Physics analyses with LHC data collected in CMS experiment

Kajari Mazumdar

Platter

Activities of recent times

- Standard Model (SM) physics: Drell-Yan process
  - Mass distribution
  - phi* differential spectrum
  - Transverse momentum distributions of vector bosons

- Constraining natural width of Higgs boson

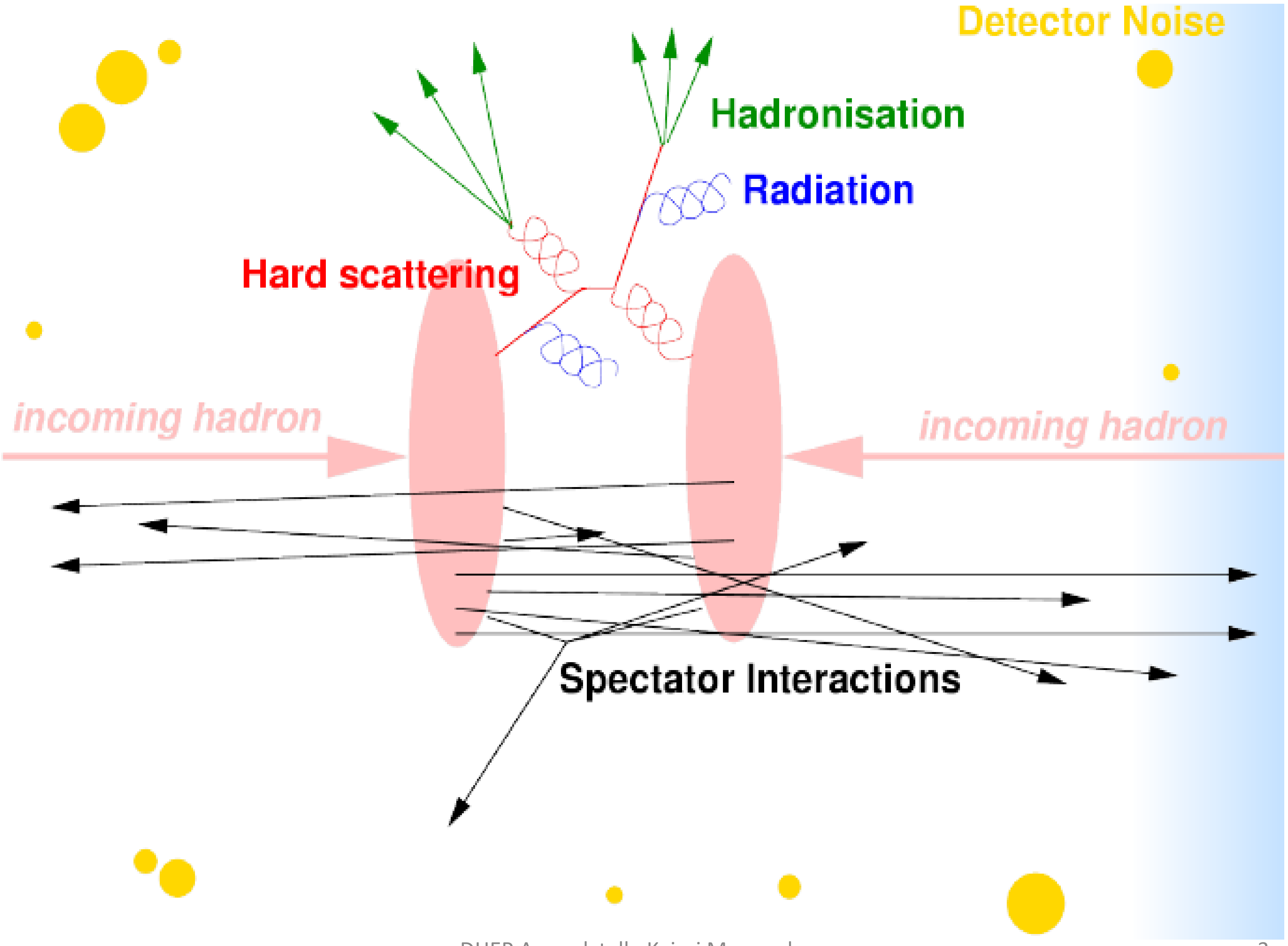
- Soft –QCD physics : double parton scattering

