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	1207.0
QCD_HT1500to2000	QCD_HT1500to2000_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	120.0
QCD_HT2000toInf	QCD_HT2000toInf_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	25.25
TTJets	TTJets_TuneCUETP8M2T4_13TeV-amcatnloFXFX-pythia8	831.76

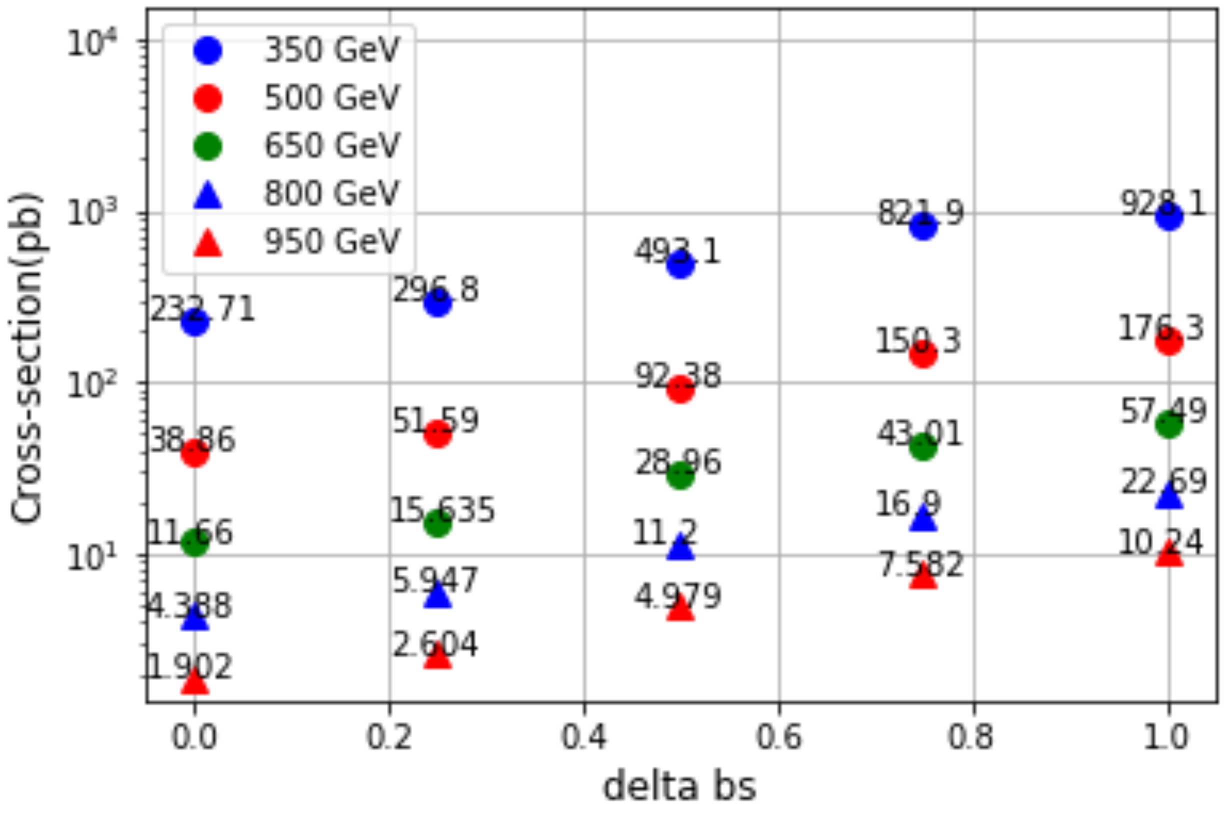
*Here, every dataset name is followed by /RunIISummer16MiniAODv2-PUMoriond17_80X_mcRun2_asymptotic_2016_TrancheIV_v6v1

Data and Simulated Samples
Monte Carlo

Signal

- Created privately and specifically for the analysis
- Parameter space considered for MC signal simulation:
  - $m_{Z'}$ = 350, 500, 650, 800, and 950 GeV
  - g_μ, g_t=0, g_b = 1.0
  - δ_{bs} = 0.0, 0.25, 0.5, 0.75, 1.0

$$\mathcal{L} \supset Z'_\alpha \left[g_\mu^V \, \bar{\mu} \, \gamma^\alpha \, \mu + g_\mu^V \, \overline{\nu}_\mu \, \gamma^\alpha \, P_L \, \nu_\mu + g_b \sum_{q=t,b} \overline{q} \, \gamma^\alpha \, P_L \, q + \left(g_b \, \delta_{bs}^L \, \overline{s} \, \gamma^\alpha \, P_L \, b + \text{h.c.} \right) \right]$$



Event Selection

Preselection

- At least 4 reconstructed jets with p_T> 30 GeV and $|\eta|$< 2.4 + Tight Jet ID
- Lepton Veto : Muon (electron) with relIso < 0.20, $p_T >$ $20\ GeV$, and $|\eta| < 2.4(2.5)$
- Exclusive selections for b-tagging in order of the nth leading jet in pT in the event:
  - Use the combination of exclusive b-tagging requirements on the first four leading jets "4T" and invert this with a second selection only on the two leading jets "2T" *mutually exclusive* to "4T"

4T	3T	2T
TTTT	TTT	TT
TTTM		
TTTL		
TTTX		
TTMT	TTM	
TTMM		
TTLT	TTL	
TMTT	TMT	TM
TMTM		
TMMT	TMM	
TLTT	TLT	TL
MTTT	MTT	MT
MTTM		
MTMT	MTM	
MMTT	MMT	MM

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Trigger

QuadJet45_TripleBTagCSV_p087

Combination of L1 seeds
+
4 calo-jets with $|\eta|$ < 2.6 and $\boldsymbol{p_T}$ > 45 GeV
+
3 calo-jets with online CSV > 0.87
+
4 PF-jets with $|\eta|$ < 2.6 and $\boldsymbol{p_T}$ > 45 GeV

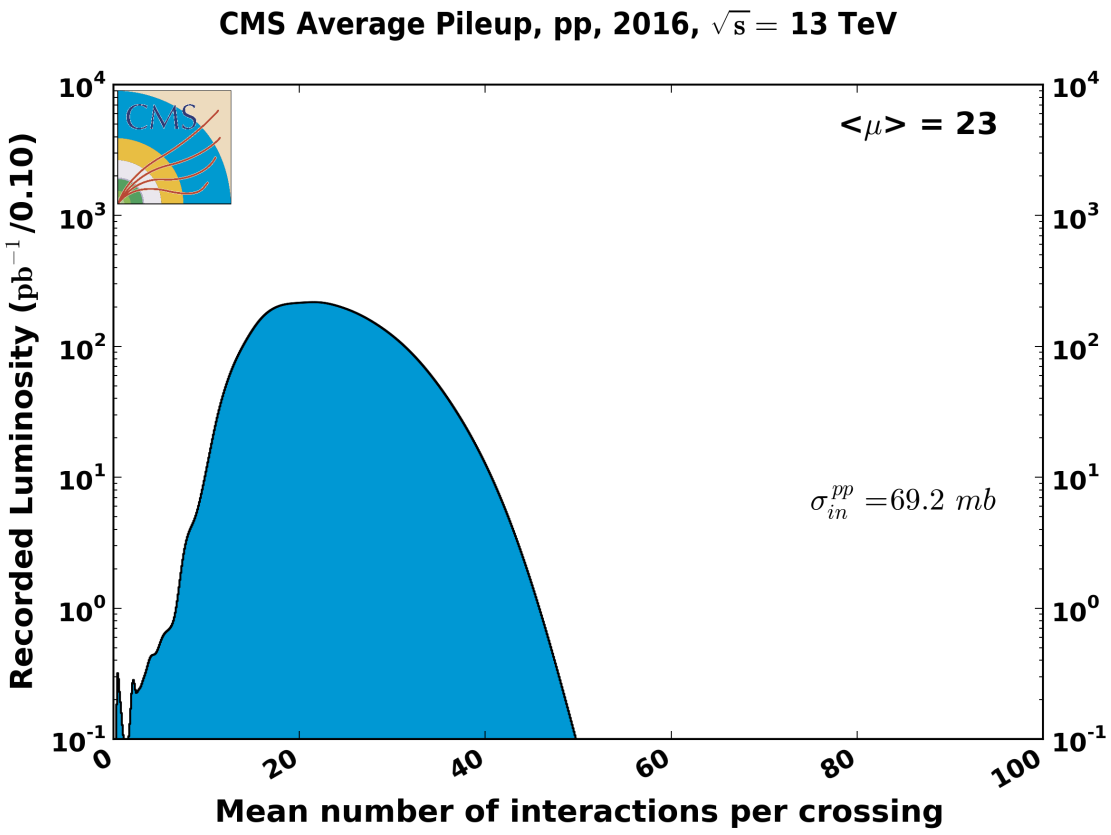
DoubleJet90_Double30_TripleBTagCSV_p087

Combination of L1 seeds
+
4 calo-jets with $|\eta|$ < 2.6 and $\boldsymbol{p_T}$ > 30 GeV
+
2 calo-jets with $|\eta|$ < 2.6 and $\boldsymbol{p_T}$ > 90 GeV
+
3 calo-jets with online CSV > 0.87
+
4 PF-jets with $|\eta|$ < 2.6 and $\boldsymbol{p_T}$ > 30 GeV
+
2 PF-jets with $|\eta|$ < 2.6 and $\boldsymbol{p_T}$ > 90 GeV

