Search for a NMSSM H(125) → 2φ_1 → 4τ @ √s = 8 TeV

arXiv:1510.06534

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Motivation

- **NMSSM is MSSM extended by a singlet superfield** $\hat{S}$
  - This extra $\hat{S}$ *introduces*
    - a *new* scalar Higgs boson
    - a *new* pseudo scalar Higgs boson
    - a *new* higgsino

  In total, the NMMSM Higgs sector contains :

    - *3 CP even ($h_{1,2,3}$) 2 CP odd ($a_{1,2}$) & 2 charged ($H^{\pm}$)*

✓NMSSM is less constrained compared to MSSM

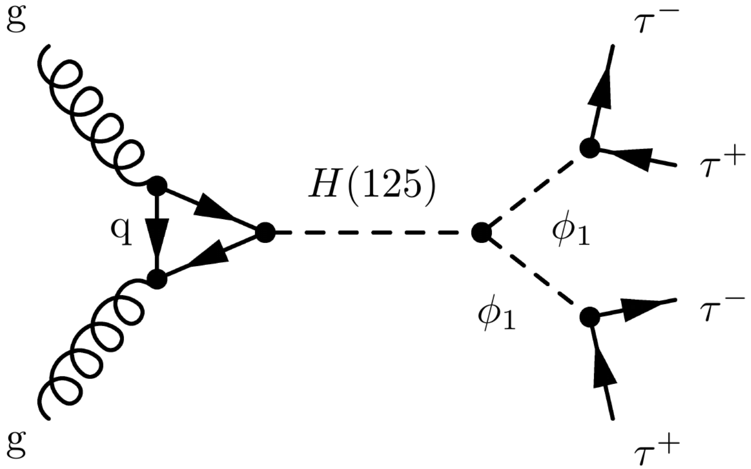
✓NMSSM solves the μ- & fine tuning problem

Signal Topology

$$h_2(h_1) \rightarrow 2\phi_1 \rightarrow 4\tau$$

Possible models

- $H(125)=h_2$, $H(125) \rightarrow h_1h_1$
- $H(125)=h_2$, $H(125) \rightarrow a_1a_1$
- $H(125)=h_1$, $H(125) \rightarrow a_1a_1$



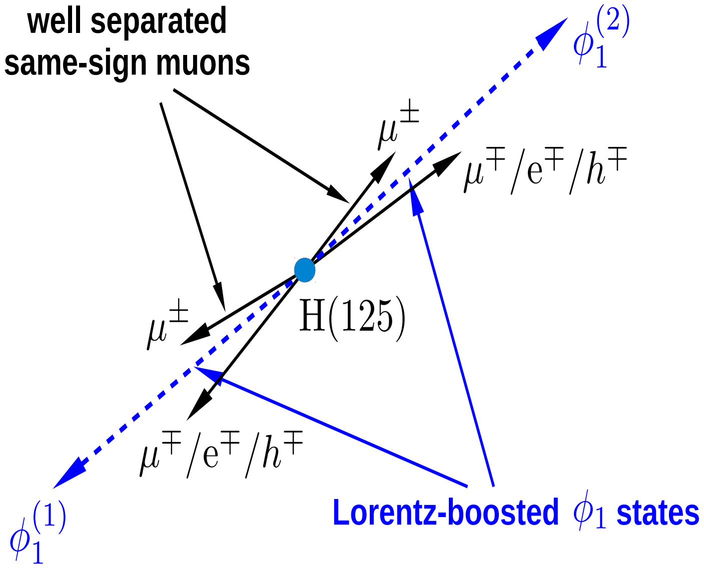
Production of NMSSM $h_{1,2}$ via gluon fusion

- $h_{1,2}$ are identified as the SM-like H(125) observed boson
- $\phi_1 = h_1, a_1$

CMS has explored $m_{\phi_1} < 2m_\tau$ but not $2m_\tau < m_{\phi_1} < 2m_b$

- Thus this analysis explores the 4 GeV < m_{ϕ_1} < 8 GeV region
- $\phi_1 \rightarrow \tau\tau$ dominates (as $\phi_1 \rightarrow b\tilde{b}$ is not kinematically allowed)

Signal Topology



Same-Sign μ with ΔR≫

⇒ Suppress $t\bar{t}$, DY, Wjet

$m_{H(125)} \gg m_{\phi_1}$ & H(125) small p_T

-ϕ_1 bosons highly *boosted* and "*back-to-back*"

-τ-leptons from the same ϕ1 overlap

⇒ thus, *hard* to reconstruct

⇒ use simple objects i.e. *μ* & tracks

τ decays

For each ϕ_1 decay leg :

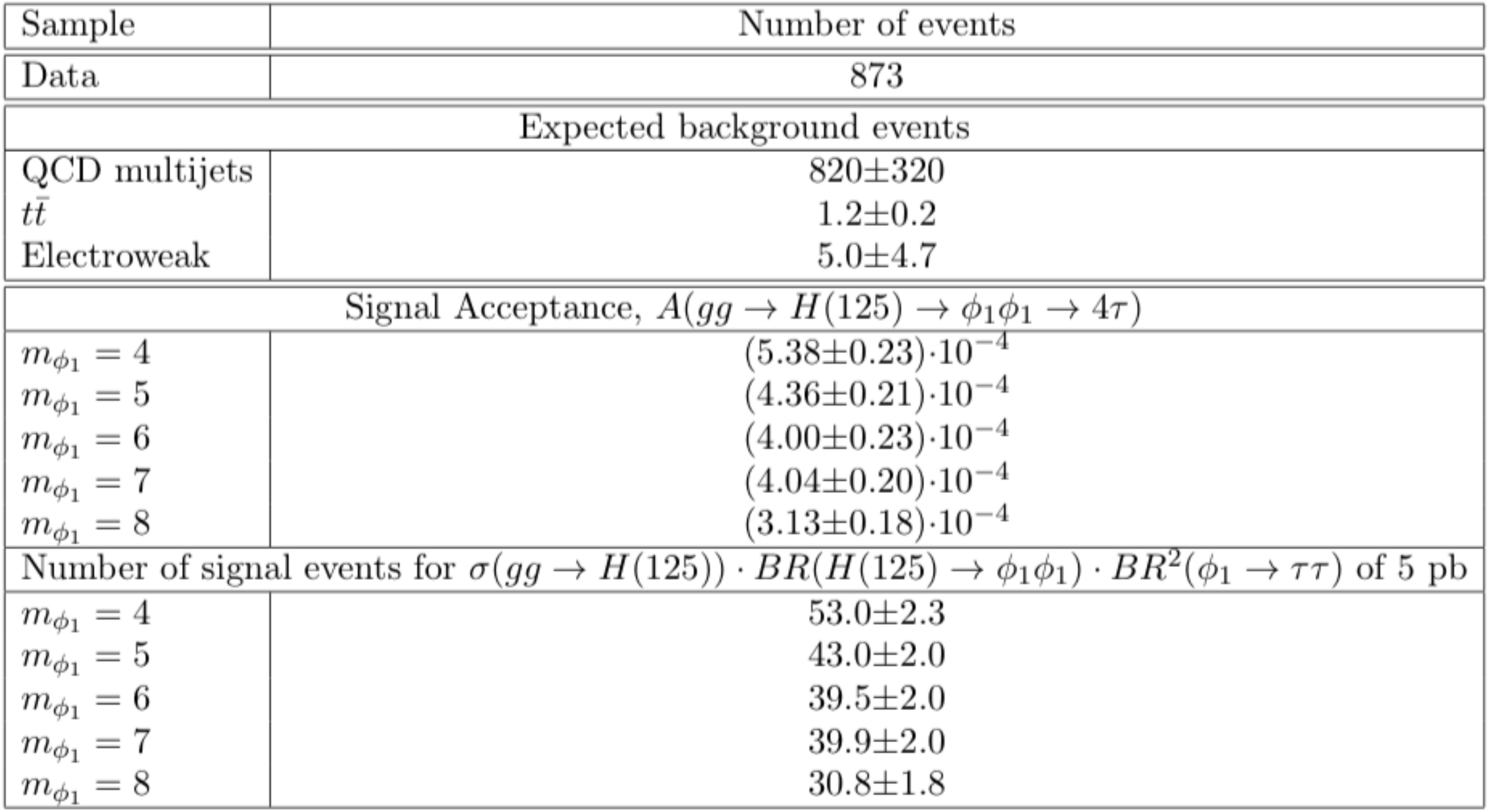
⇒ $\phi 1 \to \tau_\mu + \tau_e/\tau_\mu/\ \tau_{had,1\text{-prong}}$

⇒ All $\tau_{had,\ 1\text{-prong}}$ modes considered

⇒ Each μ is required to have exactly 1 nearby charged track ⇒ form 2 (μ-trk) pair systems

SS muons with large separation in (ϕ,η)

Event Yields after final selection



Sample	Number of events
Data	873
Expected background events	
QCD multijets	820±320
$t\bar{t}$	1.2±0.2
Electroweak	5.0±4.7
Signal Acceptance, $A(gg \to H(125) \to \phi_1\phi_1 \to 4\tau)$	
$m_{\phi_1} = 4$	$(5.38\pm0.23)\cdot10^{-4}$
$m_{\phi_1} = 5$	$(4.36\pm0.21)\cdot10^{-4}$
$m_{\phi_1} = 6$	$(4.00\pm0.23)\cdot10^{-4}$
$m_{\phi_1} = 7$	$(4.04\pm0.20)\cdot10^{-4}$
$m_{\phi_1} = 8$	$(3.13\pm0.18)\cdot10^{-4}$
Number of signal events for $\sigma(gg \to H(125)) \cdot BR(H(125) \to \phi_1\phi_1) \cdot BR^2(\phi_1 \to \tau\tau)$ of 5 pb	
$m_{\phi_1} = 4$	53.0±2.3
$m_{\phi_1} = 5$	43.0±2.0
$m_{\phi_1} = 6$	39.5±2.0
$m_{\phi_1} = 7$	39.9±2.0
$m_{\phi_1} = 8$	30.8±1.8

- QCD multijet background dominates final selected sample

  ⇒ Data driven estimation

- Other background processes < 1%

2D Mass Distributions as Final Discriminants

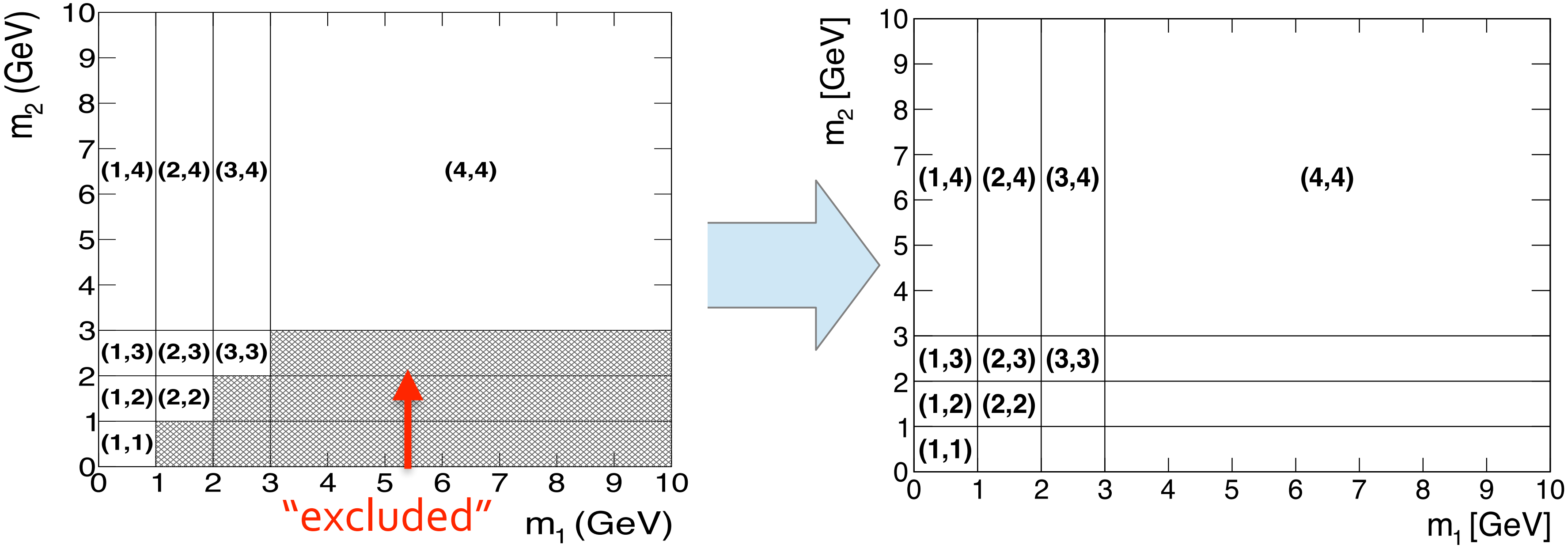
Main observable :