- Beyond SM physics: SUSY electroweak particle production at 8 TeV

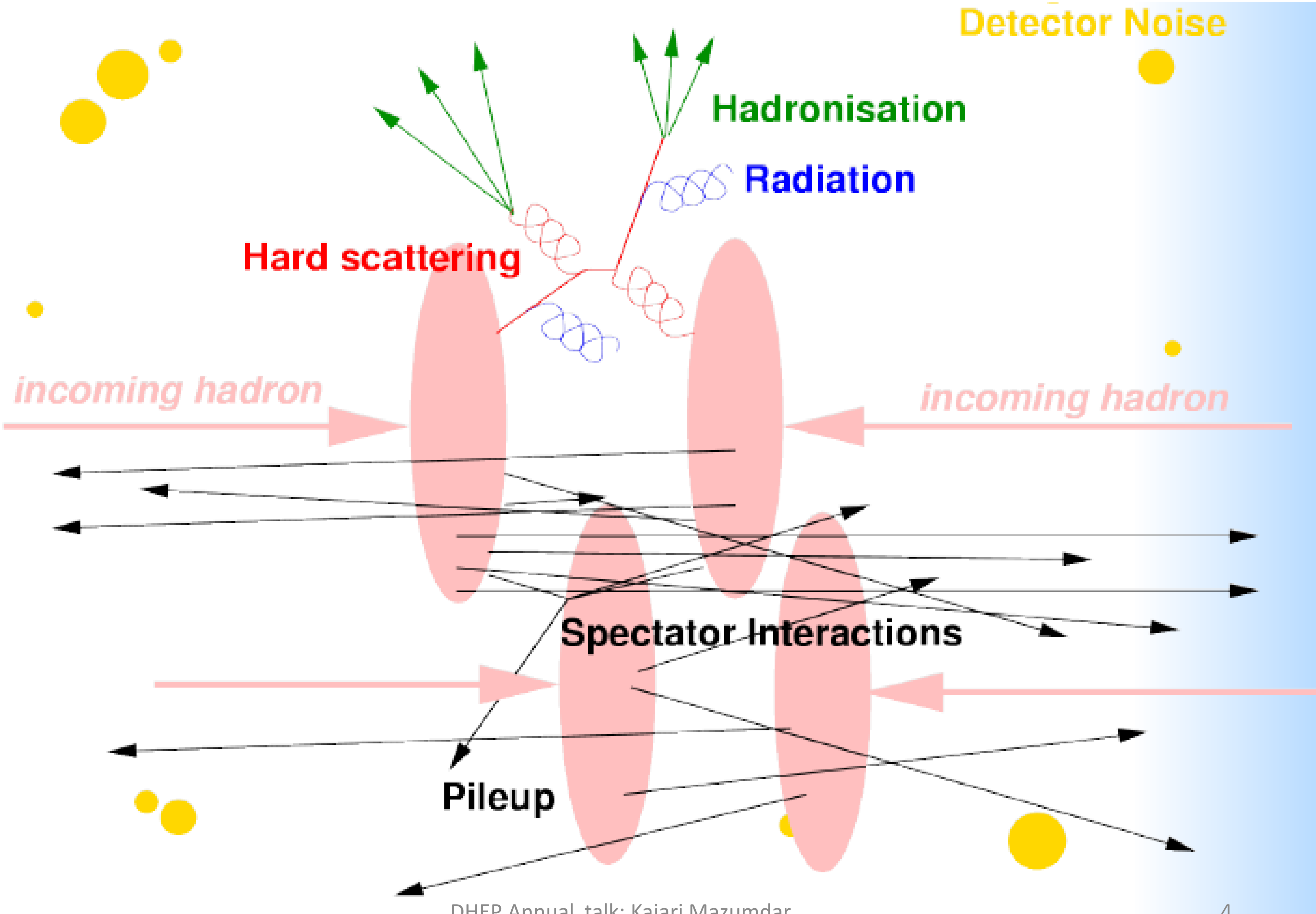
- Other involvements related to physics analyses of CMS : as member of
  i) Analyses Review Committees, ii) Standard Model Physics publication board

➔ discuss only few today highlighting different aspects

Collision of 2 hadrons at high energy



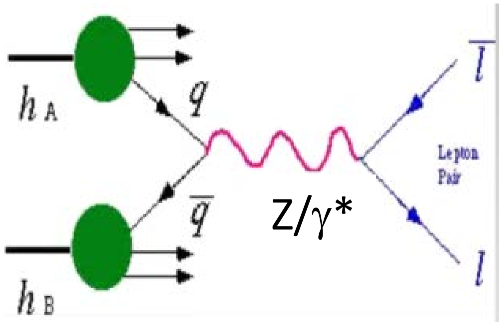
Collision of 2 hadrons at high energy and high luminosity



Electroweak Physics

Drell—Yan process

- Lepton pair production in hadron collision : benchmark process
- First studied in 1970 by Drell and Yan



- **Best experimental tool in hadron colliders**
- Playground for experimental vs. theoretical issues.