Data and MC Corrections

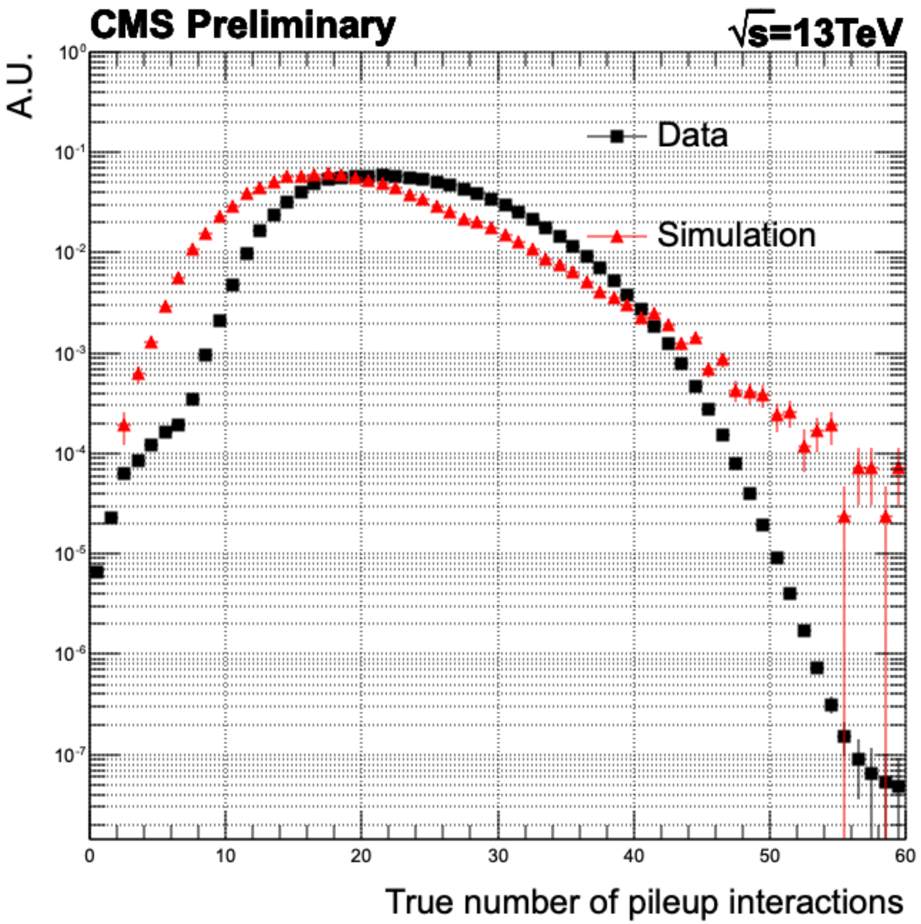
MC Corrections
Pileup Reweighting

- Pileup (PU) relates to the additional p-p interactions within an event.
- **True number of interactions** (tNPU) varies during data taking period.



MC Corrections
Pileup Reweighting

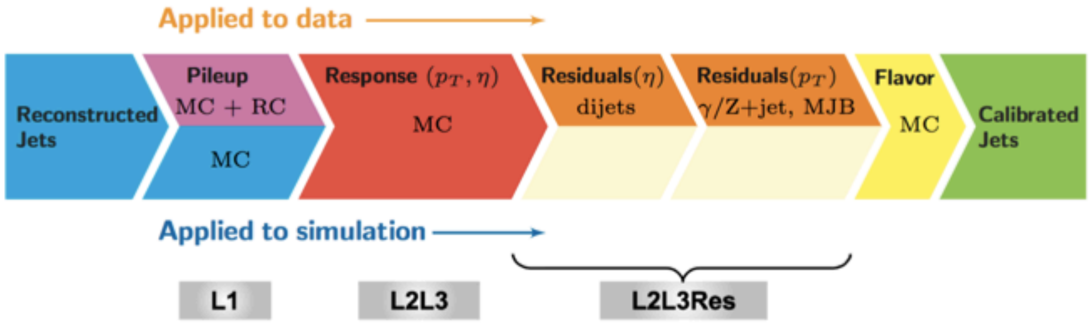
- Pileup (PU) relates to the additional p-p interactions within an event.
- **True number of interactions** (tNPU) varies during data taking period.
- PU can affect the reconstruction efficiency and observed kinematics of all objects used in analysis.
- Want MC to follow data PU distribution as close as possible!



MC Corrections
Jet Corrections

Jet Energy Corrections

- Corrects the scale of jets due to pileup and detector effects.
- L1FastJet(pileup), L2 Relative (η dependent), and L3 Absolute (p_T dependent) corrections.



MC Corrections
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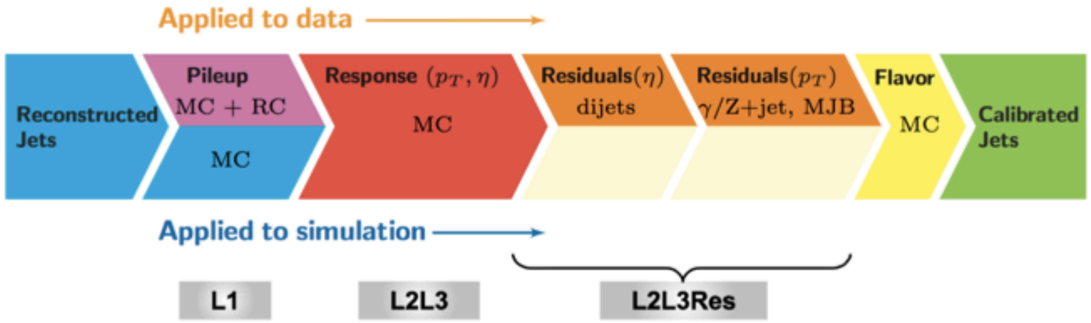
- Corrects the scale of jets due to pileup and detector effects.
- L1FastJet(pileup), L2 Relative (η dependent), and L3 Absolute (p_T dependent) corrections.



Jet Energy Resolution

- Energy distribution in MC is usually shaper than same distribution in data.
  - Unrealistic resolution.
- Scale jet p_T by a multiplicative correction factor.

$$C_{JER} = \max\left(0.0, \frac{p_T{}^{GEN}}{p_T{}^{RECO}} + C_\eta\left(1 - \frac{p_T{}^{GEN}}{p_T{}^{RECO}}\right)\right)$$

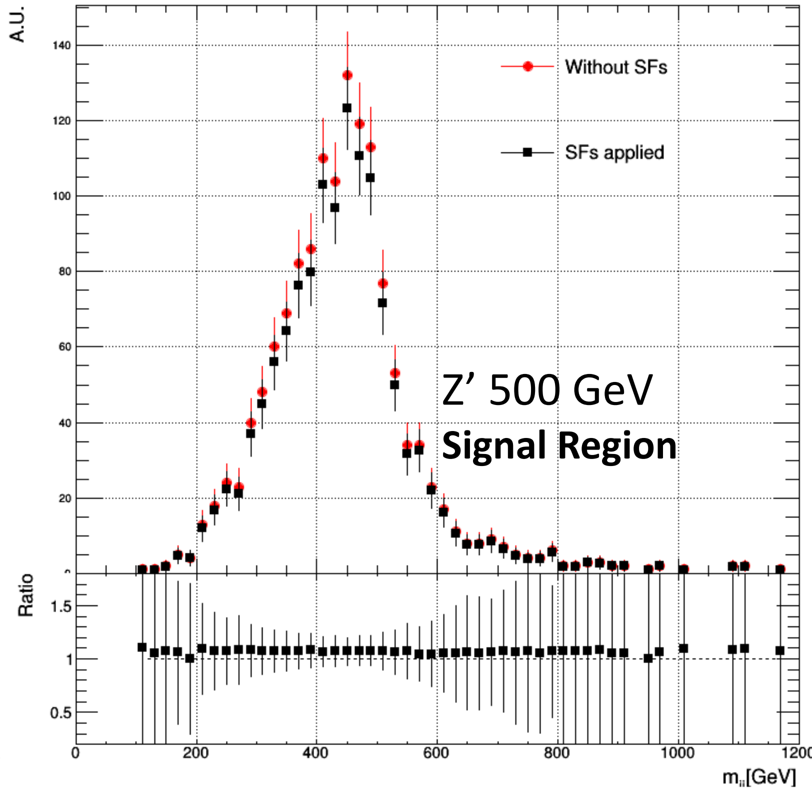
MC Corrections
DeepCSV Reweighting

- Analysis relies heavily on b-tagging.
  - *Need to make sure that b-tagging discriminant behaves the same in both data and MC.*
- Apply an event weight based on the probability of a given configuration of jets in MC and data:

$$w = \frac{P(Data)}{P(MC)}$$

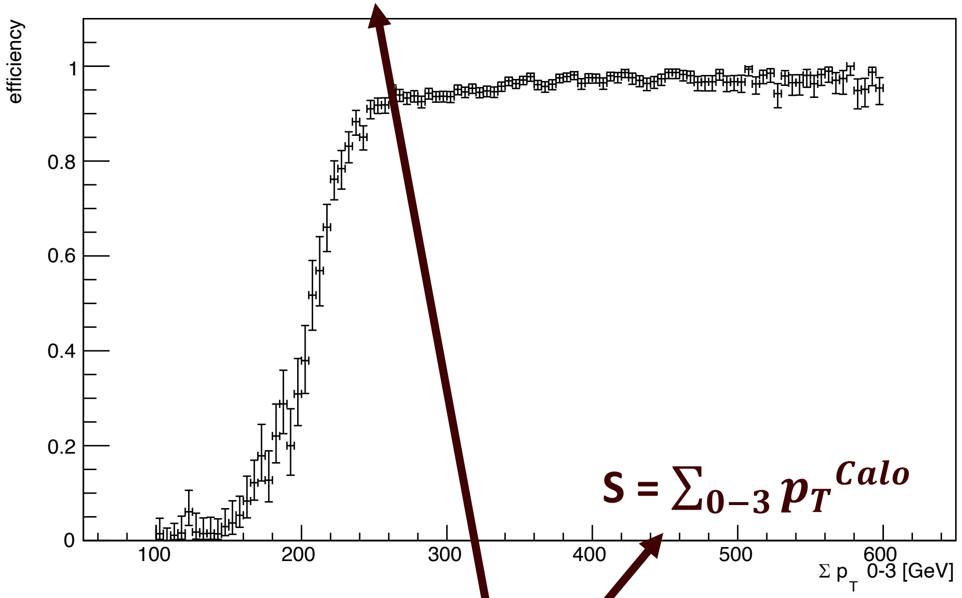
P(MC) = $\prod_{i=tagged\ T} \varepsilon_i^T \prod_{j=tagged\ M,not\ T}(\varepsilon_j^M - \varepsilon_j^T) \prod_{k=tagged\ L,not\ M}(\varepsilon_k^L - \varepsilon_k^M) \prod_{l=not\ tagged}(1 - \varepsilon_l^L)$

P(Data) = $\prod_{i=tagged\ T} SF_i^T \varepsilon_i^T \prod_{j=tagged\ M,not\ T}(SF_j^M \varepsilon_j^M - SF_j^T \varepsilon_j^T) \prod_{k=tagged\ L,not\ M}(SF_k^L \varepsilon_k^L - SF_k^M \varepsilon_k^M) \prod_{l=not\ tagged}(1 - SF_l^L \varepsilon_l^L)$



Trigger Efficiency Estimation

Trigger Efficiency Estimation
Data-driven Approach



S = $\sum_{0-3} p_T{}^{Calo}$

Efficiency = $P(T|S) = \frac{N(T\&S)}{N_{tot}}$

QuadJet45_TripleBTagCSV_p087

Combination of L1 seeds

+

4 calo-jets with $|\eta|$ < 2.6 and p_T > 45 GeV

+

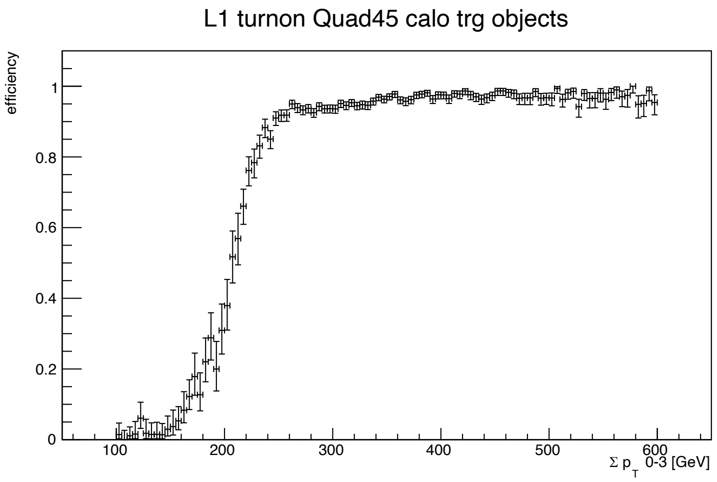
3 calo-jets with online CSV > 0.87

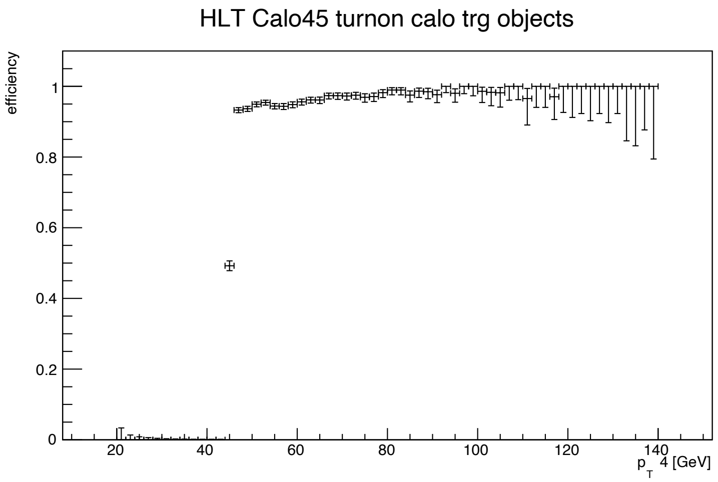
+

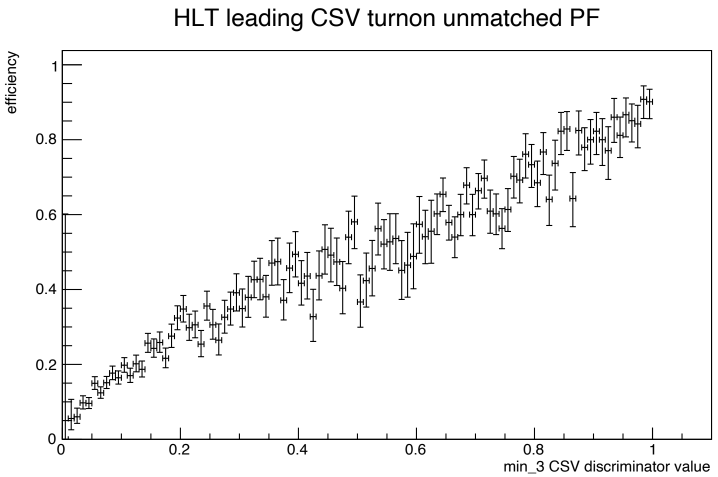
4 PF-jets with $|\eta|$ < 2.6 and p_T > 45 GeV

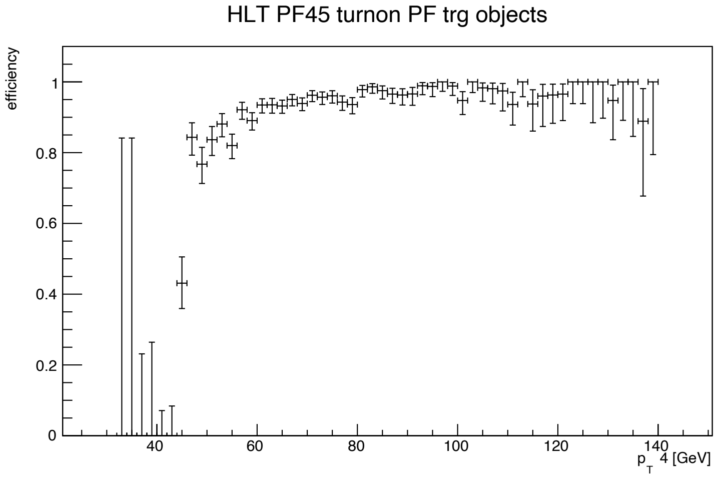
- Repeat for remaining requirements on HLT path.
- Estimate efficiencies in SingleMuon dataset.
  - HLT_BIT_HLT_IsoMu24
  - Muon: Loose Muon POG ID and p_T > 40 GeV