Invariant masses of the two *(μ,trk)* systems (m_1,m_2)

2D (m_1,m_2) distribution used for signal extraction

$$N(m_1, m_2) = N(m_2, m_1)$$

$$N_{ij} \to N_{ij} + N_{ji}, \;\; i \neq j$$



"excluded"
from signal extraction

Background Shape Modelling

Modelling of 2D (m_1,m_2) background shape in the SR

$$f_{2D}(m_1, m_2) = C(m_1, m_2) f_{1D}(m_1) f_{1D}(m_2)$$

$f_{2D}(m_1, m_2)$: the normalized 2D distr. of the (m_1,m_2) μ-track systems in the sample of QCD multijet events selected in the SR

$f_{1D}(m_i)$: the normalized 1D distr. of the inv. mass of the i^{th} μ-track system in the sample of QCD multijet events selected in the SR

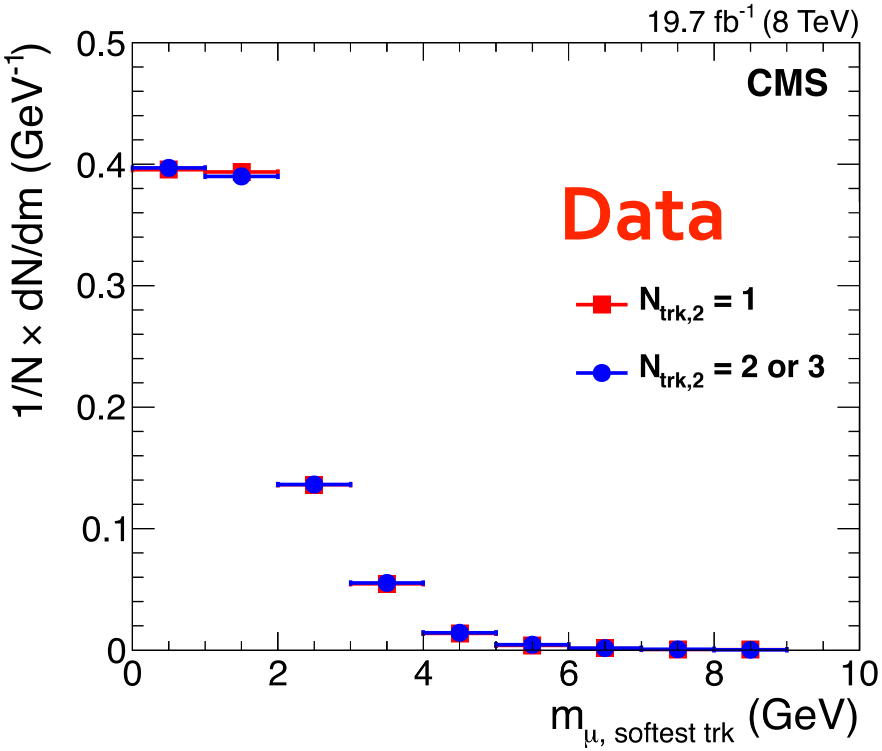
$C(m_1, m_2)$: accounts for correlations between (m_1,m_2)

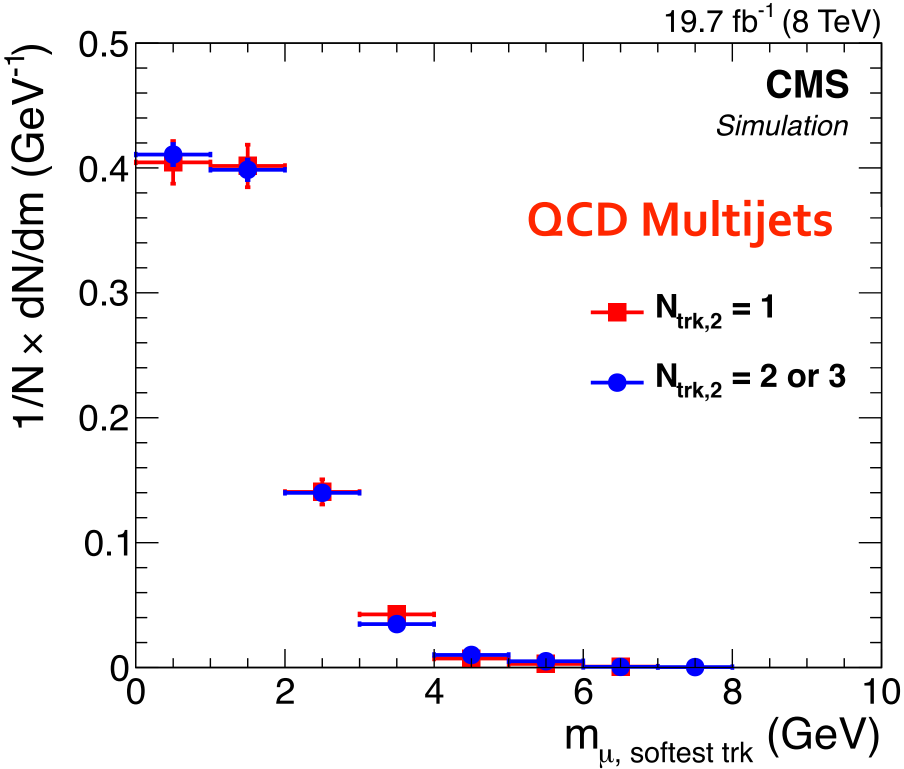
$C(m_1, m_2) = 1$: means no correlations between (m_1,m_2).

Background Shape Modelling

Shape of m_1 is independent of N_{trk} in $\Delta R<0.5$ around 2^{nd} μ (left plot)

- Use sideband (CR-A) with $N_{trk}=2,3$ around μ to model $f_{1D}(m)$
- Shapes in SR and sideband are compatible (validated at GEN level)

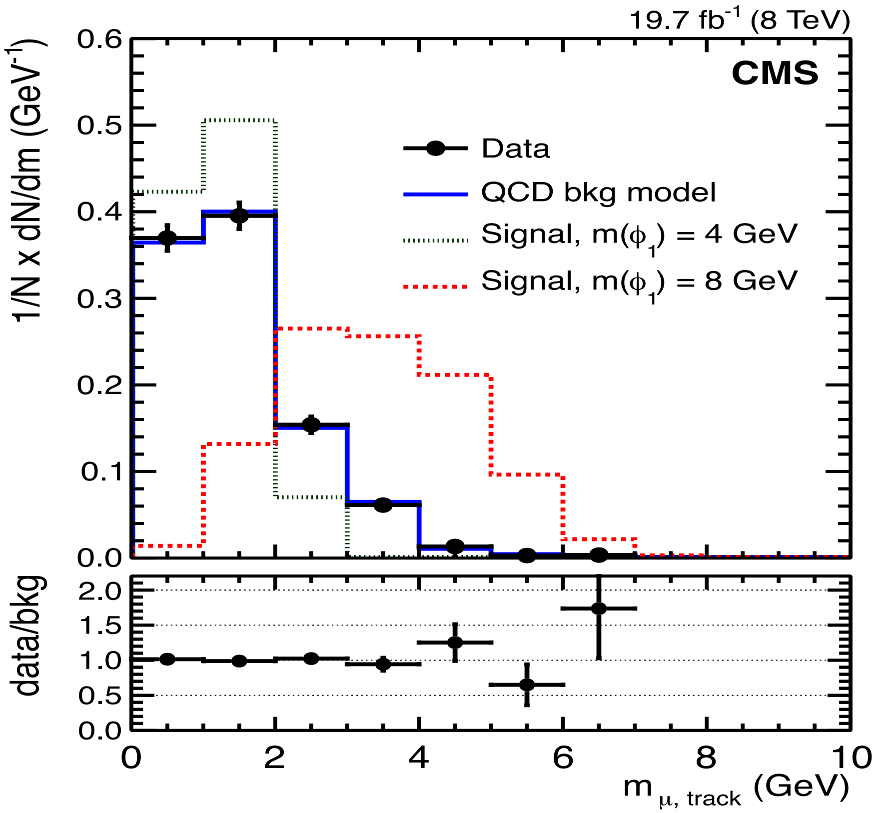




Shape of 1D mass distribution

μ-track system inv. mass is good discriminator of QCD vs signal

Normalized distr. of the μ-track system invariant mass



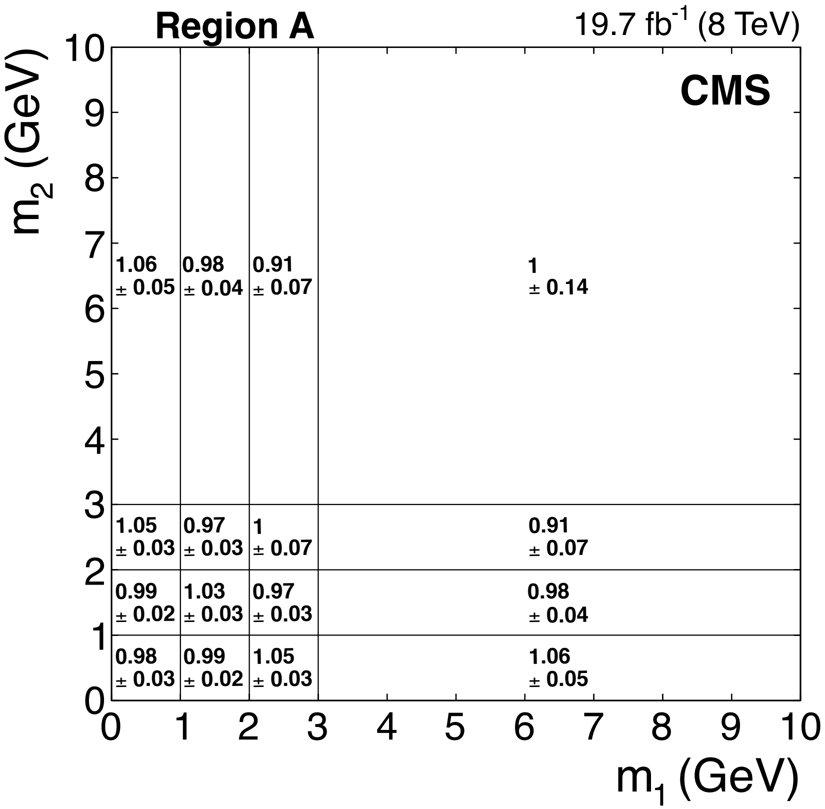
Data in SR

QCD from sideband

- Good separation for m_{ϕ_1} = 8 GeV
- Separation power decreases with decreasing m_{ϕ_1}