-- Benchmark process in standard model,

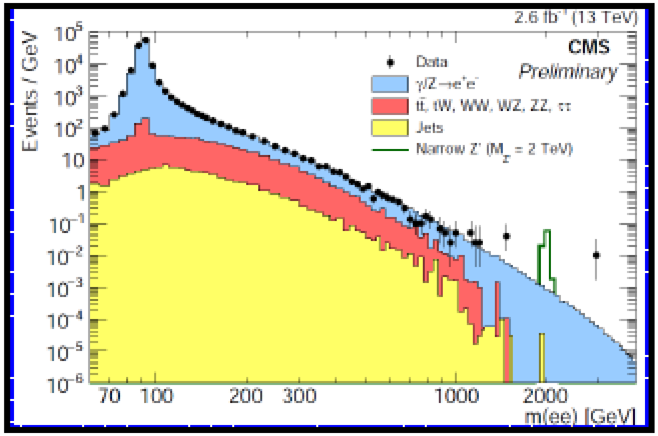
-- Theoretical cross section calculated up to NNLO accuracy in α_s

-- Tool to understand the detector

-- Tool for early new physics search

-- Tool for validation of pQCD calculation

-- evaluation of PDF,….



Dimuon channel

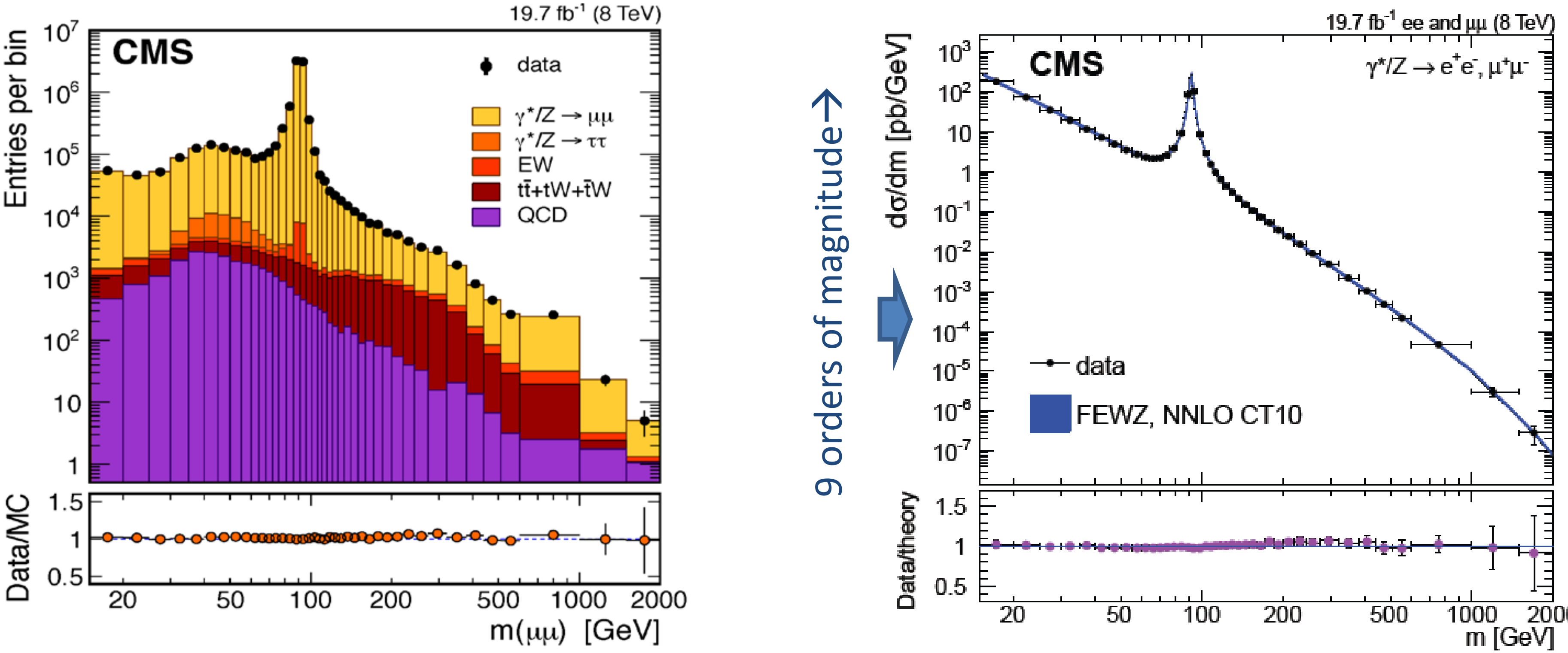
Provides clean signature and low backgrounds