Trigger Efficiency Estimation
QuadJet45_TripleBTagCSV_p087









QuadJet45_TripleBTagCSV_p087

Combination of L1 seeds

+

4 calo-jets with $|\eta| < 2.6$ and $\boldsymbol{p_T} > 45$ GeV

+

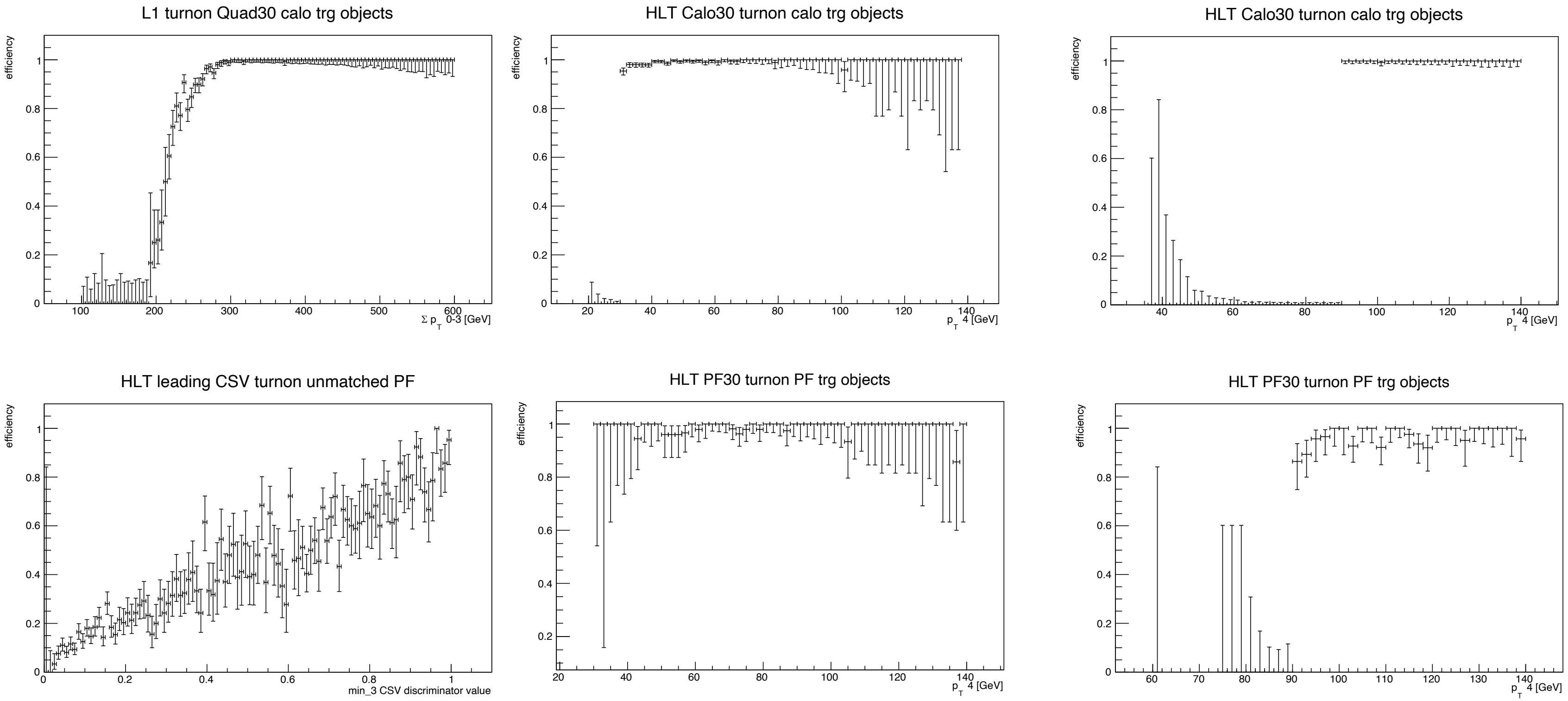
3 calo-jets with online CSV > 0.87

+

4 PF-jets with $|\eta| < 2.6$ and $\boldsymbol{p_T} > 45$ GeV

$$w_{Quad45}(p_{T1}, p_{T2}, p_{T3}, p_{T4}, CSV_3)$$
$$= Turn\ On\ L1\left(p_{T1}{}^{calo} + p_{T2}{}^{calo} + p_{T3}{}^{calo} + p_{T4}{}^{calo}\right)$$
$$\cdot\ TurnOn\ QuadCalo45(p_{T4}{}^{calo}) \cdot Eff(CSV_3)$$
$$\cdot\ TurnOn\ QuadPFJet45(p_{T4}{}^{PF})$$

Trigger Efficiency Estimation
QuadJet45_TripleBTagCSV_p087



DoubleJet90_Double30_TripleBTagCSV_p087

Combination of L1 seeds

+

4 calo-jets with $|\eta| < 2.6$ and $\boldsymbol{p_T} > 30$ GeV

+

2 calo-jets with $|\eta| < 2.6$ and $\boldsymbol{p_T} > 90$ GeV

+

3 calo-jets with online CSV > 0.87

+

4 PF-jets with $|\eta| < 2.6$ and $\boldsymbol{p_T} > 30$ GeV

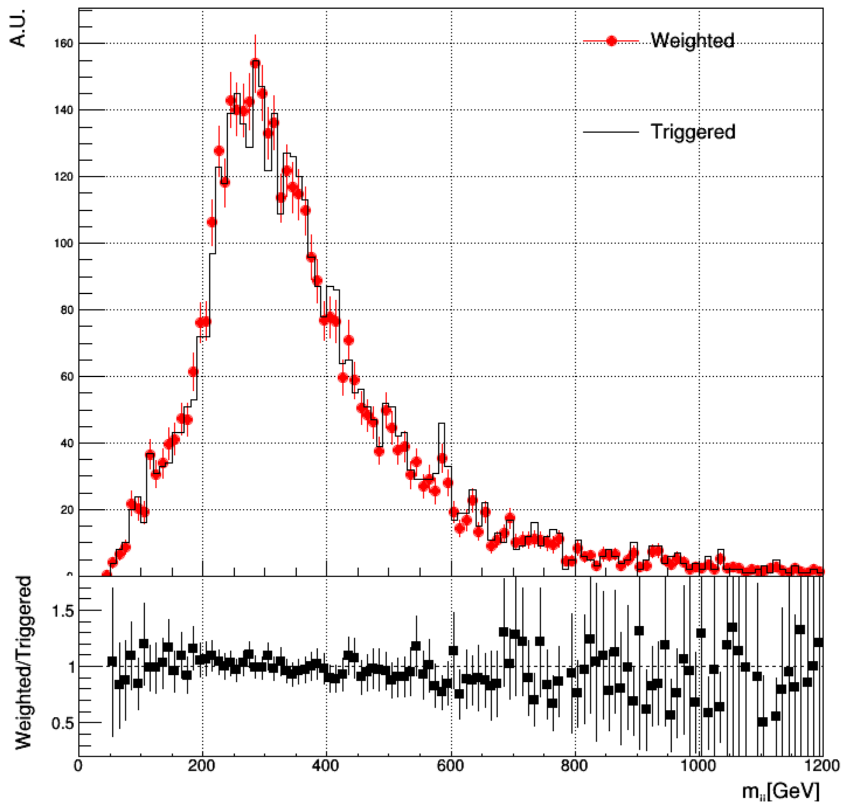
+

2 PF-jets with $|\eta| < 2.6$ and $\boldsymbol{p_T} > 90$ GeV

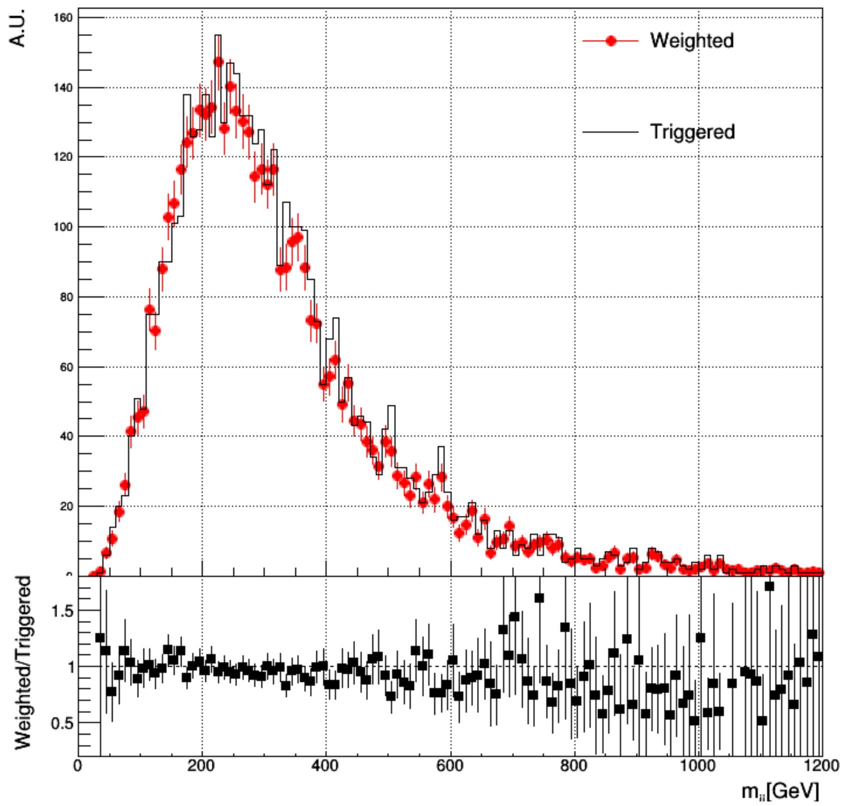
$$w_{Di90Di30}(p_{T1}, p_{T2}, p_{T3}, p_{T4}, CSV_3) = Turn\ On\ L1\left({p_{T1}}^{calo} + {p_{T2}}^{calo} + {p_{T3}}^{calo} + {p_{T4}}^{calo}\right) \cdot TurnOn\ QuadCalo30({p_{T4}}^{calo}) \cdot$$
$$TurnOnDoubleCalo30({p_{T2}}^{calo}) \cdot Eff(CSV_3) \cdot TurnOn\ QuadPFJet30({p_{T4}}^{PF}) \cdot TurnOnDoublePFJet90({p_{T2}}^{PF})$$