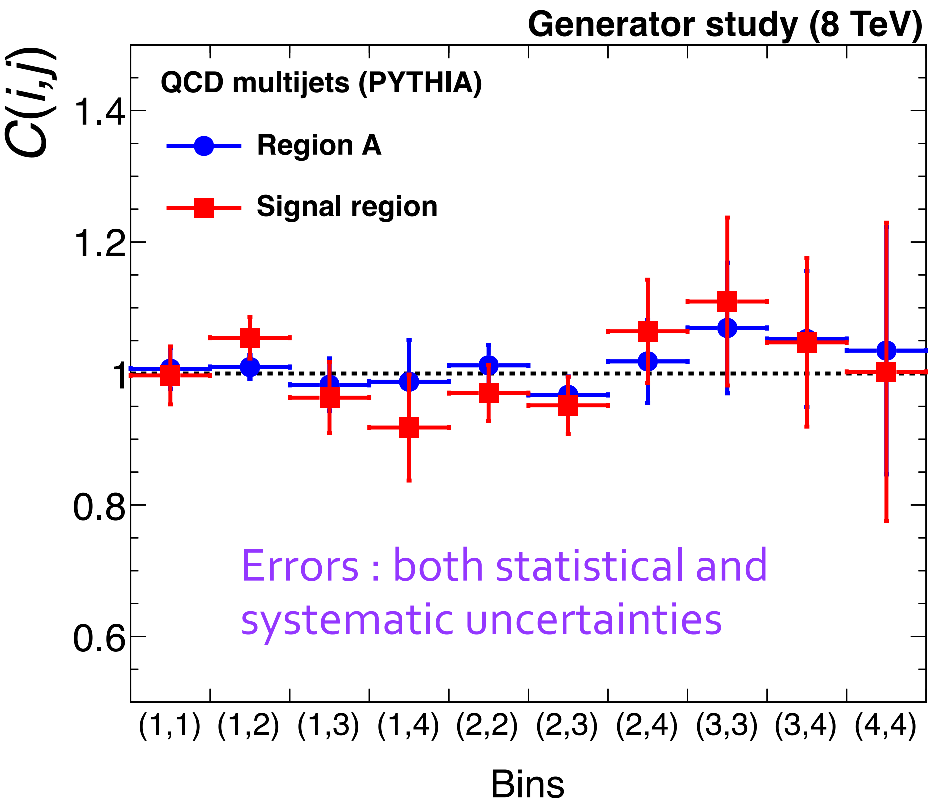
C (i,j) Mass Correlations

C(i,j) obtained in **CR-A (Data)**



C(i,j) from dedicated

$gg(q\bar{q}) \rightarrow b\bar{b}$ sample



Errors : both statistical and systematic uncertainties

C(i,j) obtained from QCD MC are consistent (within stat. uncertainties) with *C(i,j)* obtained from those in the background CR-A

Red :

Systematic Uncertainties on Background

Statistical uncertainty in background shape modelling :

- $f_{2D}(m_1,m_2)$ is dominated by uncert. in $C(i,j)$
- Bin-by-bin stat. uncertainties between 2-14%.
  - Accounted for by 10 nuisance parameters (1 per bin)

Systematic uncert related to extrapolation of C(i,j) from CR-A to SR:

- It is derived from dedicated MC study.
- Correlation coefficients between CR-A and SR are 2-22%
- Signal Contamination has been taken into account (small effect)

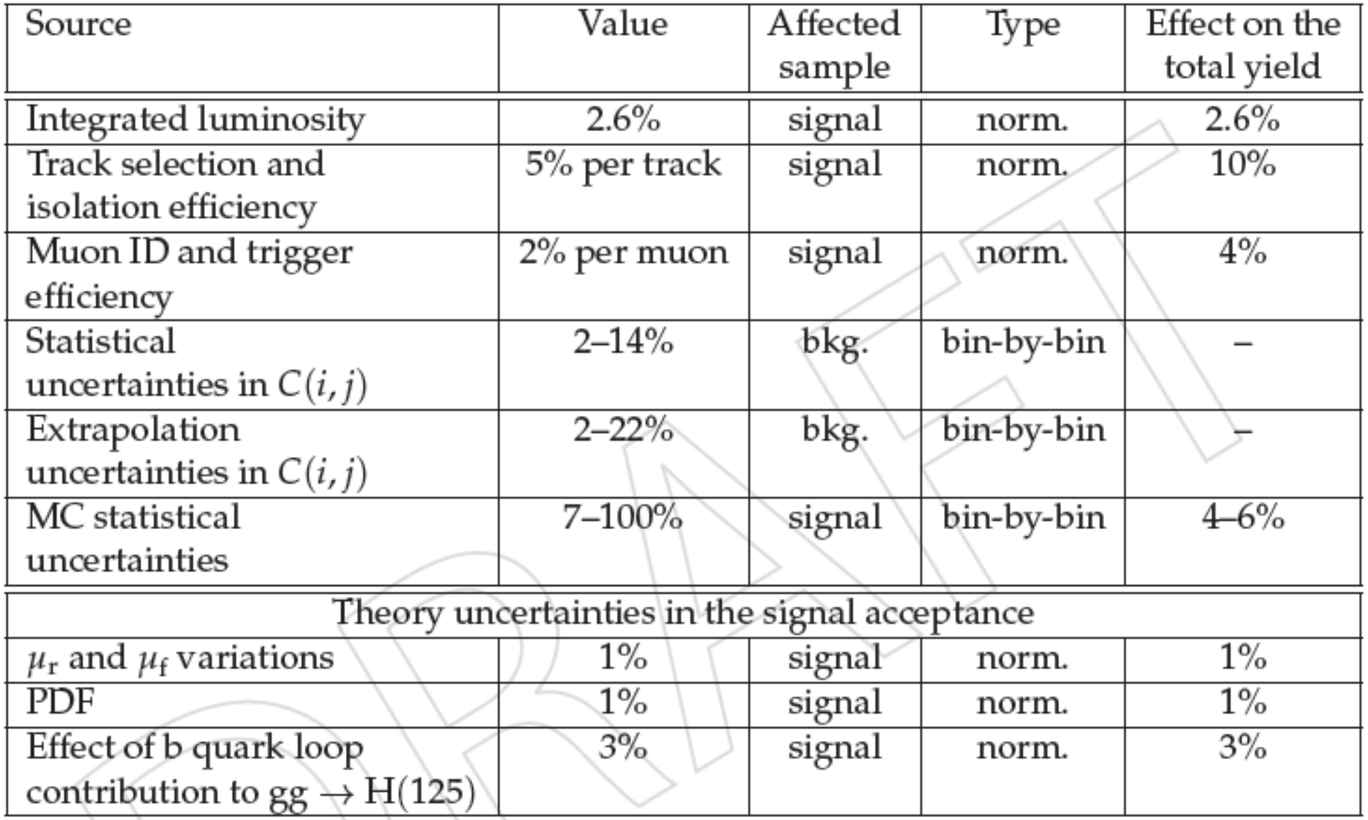
Systematic Uncertainties on Signal

Luminosity : 2.6 %

Muon-ID & Trigger efficiency : From T&P 2% per μ = 4%

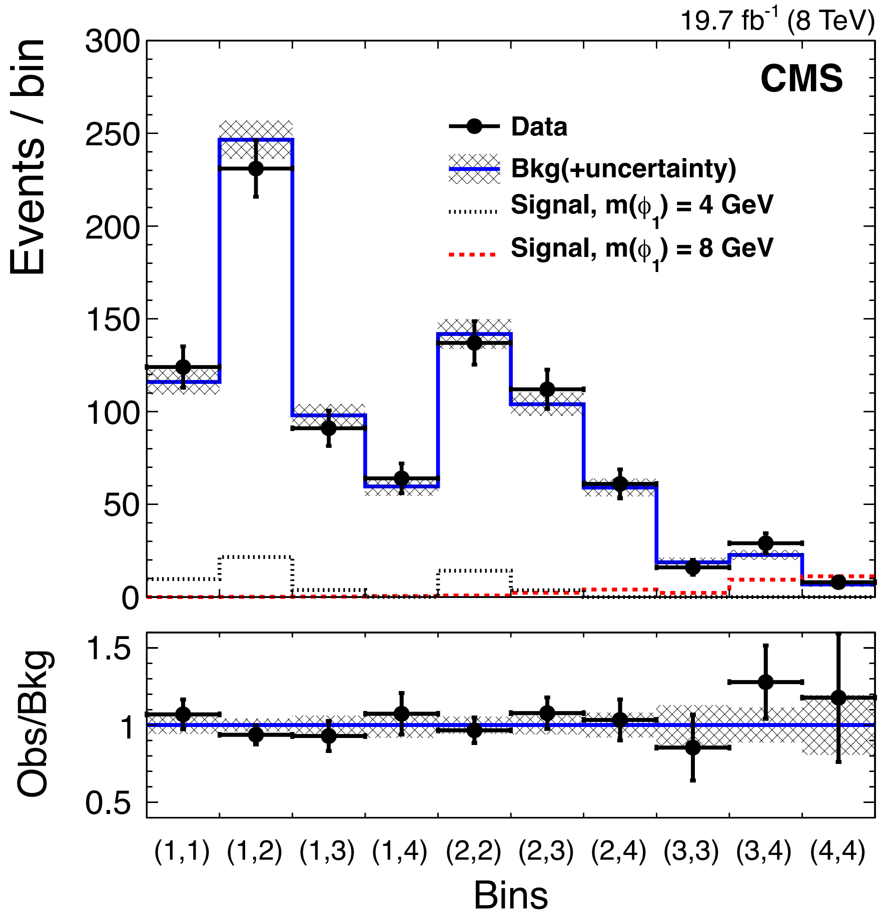
Track selection & Isolation : 10 % from dedicated study of Z→ττ→μ+Iso track

Muon & Track momentum scale : <0.5%, negligible effect on signal extraction

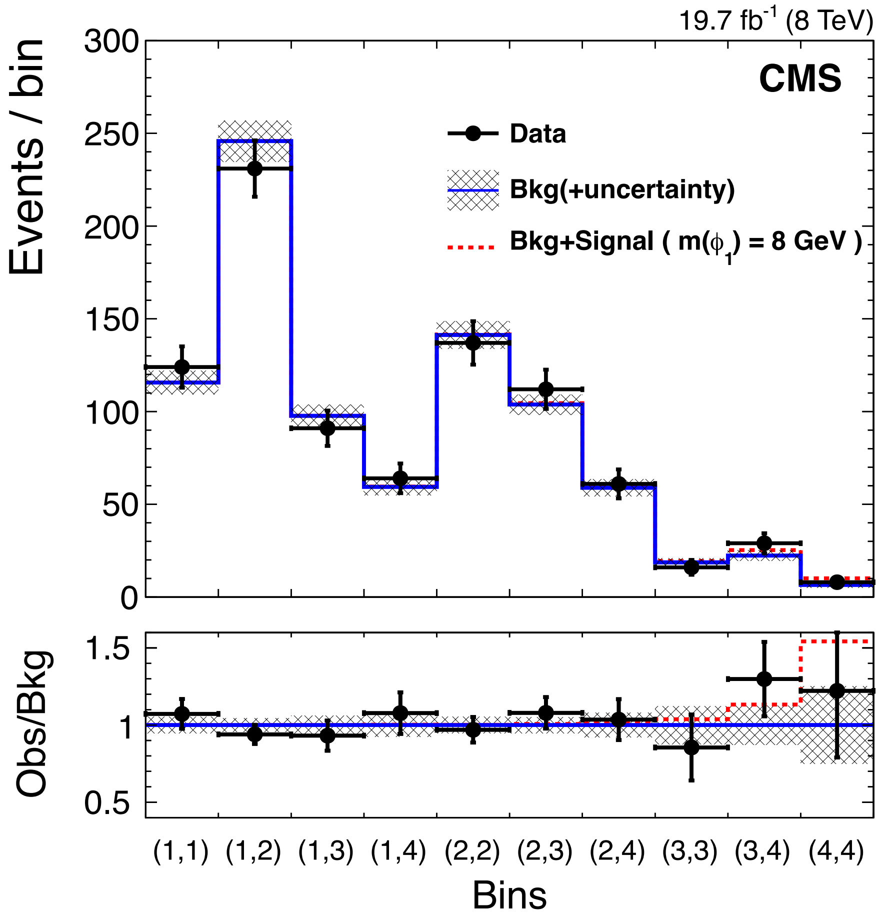


Source	Value	Affected sample	Type	Effect on the total yield
Integrated luminosity	2.6%	signal	norm.	2.6%
Track selection and isolation efficiency	5% per track	signal	norm.	10%
Muon ID and trigger efficiency	2% per muon	signal	norm.	4%
Statistical uncertainties in $C(i,j)$	2–14%	bkg.	bin-by-bin	–
Extrapolation uncertainties in $C(i,j)$	2–22%	bkg.	bin-by-bin	–
MC statistical uncertainties	7–100%	signal	bin-by-bin	4–6%
Theory uncertainties in the signal acceptance				
μ_r and μ_f variations	1%	signal	norm.	1%
PDF	1%	signal	norm.	1%
Effect of b quark loop contribution to gg → H(125)	3%	signal	norm.	3%