High-precision muon detectors, good mass resolution

Low systematic uncertainty

Historically has been a fruitful channel for discoveries (*J/ψ, Υ, Z*)

From number counting to physical observable



$$\frac{d\sigma}{dM}(\gamma^*/Z) \cdot BR(\gamma^*/Z \rightarrow \mu^+\mu^-) = \frac{N_{candidates} - N_{bkg}}{A \cdot \epsilon_{trig} \cdot \epsilon_{reco}^2 \cdot \epsilon_{evsel} \cdot \Delta M \cdot \int Ldt}$$

σ_{ot} in Z-peak region at √s of 8 TeV = 1138 ± 8(exp.) ± 25(theo.) ± 30 (lumi) pb

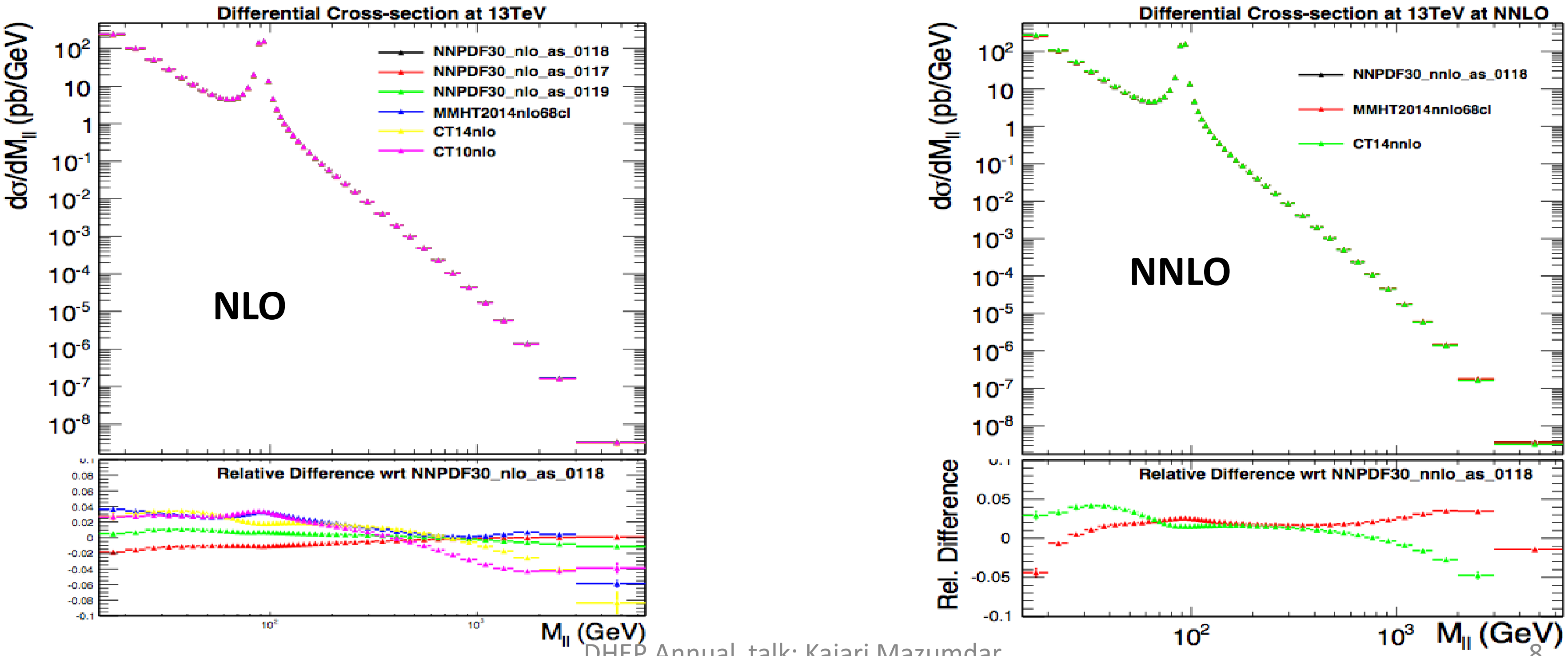
… at 13 TeV ~ 1.9 nb

DY mass spectra at 13 TeV: work in progress CMS Analysis note: AN-15-324

(S.Jain, G.Majumder, KM)