Trigger Efficiency Estimation
Closure

DoubleJet90DoubleJet30_TripleBTagCSV Trigger



QuadJet45_TripleBTagCSV Trigger

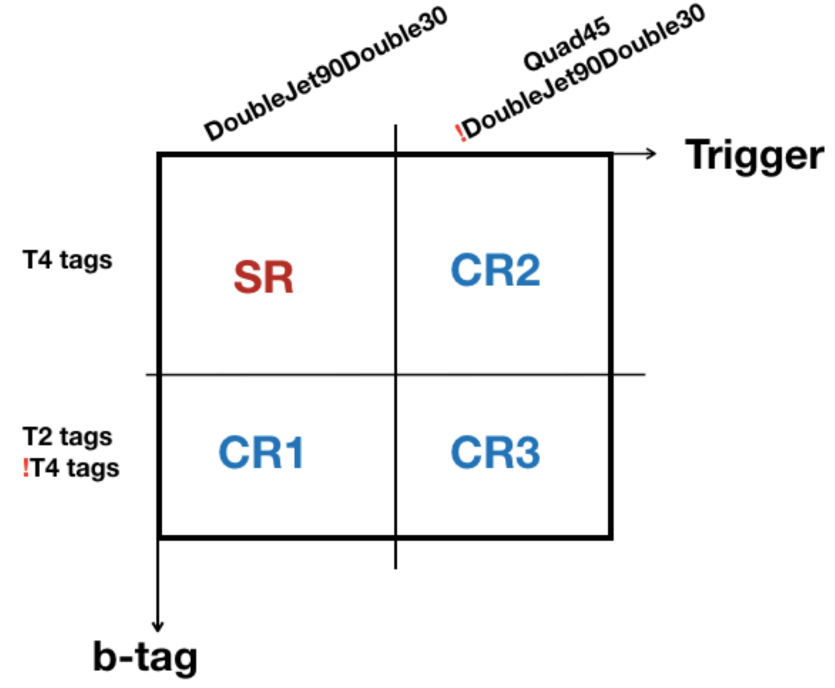


Data-driven Background Estimation

Data-driven Background Estimation
Control/Signal Region Definitions

- Goal is to minimize systematic uncertainties arising from poorly understood QCD background.
- Background contribution can be estimated from data by defining appropriate signal/control regions.
- Optimal SR:
  - Good signal/background ratio
- Good SR:
  - Low signal contamination
  - High-statistics background shape

A sensible way to extrapolate the background events in the CR to the background events in the SR

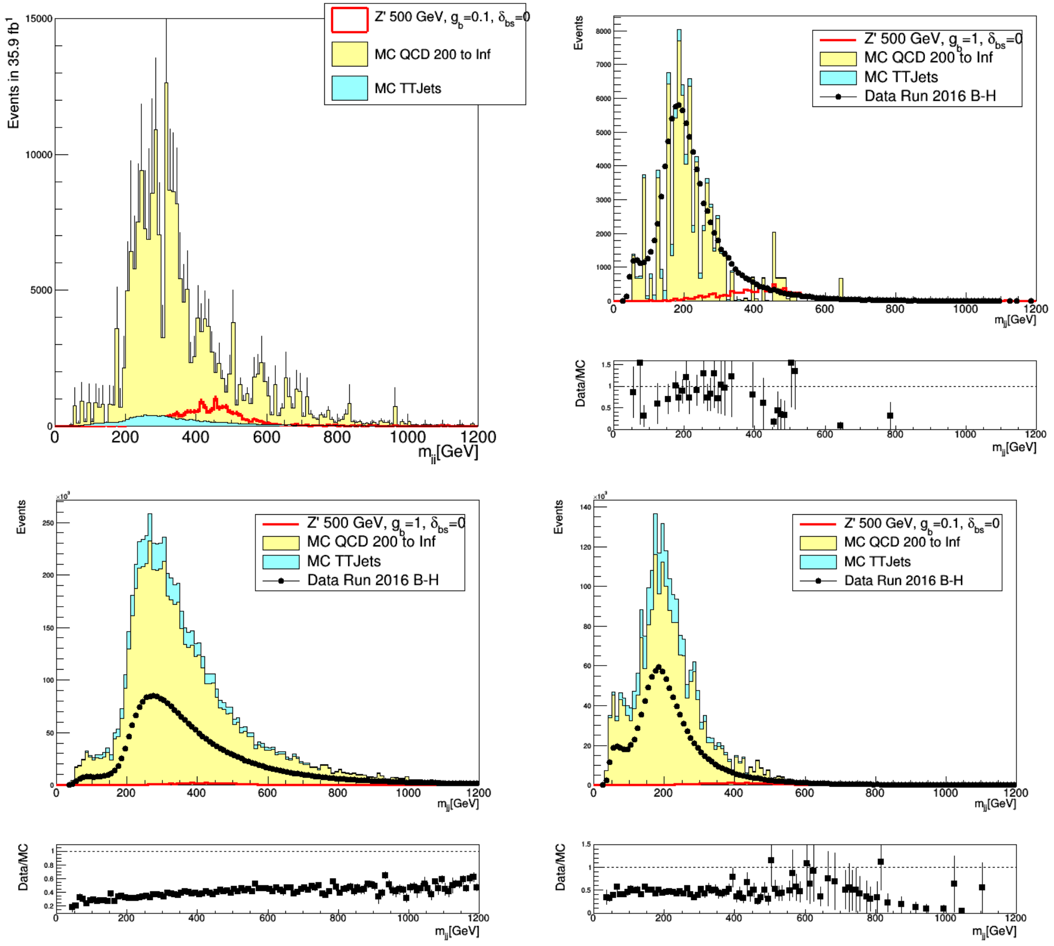


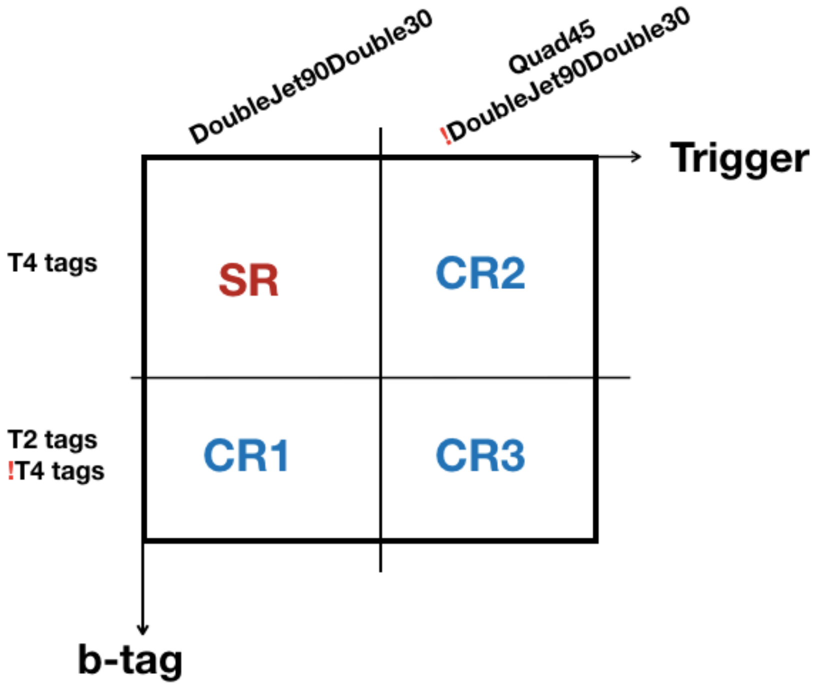
$$\frac{\text{SR}\ \ \text{DoubleJet90Double30, T4 tags}}{\text{CR1}\ \ \text{DoubleJet90Double30, T2 tags, !T4 tags}} = \frac{\text{CR2}\ \ \text{Quad45, !DoubleJet90Double30, T4 tags}}{\text{CR3}\ \ \text{Quad45, !DoubleJet90Double30, T2 tags, !T4 tags}}$$