Final 2D (m ,m) distribution “unrolled” into 1D array of bins

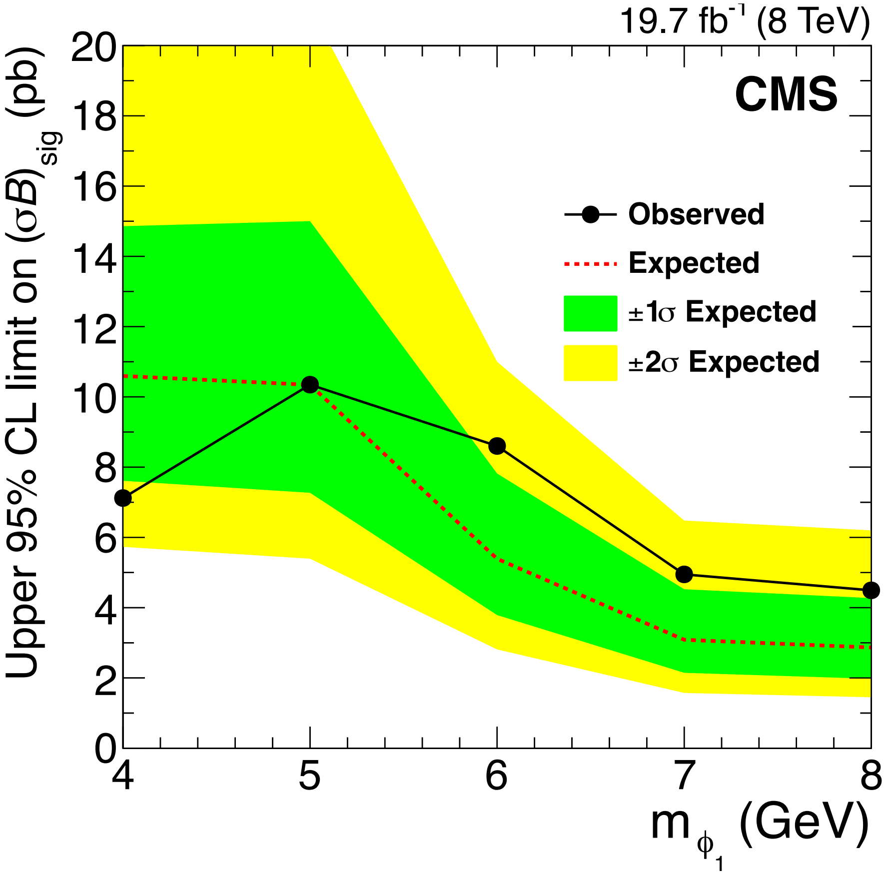


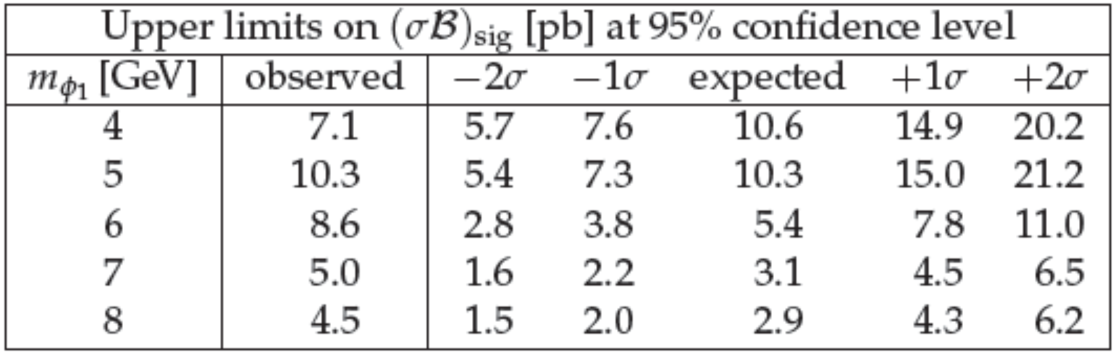
Bkg only hypothesis (signal for illustration)



Bkg+Sign hypothesis

Final Results





Upper limits on $(\sigma\mathcal{B})_{sig}$ [pb] at 95% confidence level						
m_{ϕ_1} [GeV]	observed	-2σ	-1σ	expected	$+1\sigma$	$+2\sigma$
4	7.1	5.7	7.6	10.6	14.9	20.2
5	10.3	5.4	7.3	10.3	15.0	21.2
6	8.6	2.8	3.8	5.4	7.8	11.0
7	5.0	1.6	2.2	3.1	4.5	6.5
8	4.5	1.5	2.0	2.9	4.3	6.2

Summary

Search for NMSSM $H(125) \rightarrow 2\phi_1 \rightarrow 4\tau$ in $[4 < m_{\phi 1} < 8]$ GeV

Performed with full RunI dataset (19.7 fb^{-1})

No significant excess above background expectation

-Set upper limits on the production *σ x BR*

-Observed upper limit @ 95 % C.L. [4.5 -10.3] pb for [8 - 5 GeV] $m_{\phi 1}$

The analysis is in arXiv:1510.06534 and soon to appear in JHEP

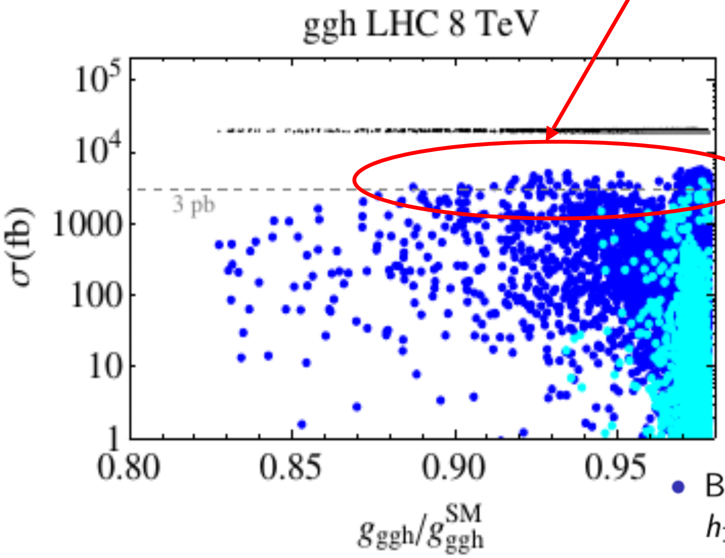
Backup

Signal Benchmark

NMMSM models are possible which predict

$\sigma(gg \to H(125)) \times BR(H(125) \to 2\phi_1 \to 4\tau)$ ~ few pb

D. Barducci, A. Belyaev S.Moretti



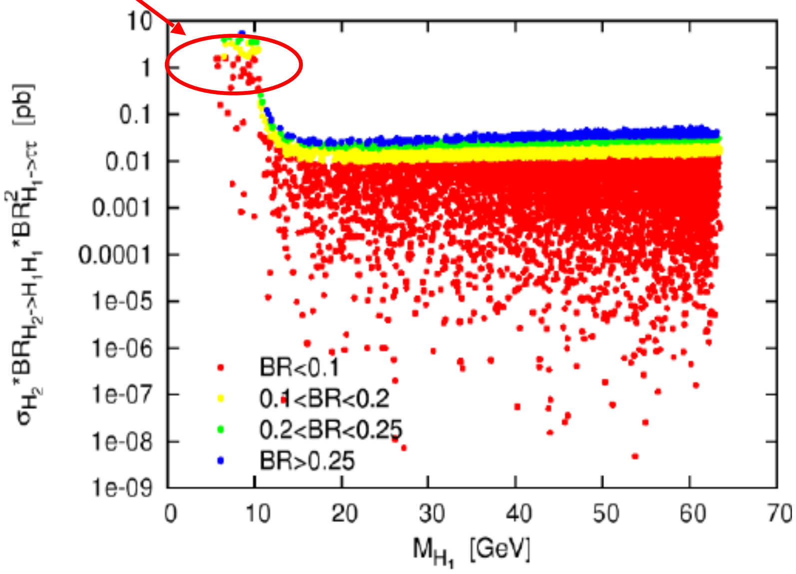
- Blue/Cyan: h_1/h_2 SM Higgs boson
- Black/Gray: $\sigma(pp \to h_{1/2}^{SM} X)$

$m_{a_1} \leq 10$ GeV

S.F. King, M. Muehlleitner, R. Nevzorov

Nucl. Phs. B860 (2012) [arXiv:1201.2671[hep-ph]]

"NMSSM Higgs Benchmarks Near 125 GeV"



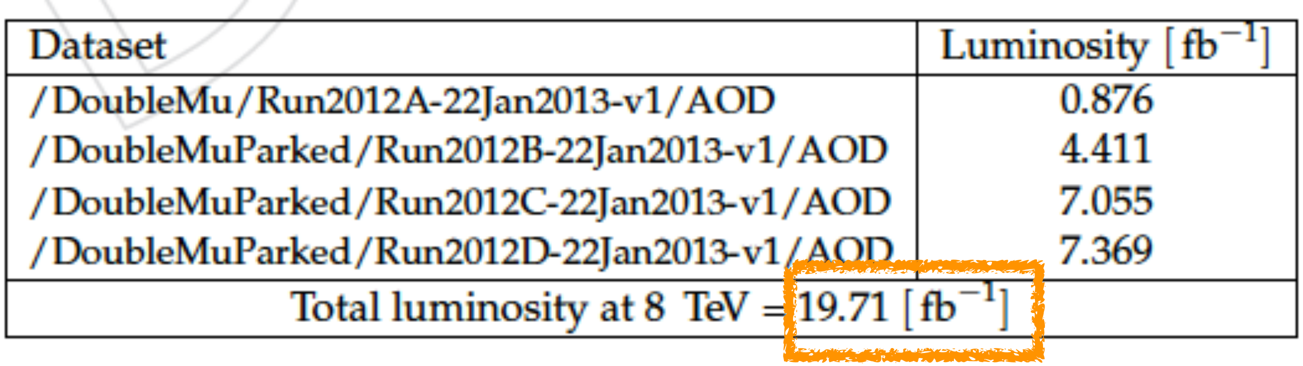
$\sigma(gg \to H(125) \times BR(H(125) \to 2\phi_1 \to 4\tau)$