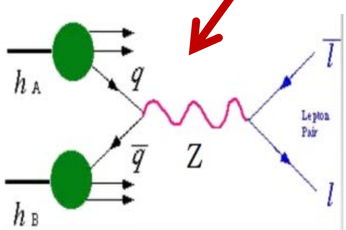
FEWZ calculation on CMS Tier 2 Grid facility at TIFR

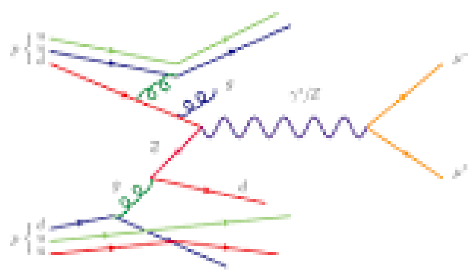
- FEWZ (Fully Exclusive W and Z production) code for the calculation of W and γ^*/Z production at next-to-next-to-leading order in the strong coupling.
- analytical calculation → lot of computing power → T2 is the best resource
- $d\sigma/dM$ (in 4π acceptance) computed by S.Jain at T2-IN-TIFR for different sets of parton density functions → each set ~ 2 weeks

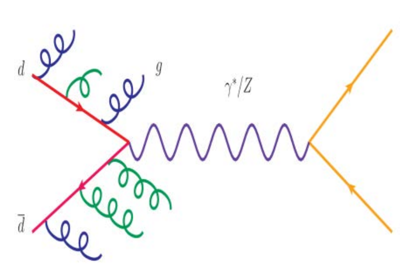


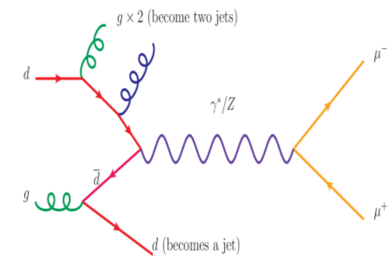
Transverse momentum of vector boson in inclusive Drell-Yan process

- Inclusive measurement ➔ identify only 2 leptons in the event
- Various possibilities corresponding to different orders of perturbation theory
- Z may be at rest or have longitudinal momentum ➔ leading order (LO)









- Z can have transverse momentum **(p_T)**

- Theoretical description includes: i) resummation techniques at low p_T

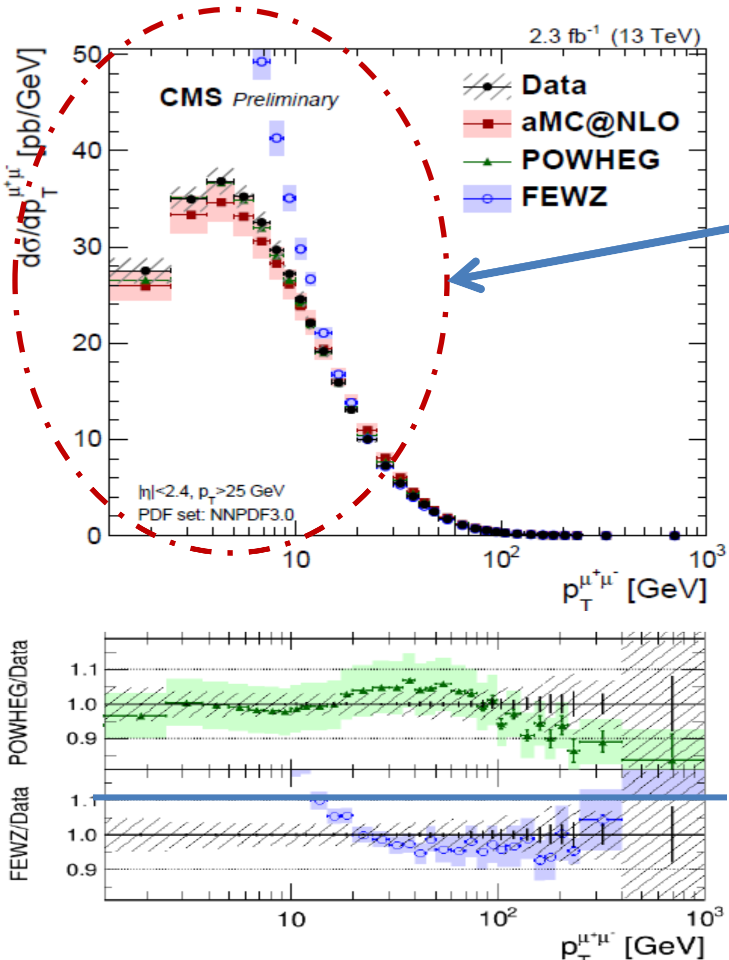
  ii) perturbation theory for high p_T region

  iii) suitable tuning for underlying event which controls ISR

Transverse momentum spectrum of dilepton system

- Precise measurement of p_T of W/Z is crucial to achieve very high accuracy in measurement of W-mass.