Data-driven Background Estimation

Control/Signal Region m_{jj} distribution

Signal Region

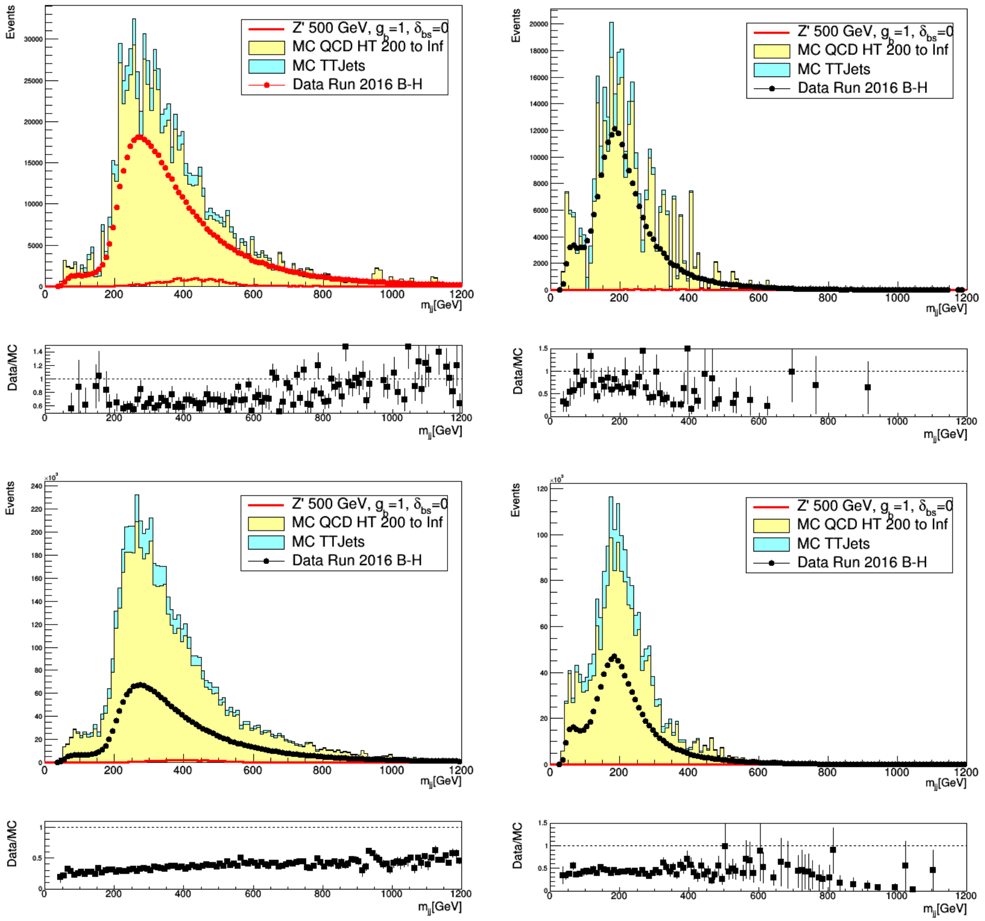


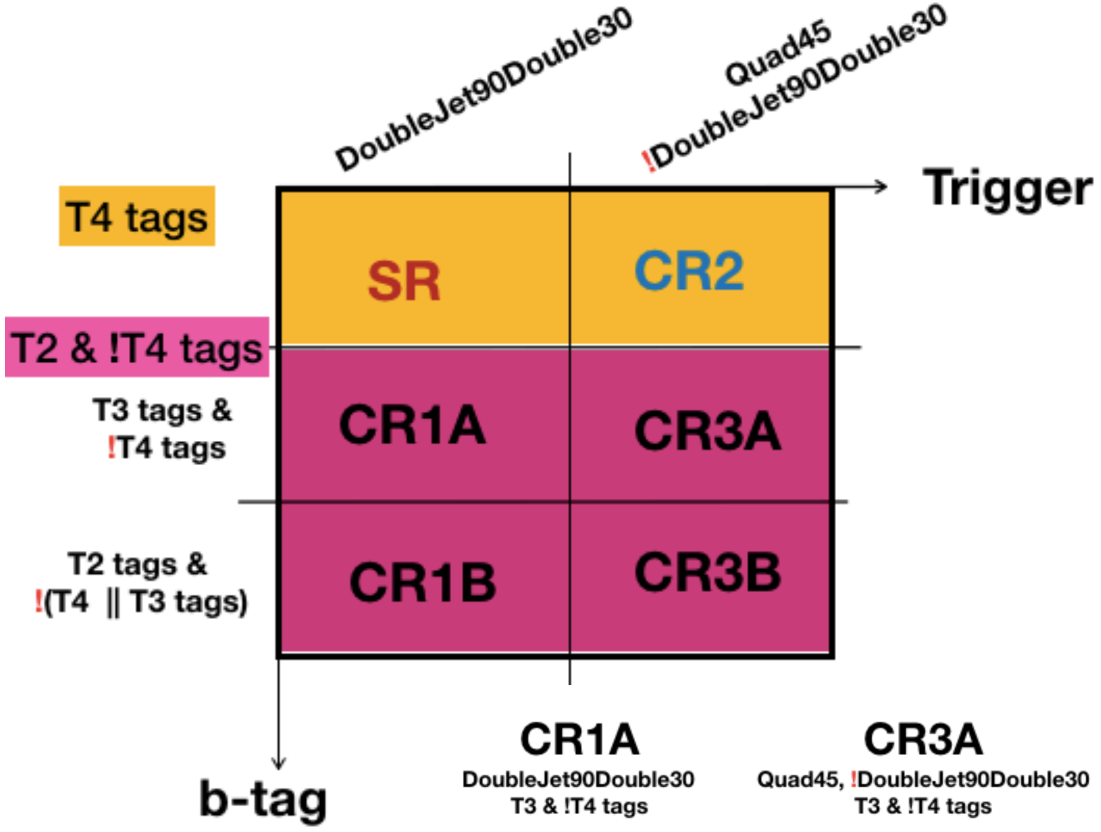


SR DoubleJet90Double30 T4 tags	=	CR2 Quad45, !DoubleJet90Double30 T4 tags
CR1 DoubleJet90Double30 T2 tags, !T4 tags		CR3 Quad45, !DoubleJet90Double30 T2 tags, !T4 tags