vs. m_{H_1}

$$\sigma(gg \to H(125)) \times BR\ (H(125) \to 2\phi_1 \to 4\tau)$$

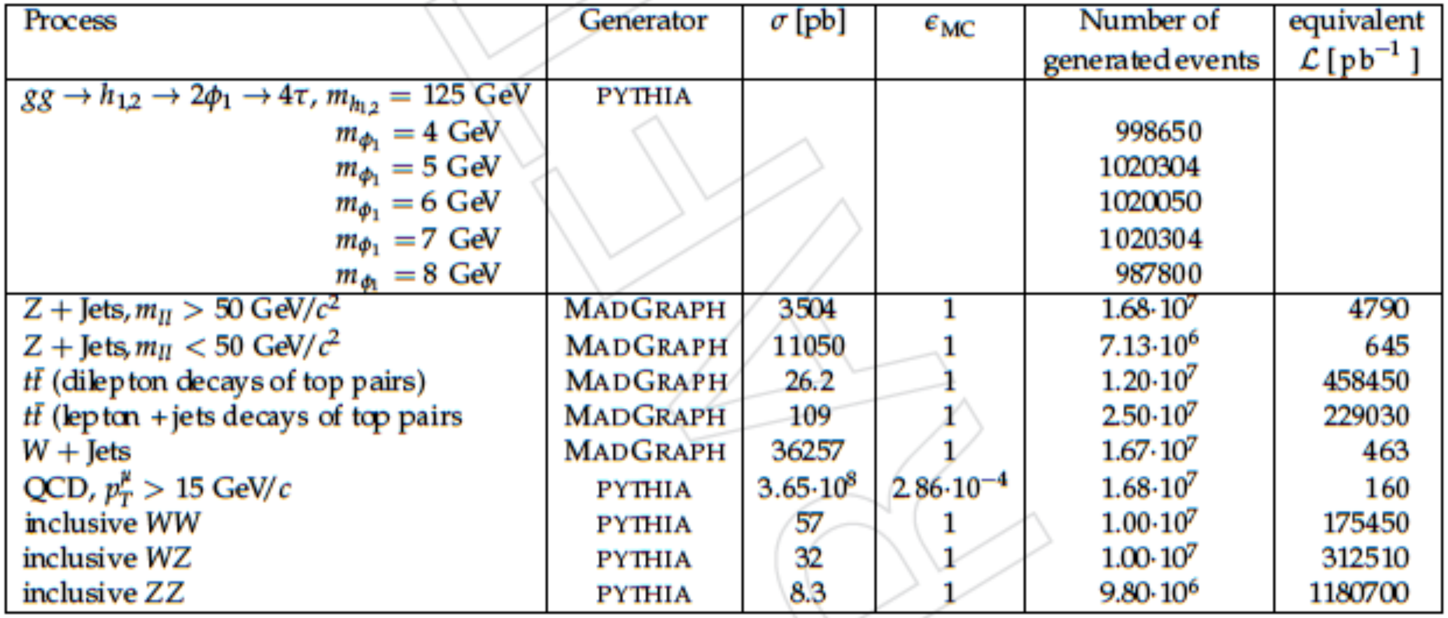
signal is benchmarked with $\sigma \times BR = 5$ pb

Datasets



Dataset	Luminosity [fb^{-1}]
/DoubleMu/Run2012A-22Jan2013-v1/AOD	0.876
/DoubleMuParked/Run2012B-22Jan2013-v1/AOD	4.411
/DoubleMuParked/Run2012C-22Jan2013-v1/AOD	7.055
/DoubleMuParked/Run2012D-22Jan2013-v1/AOD	7.369
Total luminosity at 8 TeV = 19.71 [fb^{-1}]	

JSON :Cert 190456-208686 8TeV 22Jan2013ReReco Collisions12 JSON.txt



Process	Generator	σ [pb]	ϵ_{MC}	Number of generated events	equivalent $\mathcal{L}$ [pb^{-1}]
$gg \to h_{1,2} \to 2\phi_1 \to 4\tau$, $m_{h_{1,2}} = 125$ GeV	PYTHIA				
$m_{\phi_1} = 4$ GeV				998650	
$m_{\phi_1} = 5$ GeV				1020304	
$m_{\phi_1} = 6$ GeV				1020050	
$m_{\phi_1} = 7$ GeV				1020304	
$m_{\phi_1} = 8$ GeV				987800	
Z + Jets, $m_{ll} > 50$ GeV/c^2	MADGRAPH	3504	1	$1.68 \cdot 10^7$	4790
Z + Jets, $m_{ll} < 50$ GeV/c^2	MADGRAPH	11050	1	$7.13 \cdot 10^6$	645
$t\bar{t}$ (dilepton decays of top pairs)	MADGRAPH	26.2	1	$1.20 \cdot 10^7$	458450
$t\bar{t}$ (lepton +jets decays of top pairs	MADGRAPH	109	1	$2.50 \cdot 10^7$	229030
W + Jets	MADGRAPH	36257	1	$1.67 \cdot 10^7$	463
QCD, $p_T^\mu > 15$ GeV/c	PYTHIA	$3.65 \cdot 10^8$	$2.86 \cdot 10^{-4}$	$1.68 \cdot 10^7$	160
inclusive WW	PYTHIA	57	1	$1.00 \cdot 10^7$	175450
inclusive WZ	PYTHIA	32	1	$1.00 \cdot 10^7$	312510
inclusive ZZ	PYTHIA	8.3	1	$9.80 \cdot 10^6$	1180700

Simulation samples used only for optimization studies

Signal selection

Triggers

Double muon: **HLT Mu17 Mu8 OR HLT Mu17 TkMu8**

μ

***muons fulfil PF-tight criteria** (from Muon POG)*

- Same-Sign (SS) muons with $\Delta R(\mu\text{-}\mu) > 2.0$
- $p_T > 17$ (10) GeV/c for 1st (2nd) μ , $|\eta| < 2.1$ & $|d_0|<0.03$ cm, $|d_z| < 0.1$ cm

tracks

Use of high-purity tracks (from Tracker POG)

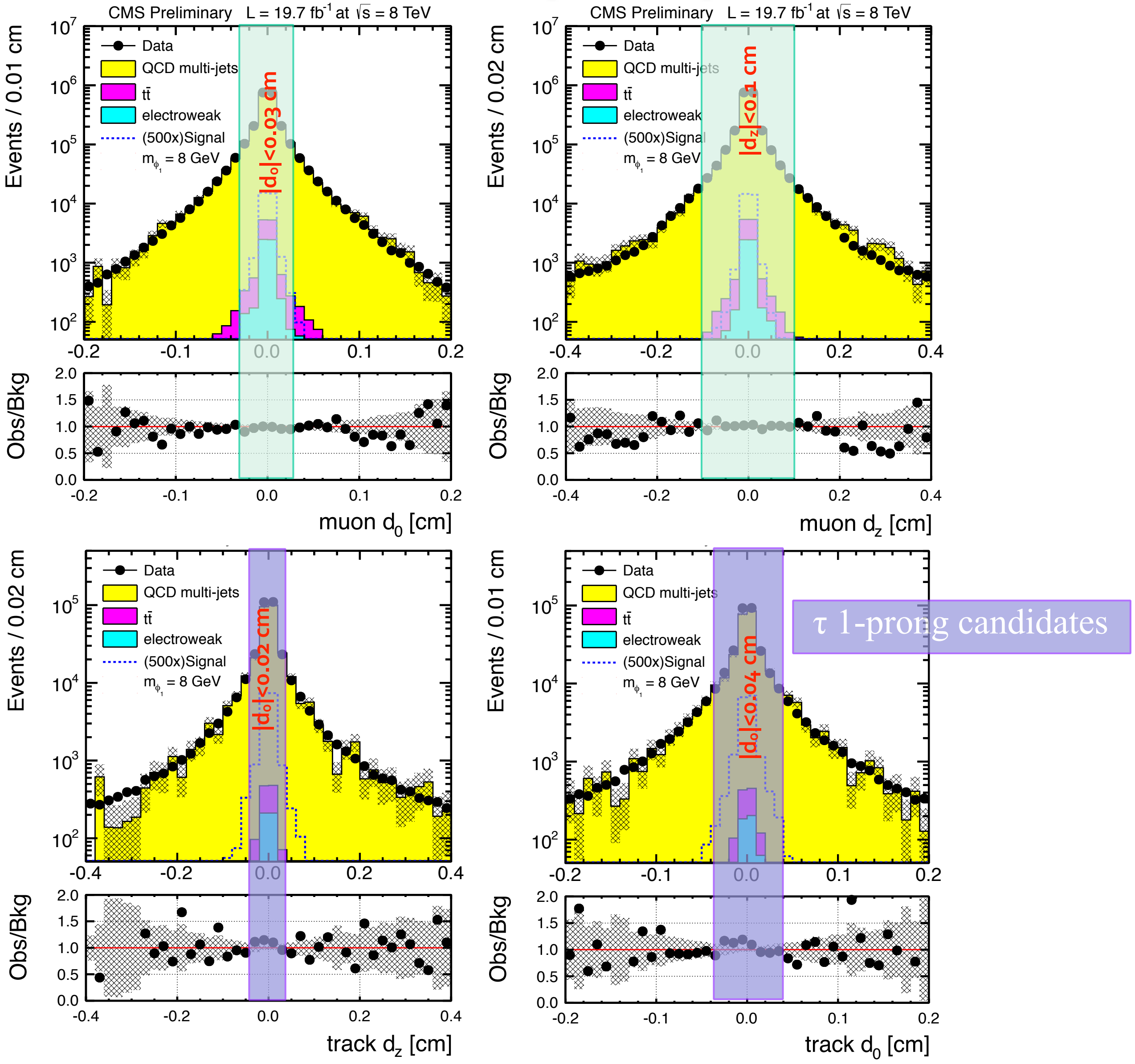
"*Isolation*" requirement for each μ :

== 1 track with $p_T > 1$ GeV/c, $|\eta| < 2.4$, $|d_0|<1$ cm, $|d_z| < 1$ cm in $\Delta R<0.5$ around μ

1-prong τ-decay candidates :

- charge opposite to that of μ i.e. $q_\mu + q_{trk} = 0$
- $p_T > 2.5$ GeV/c, $|\eta| < 2.4$ & $|d_0| < 0.02$ cm, $|d_z| < 0.04$ cm

Impact parameters



τ 1-prong candidates

Selection:

- trigger
- SS muons
- p_T>17 (10) GeV/c
- |n| < 2.1
- no track req.

Selection:

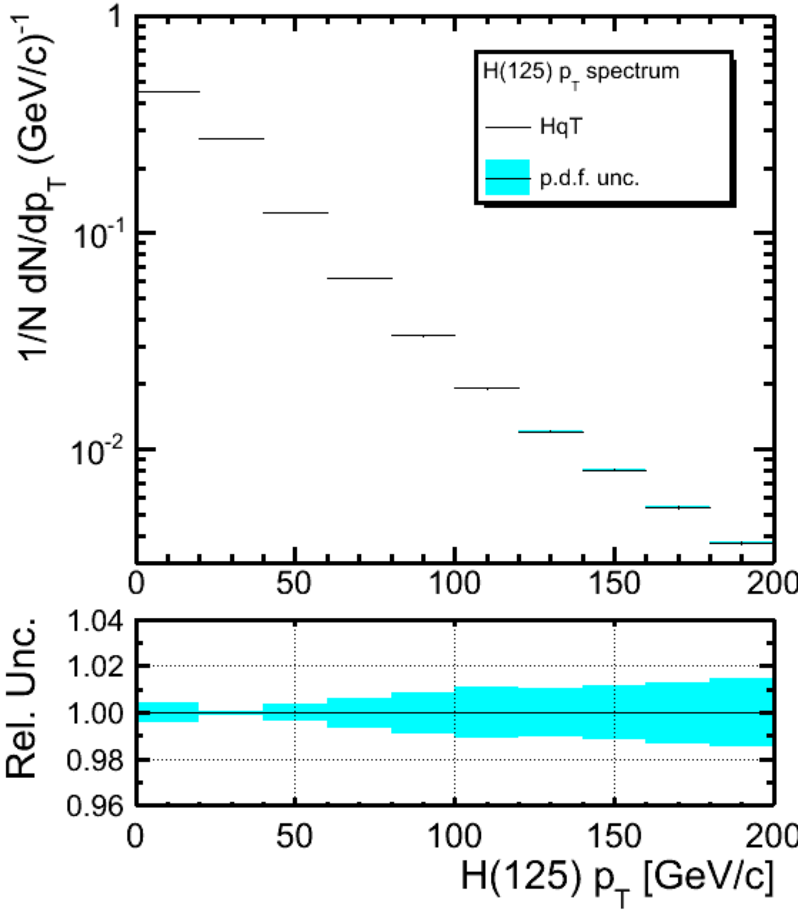
- trigger
- SS muons
- p_T>17 (10) GeV/c
- |n| < 2.1
- tracker isolation req.

tighter d_z/d_0 cuts suppress further the bkg. contribution

Theoretical Uncertainties on Signal

Renormalization / factorization scales : 1 % (with HqT)

PDF : 1% - vary PDF param. set in HqT and recompute signal acc. (MSTWnlo2008.)