➢ **Experimental measurement of the p_T spectrum is important.**

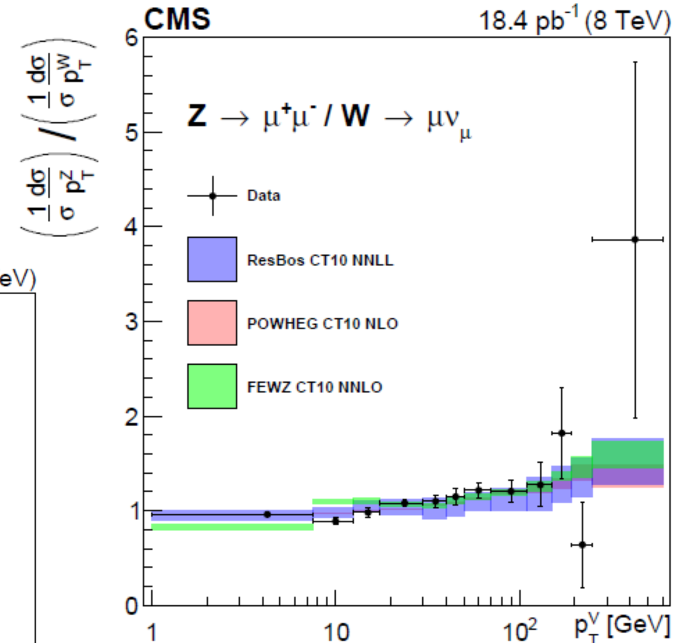


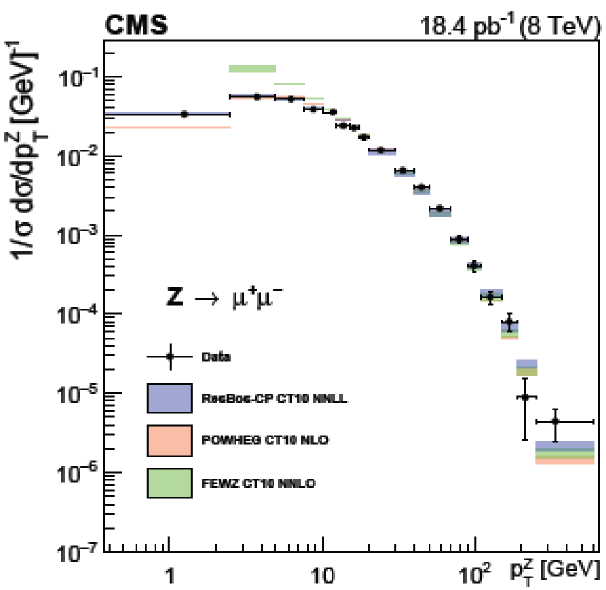
Re-summation of soft gluons at low values tames the spectrum.

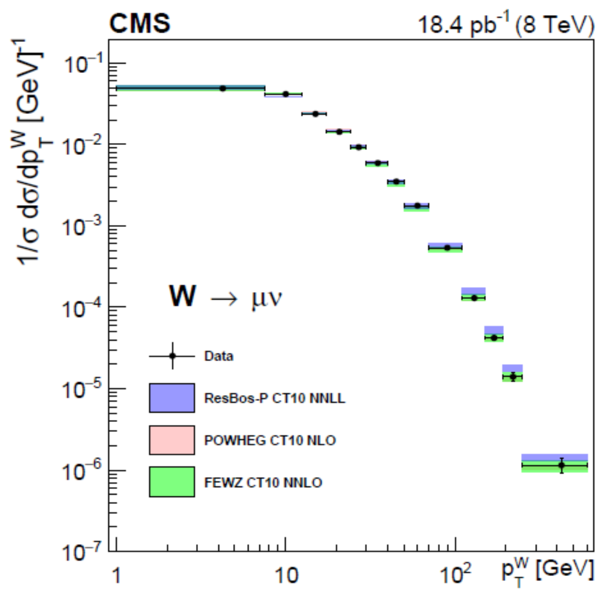
Similar considerations for Higgs transverse momentum in gg→ H process