Data-driven Background Estimation

Additional Control/Signal Region Definitions

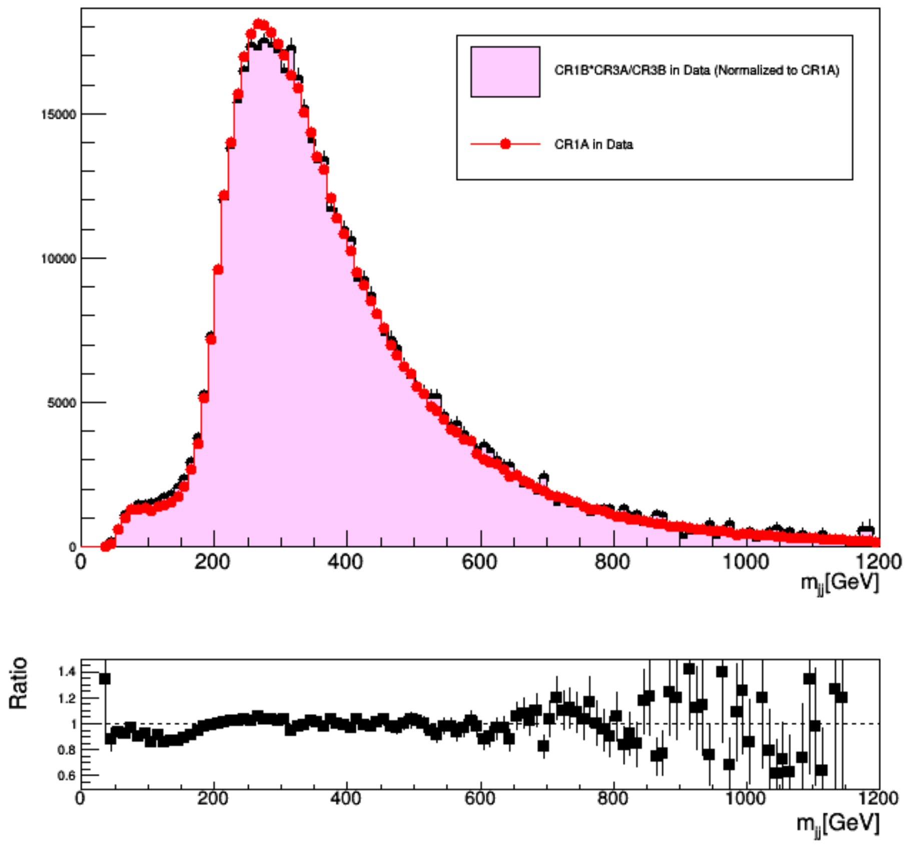


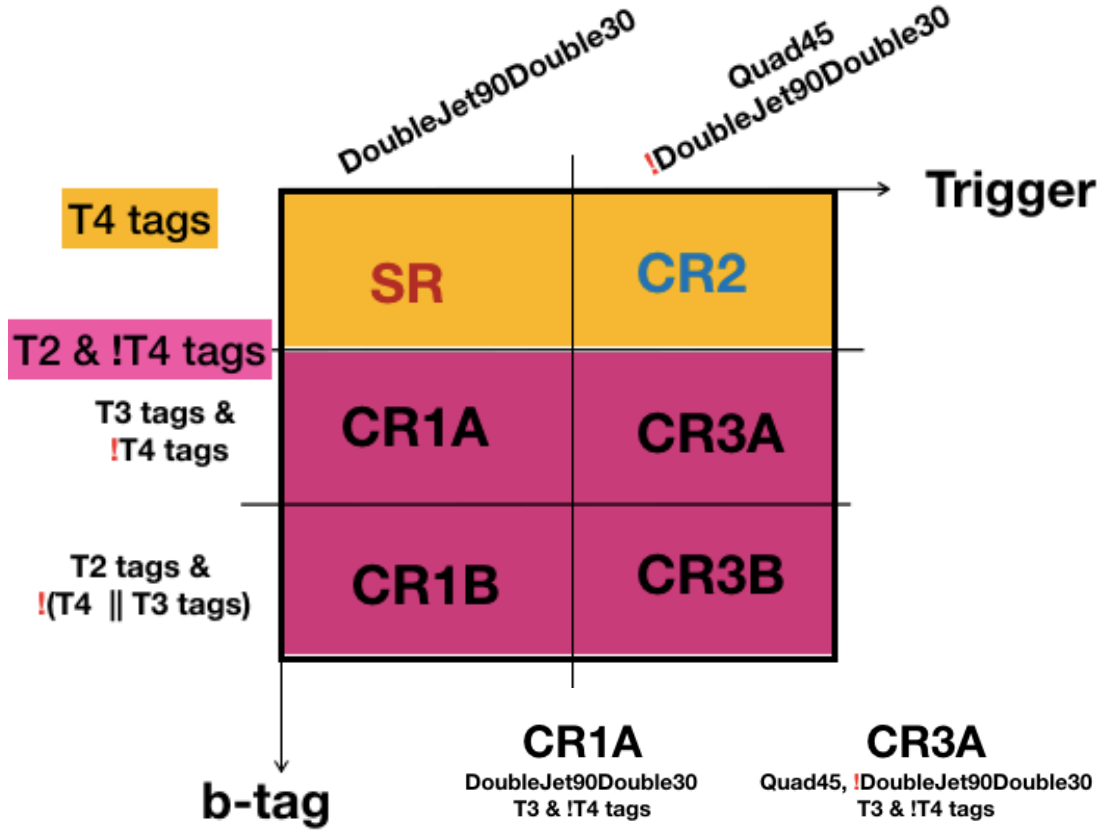


$$\frac{\text{CR1A}}{\text{CR1B}} = \frac{\text{CR3A}}{\text{CR3B}}$$

CR1A DoubleJet90Double30 T3 & !T4 tags	**CR3A** Quad45, !DoubleJet90Double30 T3 & !T4 tags
CR1B DoubleJet90Double30 T2 tags & !(T3 ||T4 tags)	**CR3B** Quad45, !DoubleJet90Double30 T2 tags & !(T3 ||T4 tags)

Data-driven Background Estimation
Closure





$$\frac{\text{CR1A} \; \substack{\text{DoubleJet90Double30} \\ \text{T3 \& !T4 tags}}}{\text{CR1B} \; \substack{\text{DoubleJet90Double30} \\ \text{T2 tags \& !(T3 ||T4 tags)}}} = \frac{\text{CR3A} \; \substack{\text{Quad45, !DoubleJet90Double30} \\ \text{T3 \& !T4 tags}}}{\text{CR3B} \; \substack{\text{Quad45, !DoubleJet90Double30} \\ \text{T2 tags \& !(T3 ||T4 tags)}}}$$

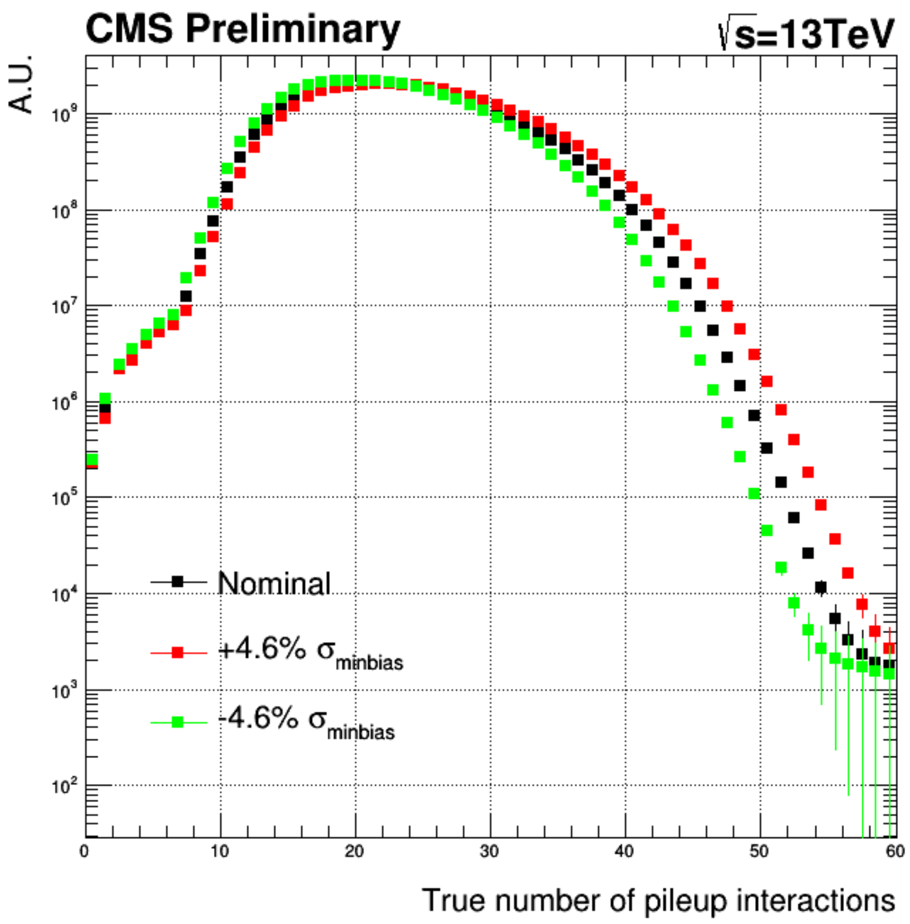
Uncertainty Estimation

Systematic Uncertainties
Pileup Weights

- The tNPU interactions in a single bunch crossing is given by:

$$N_i = \frac{\mathcal{L} \cdot \sigma_{minimum\ bias}}{\nu_{orbit}}$$

- Uncertainty comes from assuming a value for $\sigma_{minimum\ bias}$.
- To assess systematics, a $\pm 4.6\%$ variation was used, and PU weights were recalculated.



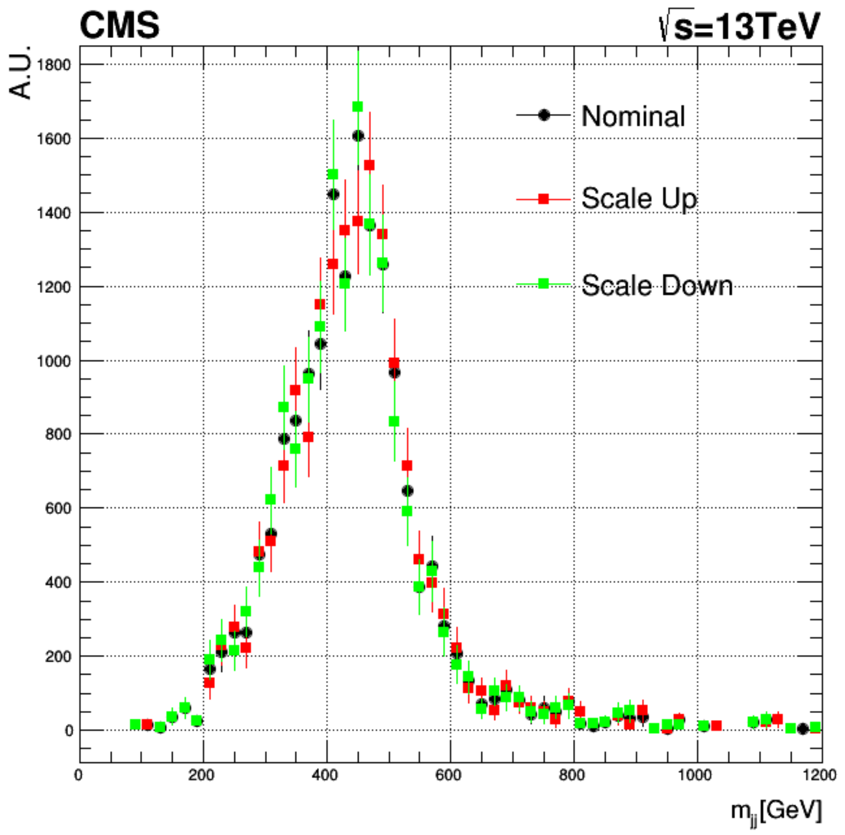
Systematic Uncertainties
Jet Energy Scale

- The uncertainty in the JEC comes from several uncorrelated sources such as:
  - Pileup
  - Jet flavor
- For M uncorrelated sources, the total uncertainty is given by:

$$S(p_T,\eta) = \sqrt{\sum_{i}^{M} {s_i}^2(p_T,\eta)}$$

Where s_i is the uncertainty for a single source.