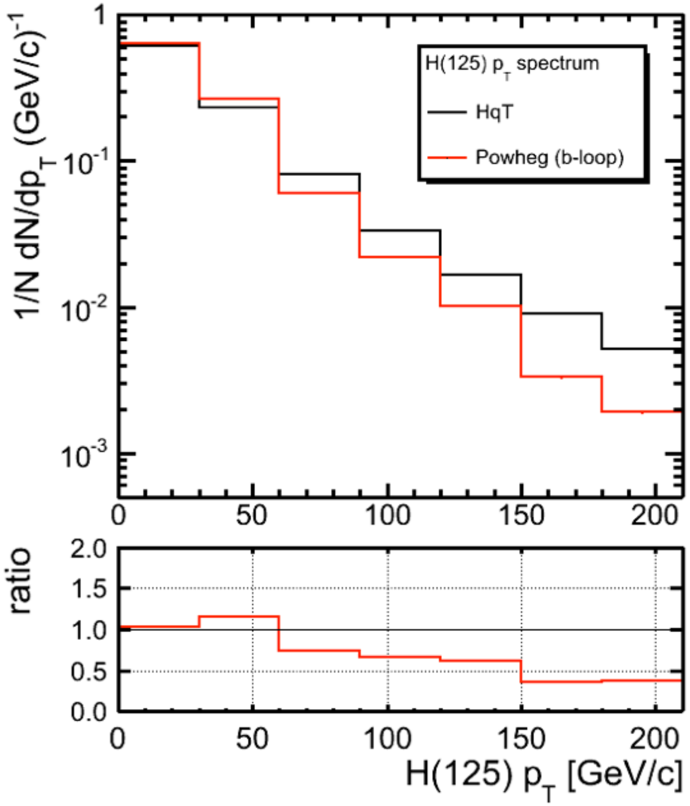
Effect of pdf uncertainty on H(125) p_T spectrum

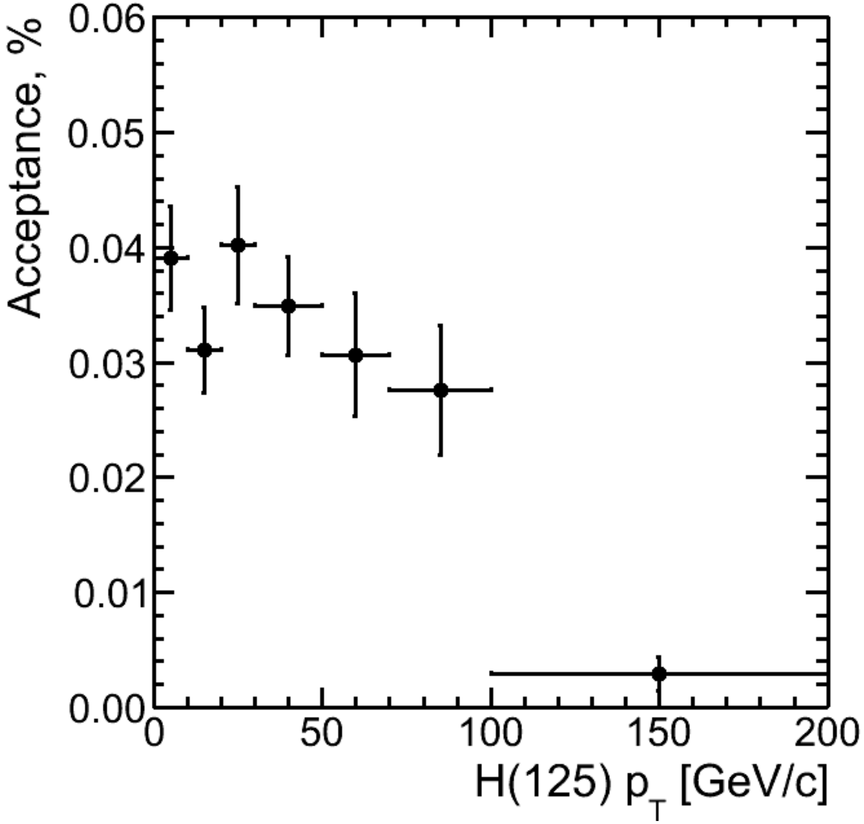
Theoretical Uncertainties on Signal

Renormalization / factorization scales : 1 % (with HqT)

PDF : 1% (vary PDF set in HqT and recompute signal acceptance)

b-loop to gluon fusion: 3% (Powheg sample with only b-loop contribution)





Signal acceptance is nearly flat vs H(125) p$_T$ up to ~ 100 GeV/c

Modeling of $C(m_1,m_2)$ & background CR

To study (m_1,m_2) correlations we introduce QCD background enriched Control Regions (CR)

Definition of CR

A : 2 SS μ in SR **+** each μ has **2 or 3** tracks within $\Delta R < 0.5$ - **1** track has to satisfy 1-prong τ-lepton req. while rest tracks **$1 < p_T < 2.5$ GeV/c (QCD multisite sample)**

B : Used to assess differences of *C(i,j)* in SR vs **A. (dedicated MC sample)**

- At least **1** track has to satisfy 1-prong τ-lepton req. with any number of tracks
- **Muons can be paired with softest/hardest 1-prong τ-lepton cand.**

- Both CR are dominated by QCD background
- Background over Signal ratio is enhanced in CR by a factor 12-20

Mu Id and Iso Efficiency

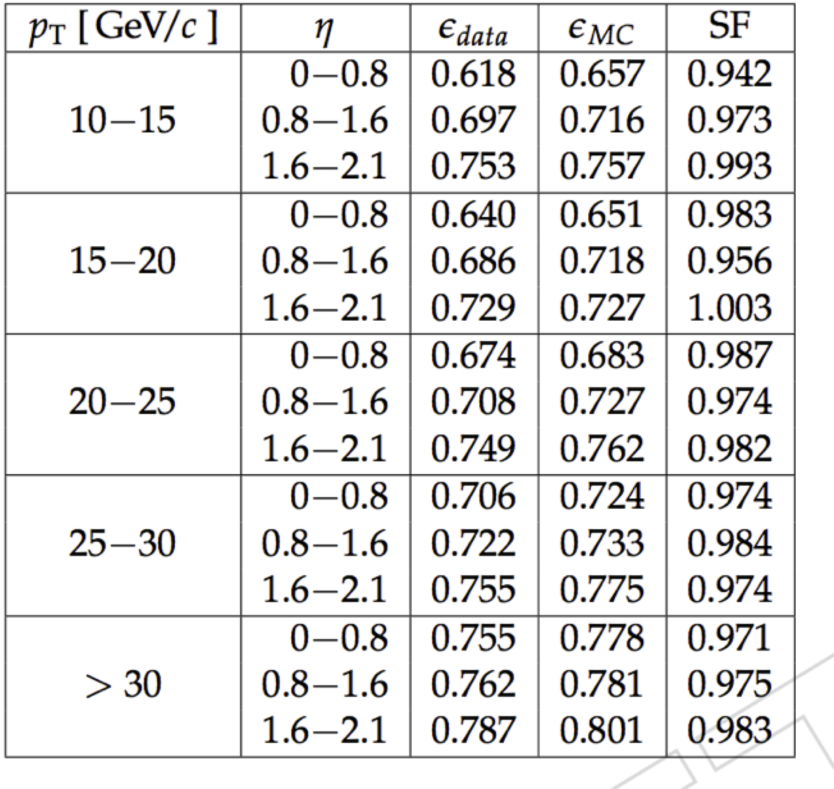
A. Tag-and-probe with Z → μμ events

B. Tight-PF Muon Id
   A. global and PF muon
   B. chi2 / ndof < 10
   C. at least on muon hit
   D. muon segments in at least two muon stations
   E. # pixel hits ≥ 1
   F. # tracker hits ≥ 6
   G. $|d_0| < 0.03$ cm and $|d_z| < 0.1$ cm

C. Isolation (in correspondence with H → 2h → 4τ analysis)
   A. no tracks with $p_T > 1$ GeV, $|d_0| < 1$ cm and $|d_z| < 1$ cm in the ΔR cone of 0.5 around muon direction

Muon-ID & isolation efficiencies

- **Tag&Probe** on Z →μμ passing HLT_IsoMu24_eta2p1 trigger
- **Tag muon** : satisfies PF tight Muon ID & HLT trigger object
- **Probe muon** : muon ID + track iso criteria (no track with pT>1 GeVm |d0| < 1 cm, |dz| < 1 cm within ΔR < 0.5 around μ



p_T [GeV/c]	η	ϵ_{data}	ϵ_{MC}	SF
10–15	0–0.8	0.618	0.657	0.942
	0.8–1.6	0.697	0.716	0.973
	1.6–2.1	0.753	0.757	0.993
15–20	0–0.8	0.640	0.651	0.983
	0.8–1.6	0.686	0.718	0.956
	1.6–2.1	0.729	0.727	1.003
20–25	0–0.8	0.674	0.683	0.987
	0.8–1.6	0.708	0.727	0.974
	1.6–2.1	0.749	0.762	0.982
25–30	0–0.8	0.706	0.724	0.974
	0.8–1.6	0.722	0.733	0.984
	1.6–2.1	0.755	0.775	0.974
> 30	0–0.8	0.755	0.778	0.971
	0.8–1.6	0.762	0.781	0.975
	1.6–2.1	0.787	0.801	0.983

Trigger Efficiency

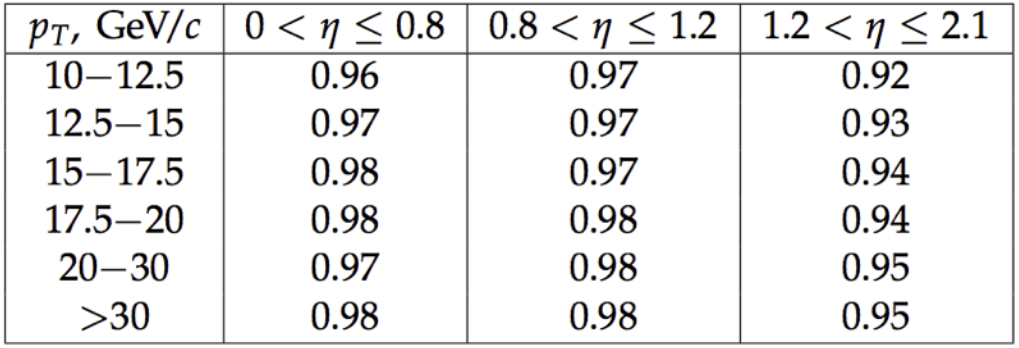
Trigger efficiency obtained from a Z →μμ sample
Each event is reweighted with

$$w_{trig} = \Big(\epsilon^{\text{leg17}}(p_{T,1},\eta_1)\cdot\epsilon^{\text{leg8}}(p_{T,2},\eta_2) + \epsilon^{\text{leg17}}(p_{T,2},\eta_2)\cdot\epsilon^{\text{leg8}}(p_{T,1},\eta_1) - \epsilon^{\text{leg17}}(p_{T,1},\eta_1)\cdot\epsilon^{\text{leg17}}(p_{T,2},\eta_2)\Big) \times\epsilon_{DzFilter}$$

- $\epsilon^{\text{leg17}}(p_T,\eta)$: p_T, η dependent efficiency of the trigger leg with $p_T > 17$ GeV
- $\epsilon^{\text{leg8}}(p_T,\eta)$: p_T, η dependent efficiency of the trigger leg with $p_T > 8$ GeV
- $p_{\text{T},1}$ and η_1 are transverse momentum and pseudo-rapidity of the first muon
- $p_{\text{T},2}$ and η_2 are transverse momentum and pseudo-rapidity of the second muon
- $\epsilon_{d_Z filter}$ - efficiency of $d_Z filter$ of the double muon trigger