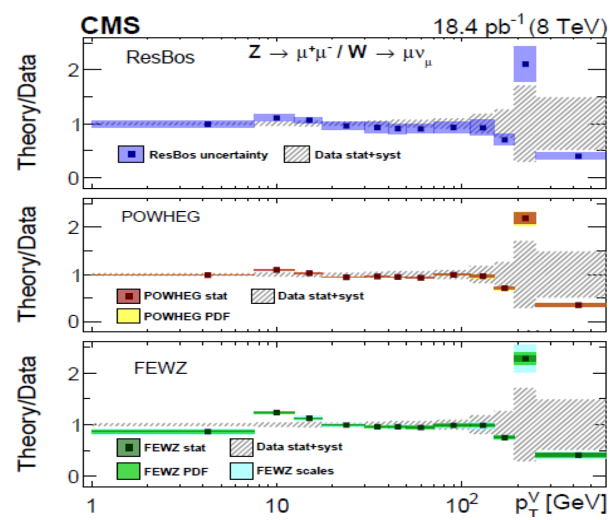
Transverse momentum spectrum of vector bosons

- pp→ W (--> ℓ ν) + X process is similar to pp→ Z (→ ℓ+ℓ -) + X process ➔ compare









Nadeesha Manohari (Sri Lanka) +KM

AN SMP-12-012,

CMS PAS/paper SMP-14-012
to be submitted to JHEP

$d\sigma/d\Phi^*$ spectrum in inclusive Drell-Yan events

R.Chatterjee, M.Guchait, KM, M.Kaur (PU), G.Walia (PU)
KM: contact person

CMS PAS SMP-15-002
analysis note: AN-14-107

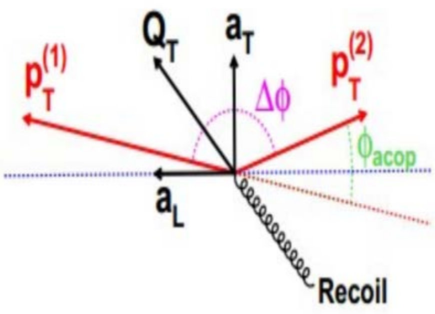
- Precise measurements of the p_T spectrum also needed to tune/test the theoretical descriptions/prediction.
- Precision of p_T estimated from individual lepton's momentum is limited in the region of low p_T
- Different strategy : utilize better experimental measurement of angles of individual leptons

→ less sensitive to experimental systematics
➔ probe p_T via angular correlation between the leptons.

$\Phi^* = \tan(\varphi_{acop}/2)\ \sin(\theta_\eta^*)$

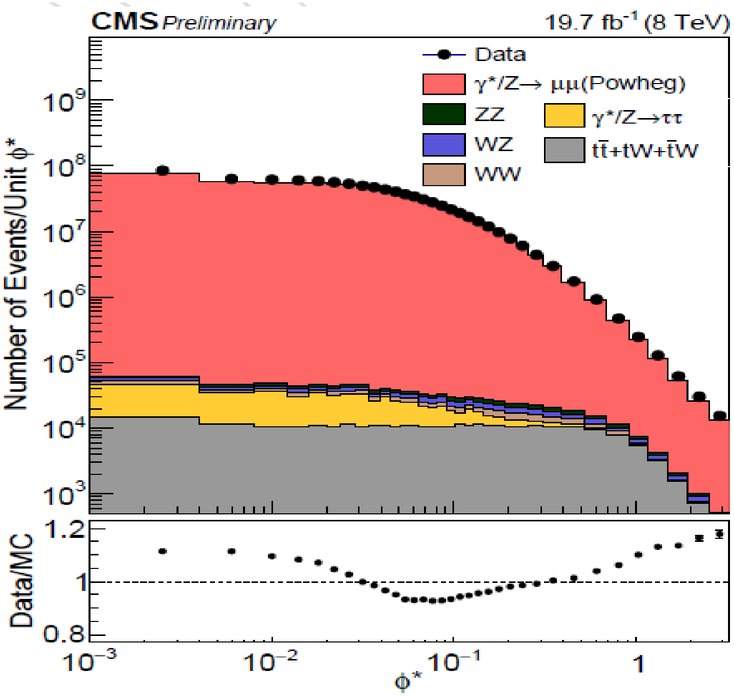
θ_η^* : scattering angle of the leptons w.r.t. proton beam direction in the rest frame of dilepton system