- The JES uncertainty varies with p_T and η but is less than 4% in all regions of phas space for the 2016 recommendations.
- A variation is $\pm 1\sigma$ is performed in order to evaluate the effect of this uncertainty.



Systematic Uncertainties
PDF and α_s

- PDF uncertainties for Hessian sets
  - NNPDF31_nnlo_hessian_pdfas
  - 103 memories stored for each event
    - 0: central value, $\alpha_s(m_z^2)$ = 0.118
    - 1-100: PDF eigenvectors
  - Assuming $\alpha_s(m_z^2) = 0.1180 \ \pm 0.0015$ at 68%CL, both at NLO and NNLO.

$$\delta^{\mathrm{pdf}}\sigma = \sqrt{\sum_{k=1}^{N_{\mathrm{mem}}} \left(\sigma^{(k)} - \sigma^{(0)}\right)^2},$$

- To compute α_s uncertainty. Use the average in the α_s uncertainty.

$$\delta^{\alpha_s}\sigma = \frac{\sigma(\alpha_s = 0.1195) - \sigma(\alpha_s = 0.1165)}{2}$$

Systematic Uncertainties

- Jet Energy Resolution
  - JER is smeared by default in the JEC workflow.
  - To estimate systematic effects related to smearing, an additional $\pm 1\sigma$ on the JES uncertainty is applied.
- DeepCSV Weights:
  - To estimate systematic effects related to smearing, an additional $\pm 1\sigma$ on the DeepCSV SFs is applied.
- Trigger Weights
  - Since the trigger efficiency is fitted in order to obtain an event weight, the uncertainty of the trigger fit is propagated to the MC samples.
- Background shape estimation
  - To estimate the uncertainty from the extrapolation of the background in the SR, an error propagation is performed on a bin-by-bin basis.

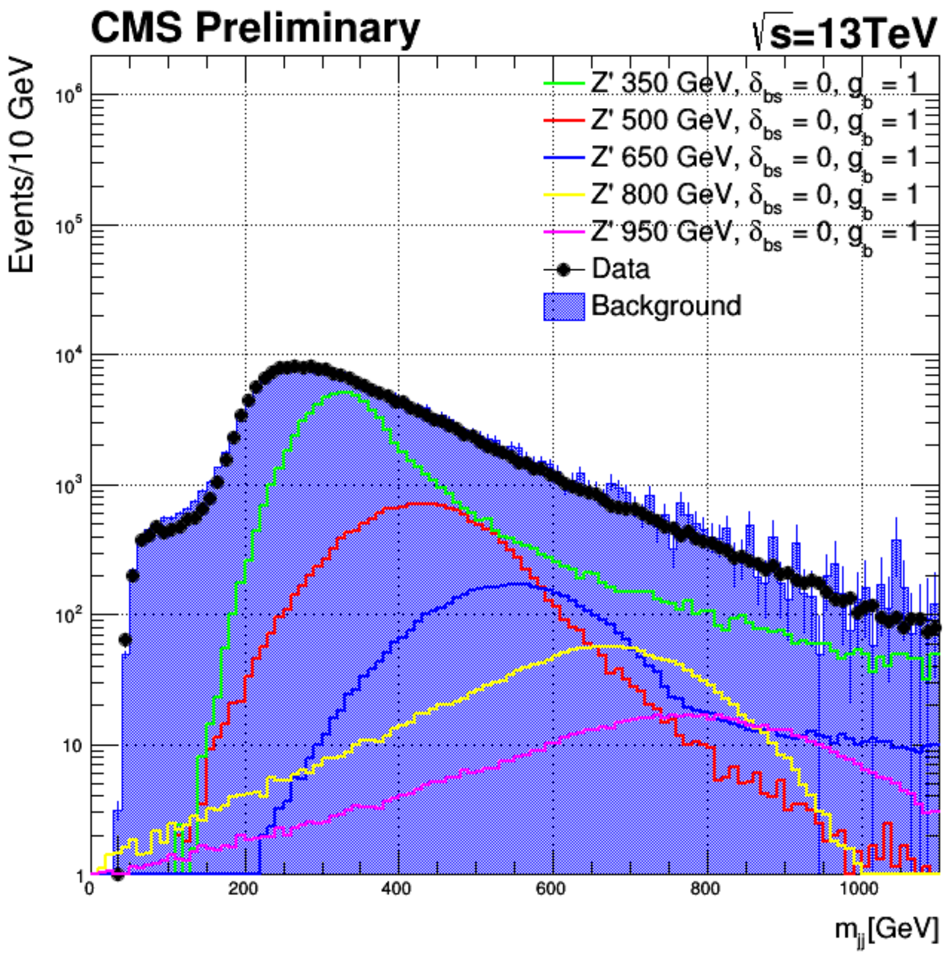
Systematic Uncertainties

Summary

Source	Type	Rate Uncertainty [%]	Notes
PDF choice	lnN	1.8-5.9	PDF uncertainty for BFF initiated processes
α_s	lnN	3.0-4.2	α_s uncertainty for BFF initiated processes
Luminosity 13 TeV	lnN	2.5	Signal
Jet Energy Scale	shape	0-0.23	Signal
Jet Energy Resolution	shape	0-0.57	Signal
Pileup Weight	lnN	6.5-9.3	Signal
DeepCSV Weight	lnN	5.6-8.5	Signal
Trigger Weight	lnN	3.2-4.9	Signal
background normalization	shape	5.0	Scale uncertainty for data-driven background prediction

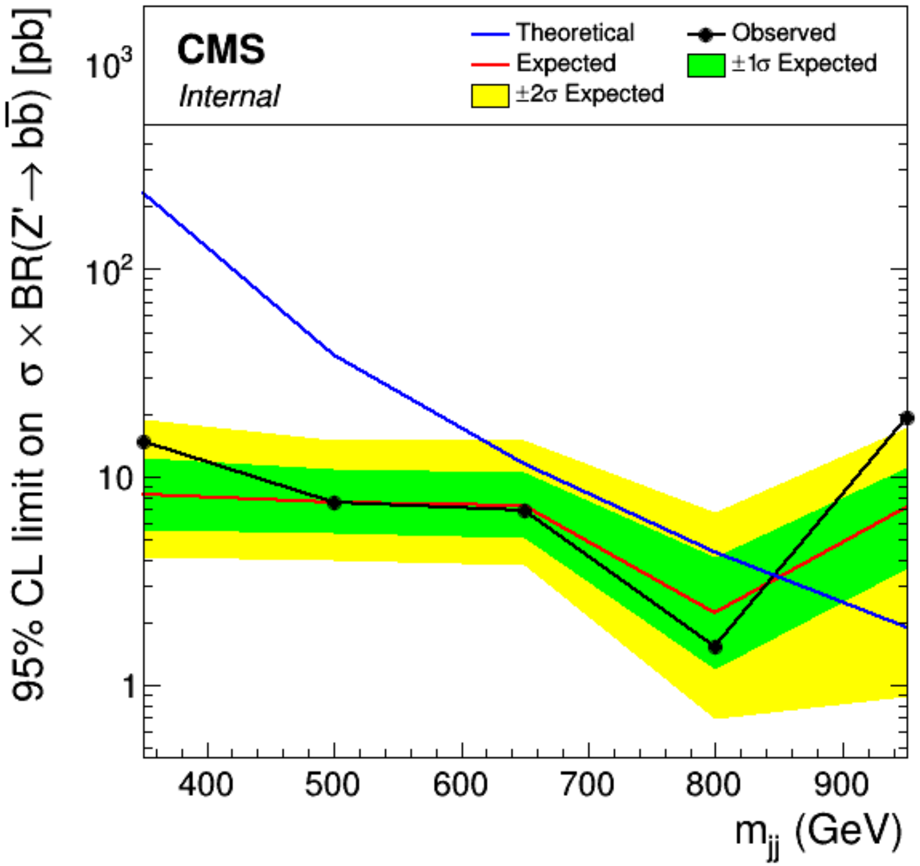
Results

m_{jj} distribution after SR unblinding



- Almost perfect agreement between SR and background estimation in data.
- In general, m_{jj} shape varies broadly with Z' mass.

Results



- Observed and median expected and 95% CLs upper limits on μ scaled by the Z' production cross section calculates with the asymptotic CLs method.
- Theoretical value is also plotted for comparison.
- The Z' production can be excluded for almost every mass point considered in the analysis, except for the case of 950 GeV.

Summary

- Search for a new heavy gauge boson decaying to a pair of b quarks in a 4 b-jet final state is presented.
- No significant excess id found in 35.9 fb^{-1} of 13 TeV data from CMS.
  - 95% CLs upper limit on Z' production cross section are set.

Future directions

- Account for different b-tagging algorithms during offline/online selection.
- Repeat analysis in officially produced signal MC datasets.
- Place limits in parameter space spanned by δ_{bs} values other then 0, for diffetent mass points