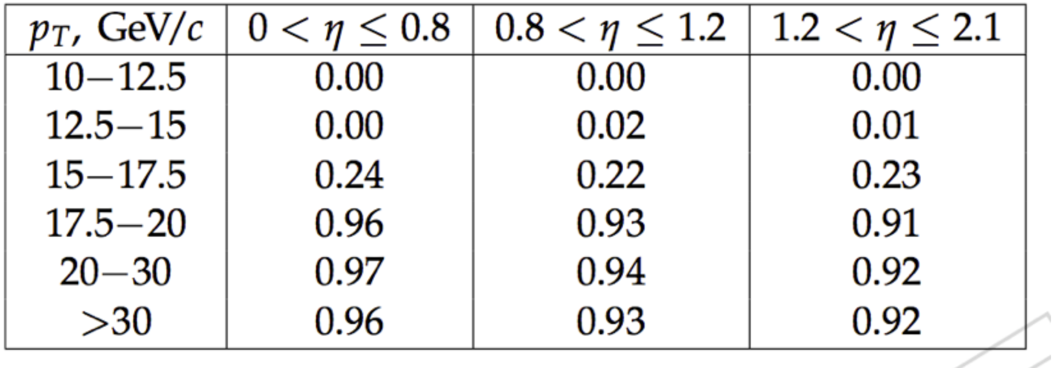
Trigger Efficiencies (relative to offline selection)

leg8



p_T, GeV/c	$0 < \eta \leq 0.8$	$0.8 < \eta \leq 1.2$	$1.2 < \eta \leq 2.1$
10–12.5	0.96	0.97	0.92
12.5–15	0.97	0.97	0.93
15–17.5	0.98	0.97	0.94
17.5–20	0.98	0.98	0.94
20–30	0.97	0.98	0.95
>30	0.98	0.98	0.95

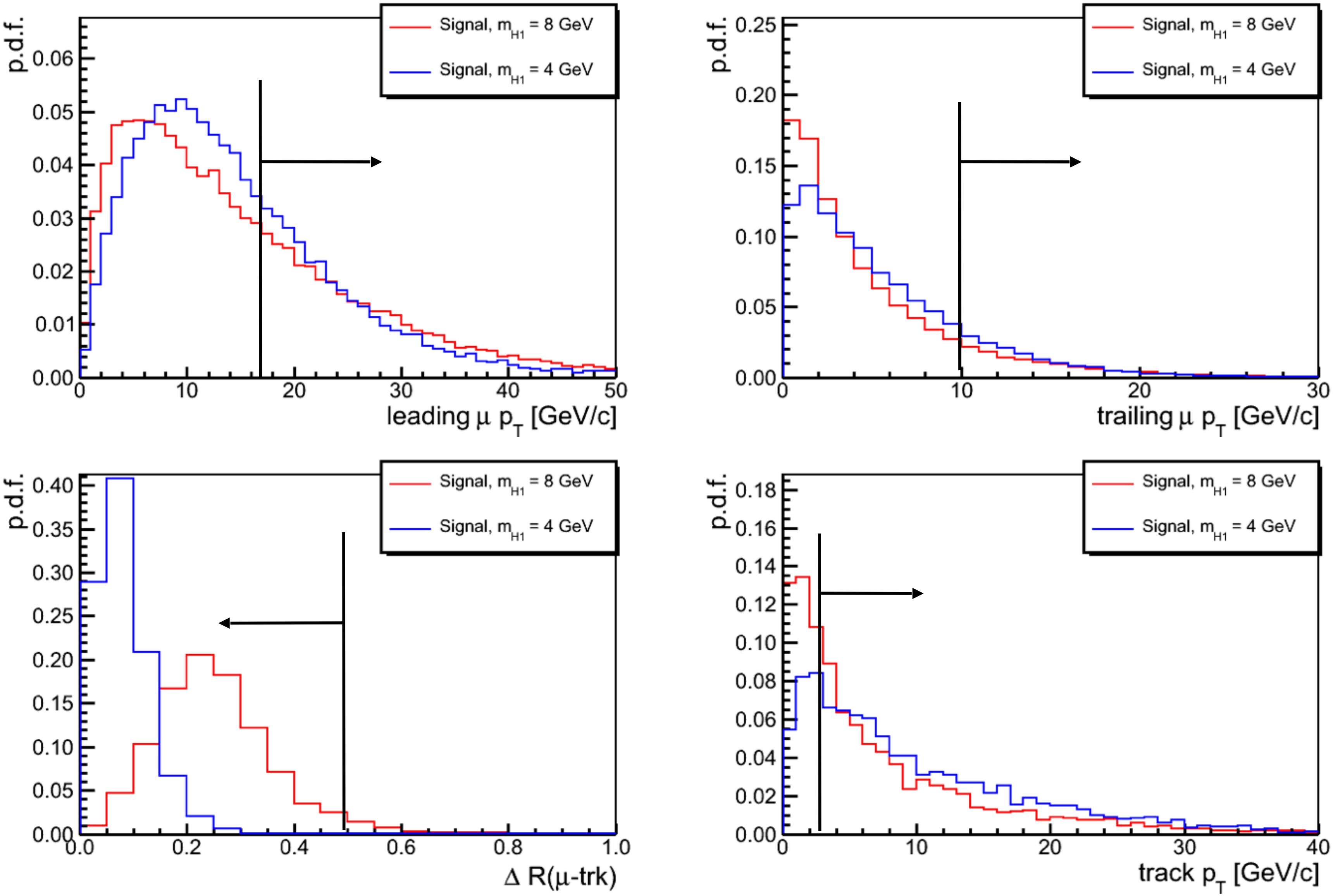
leg17



p_T, GeV/c	$0 < \eta \leq 0.8$	$0.8 < \eta \leq 1.2$	$1.2 < \eta \leq 2.1$
10–12.5	0.00	0.00	0.00
12.5–15	0.00	0.02	0.01
15–17.5	0.24	0.22	0.23
17.5–20	0.96	0.93	0.91
20–30	0.97	0.94	0.92
>30	0.96	0.93	0.92

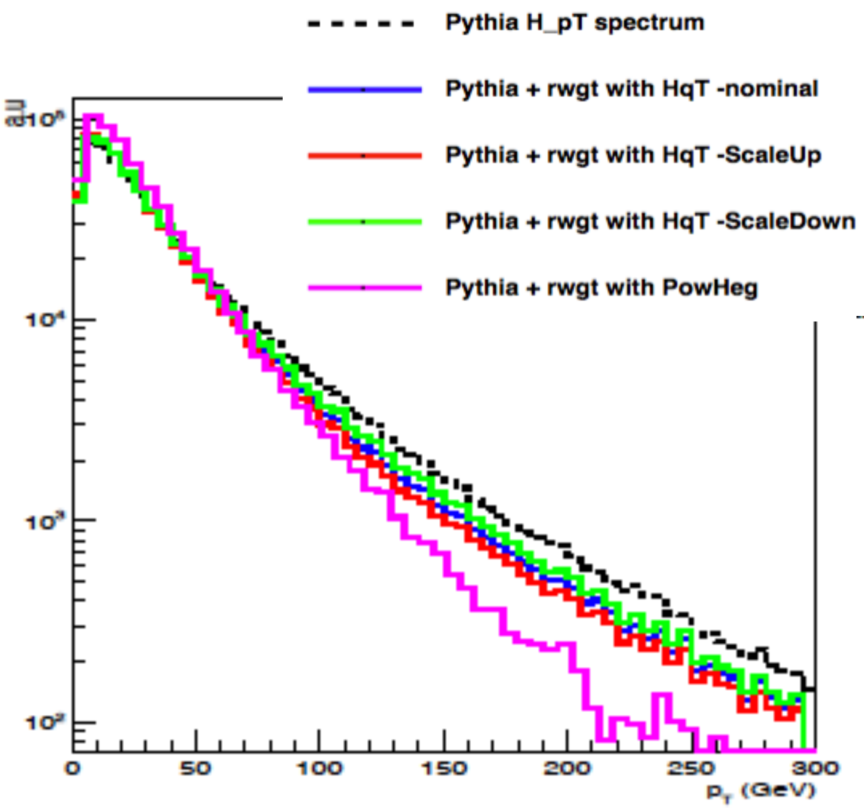
DzFilter efficiency measured to be 0.95 for entire 2012 data-taking period

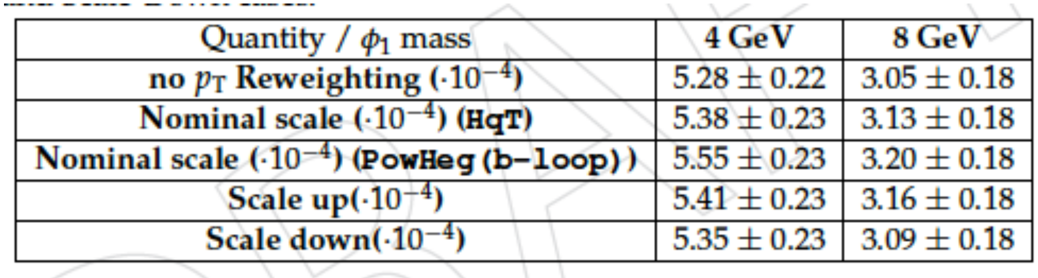
Signal acceptance for m(H_1) = 4, 8 GeV



Higgs p_T spectrum reweighting

- PYTHIA is giving LO diagrams
- Use HqT to reweight Higgs p_T spectrum to account for NLO + NNLL loops
- Also considered variation of renormation & factorization scales by ·½ & ·2
- Dedicated study with PowHeg sample to account for b &SUSY loop diagrams

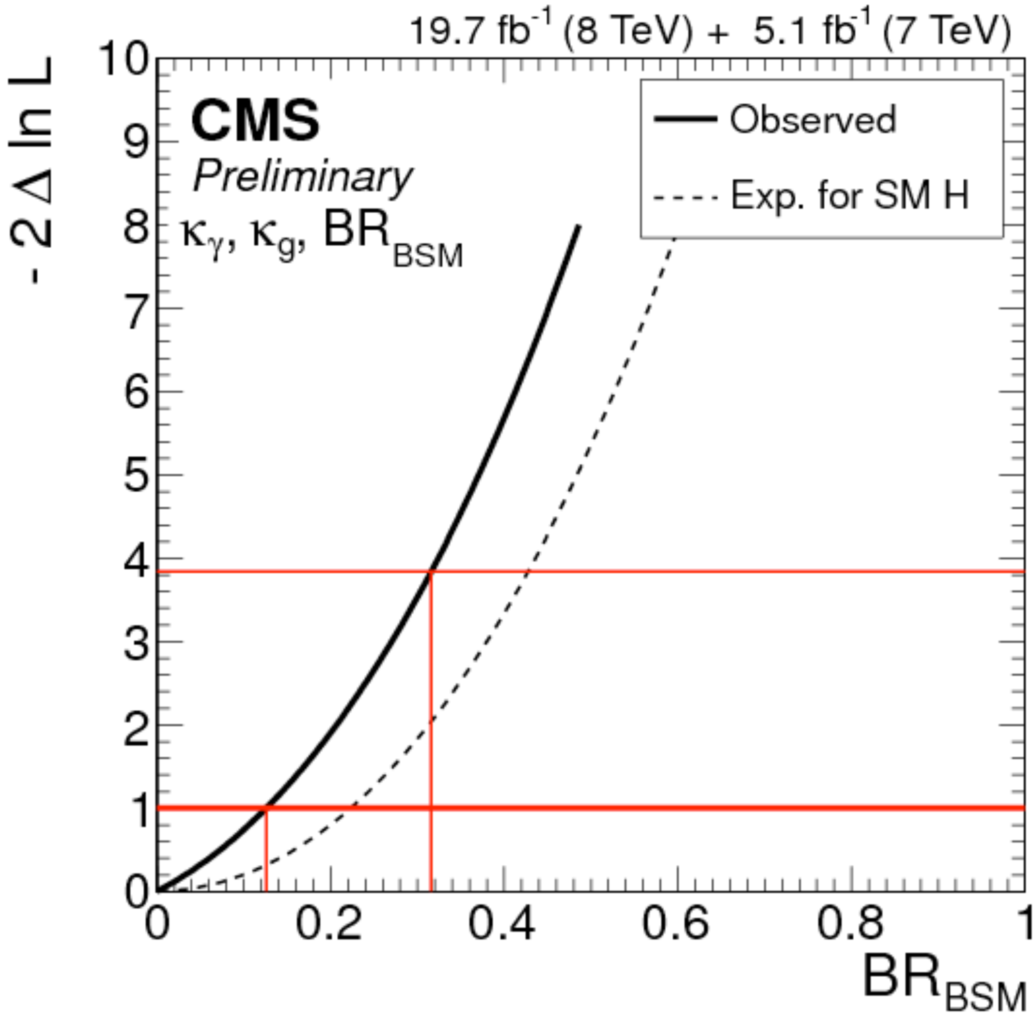




Quantity / ϕ_1 mass	4 GeV	8 GeV
no p_T Reweighting ($\cdot 10^{-4}$)	5.28 ± 0.22	3.05 ± 0.18
Nominal scale ($\cdot 10^{-4}$) (`HqT`)	5.38 ± 0.23	3.13 ± 0.18
Nominal scale ($\cdot 10^{-4}$) (`PowHeg (b-loop)`)	5.55 ± 0.23	3.20 ± 0.18
Scale up($\cdot 10^{-4}$)	5.41 ± 0.23	3.16 ± 0.18
Scale down($\cdot 10^{-4}$)	5.35 ± 0.23	3.09 ± 0.18

Signal Contamination

The coupling analysis performed by CMS constrains branching ratio of non-SM decays of the H(125) state to be $BR_{BSM}<0.32$ at 95% C.L..



Contamination of CR by Signal

Contamination of CR

Conservative estimation of the signal contamination in the CRs

⇒ σ(gg-> (H(125)) = 19.3 pb (SM prediction)

-BR (H(125) → 2ϕ1 → 4τ) = 32%

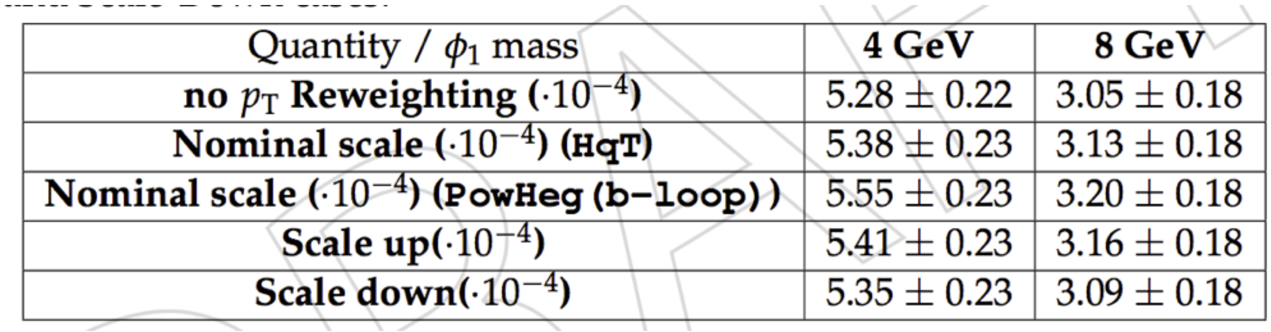
⇒ corresponds to upper limit @ 95% C.L. on BR_{BSM} (H(125)) (HIG-14-007)

-Contamination < 2% in all bins for all m_{ϕ_1} [4-8] GeV

- except bin (4,4) where contamination = 12% for m_{ϕ_1} = 8 GeV

-Effect on expected limits is ~ 1.% for each probed ϕ1 mass

- related uncertainty neglected to keep background model independent of m_{ϕ_1}



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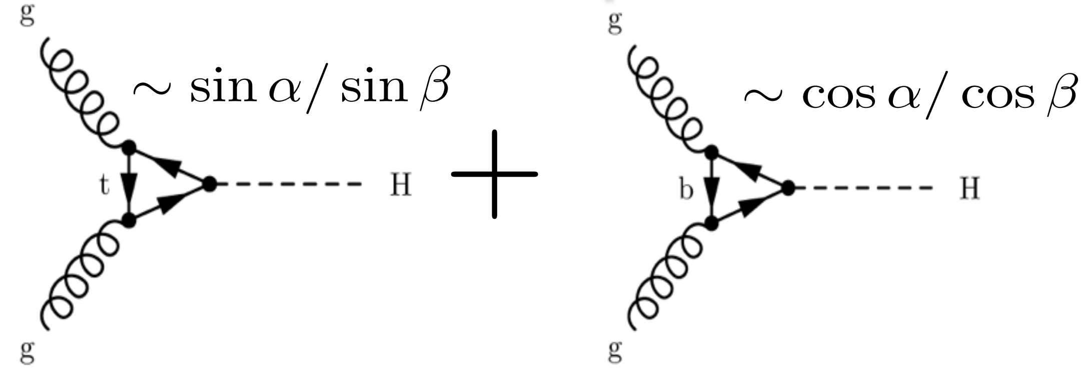
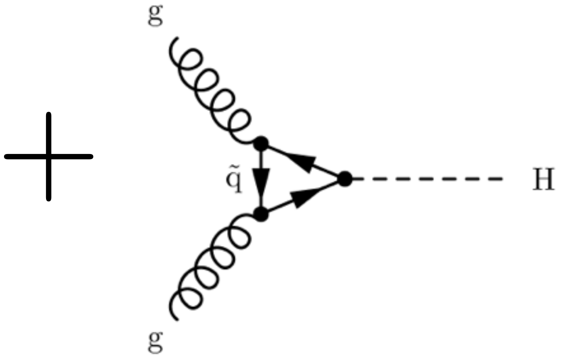
Effect of b-quark and SUSY-loops in gg → H_2





Effect of b- and SUSY-loops

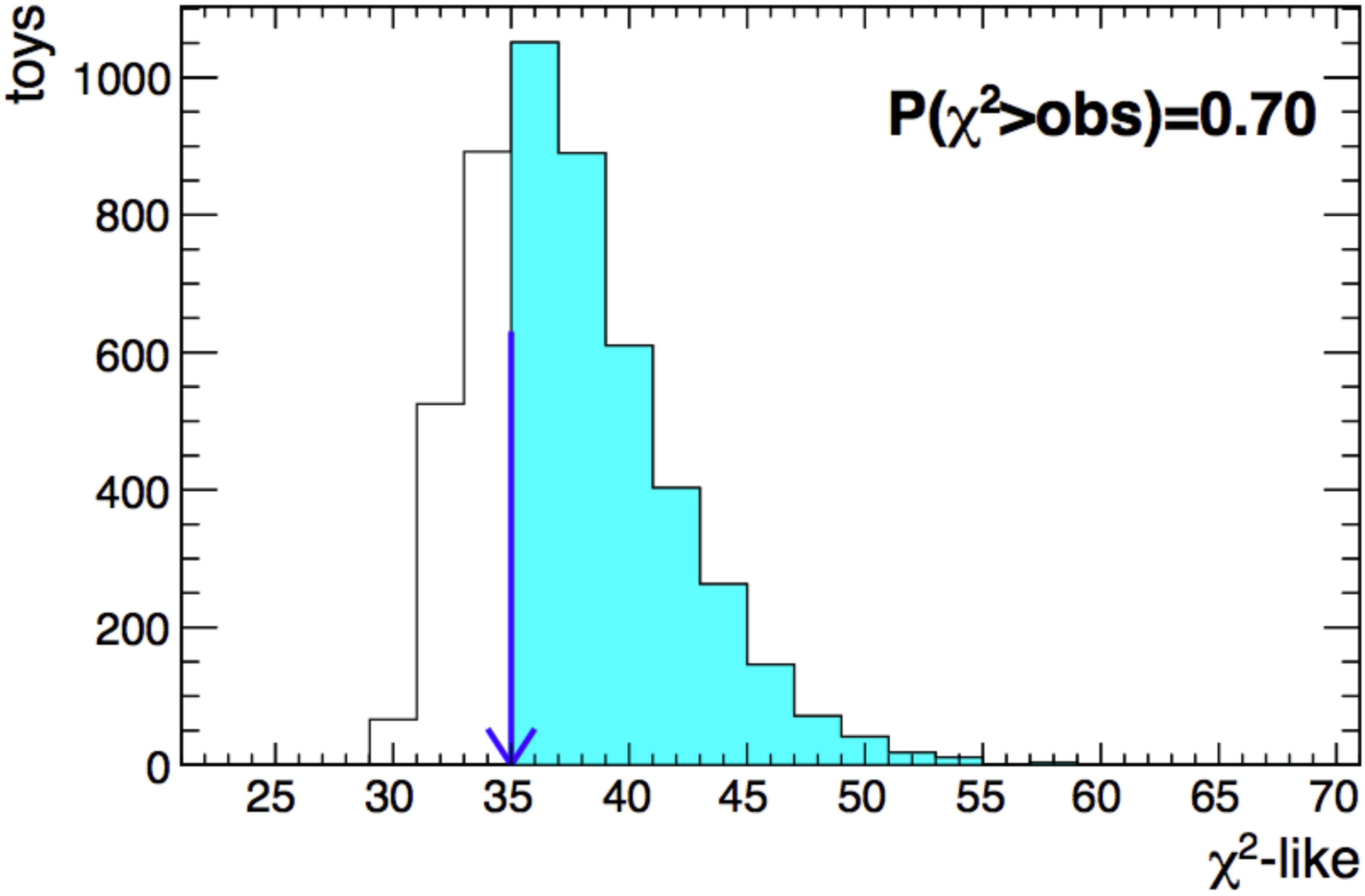
– tanβ dependent
– NLO + NNLL (ISR jets)
– effect on Higgs pt spectrum
→ effect on acceptance
– using POWHEG simulation with only b-loop included to evaluate effect

intuitive guess : small effect

Signal extraction

- Signal is extracted with **maximum-likelihood fit**
- Fitting **2D(m_1,m_2)** with **2** templates, **1** for background (data-driven template) and **1** for signal (obtained from simulation)
- Background & Signal normalization is allowed to float freely in fit
  - pure shape analysis
- **Normalization** altering uncertainties are incorporated in fit as nuisance parameters with a *Log-normal* prob. density function
- **Shape** altering uncertainties are incorporated in fit as nuisance parameters with a *Gaussian* prob. density function
  - Their variation causes continuous morphing of templates
- Background-only fit is also performed to test compatibility of Data with background-only Hypothesis
- Official *Higgs Combination* software is used for statistical analysis
  - In absence of excess we set upper limit on the **σxBR** using **Freq-CLs** approach

Goodness of fit test



s_i

Goodness of fit test

- The Goodness of fit test in the Higgs combination package is based on the χ^2 statistical indicator of the saturated model

$$\chi^2_{sat} = \sum_i \frac{(d_i - s_i - b_i)^2}{\sigma_P^2(d_i)}$$

  - d_i - number of data events in bin "i"
  - s_i - expected signal events in bin "i"
  - b_i - expected background events in bin "i"
  - $\sigma_P(d_i)$ - asymmetric Poisson error associated with the observed data events in bin "i"
- Signal and background expectation in each bin "i" are determined by MaxLikelihoodFit of data with the probed signal+background model p.d.f.
- In the next step ensemble of toy mc datasets is generated to determine the distribution of the goodness of fit indicator
  - in each toy dataset fit of model to the generated data pattern is performed yielding and of chi2 value is computed
  - when fitting model to generated toy dataset, signal strength is left floating in the fit, so that the measure is independent from the presence or absence of a signal