$\cos(\theta_\eta^*) = \tanh[(\eta^- - \eta^+)/2]$

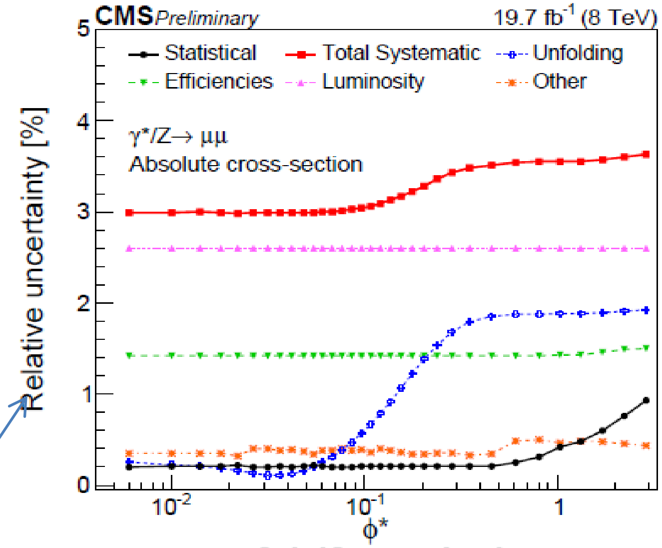


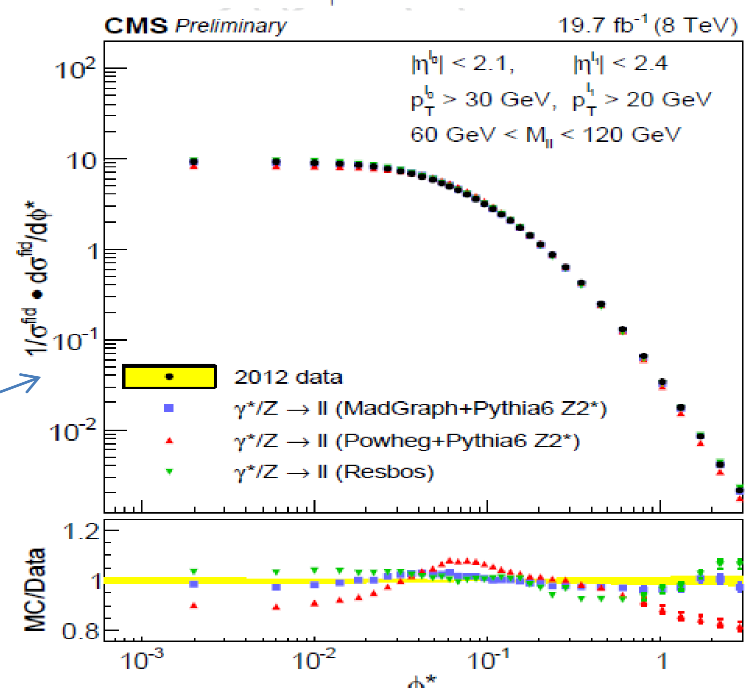
Φ^* relates to p_T / M_{ll}

Buzzword is the precision



Φ* spectrum at detector level.

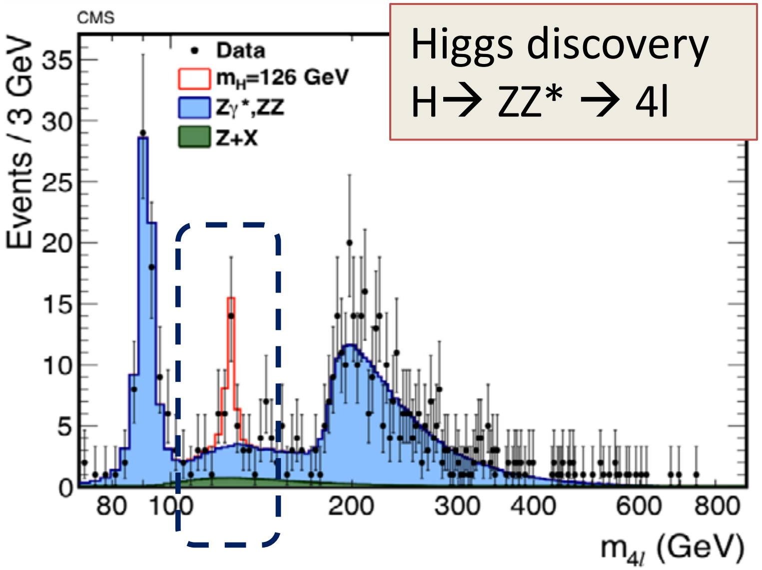




- Relative uncertainty in the measurement of absolute cross section.
- Normalized, differential cross section
- Theoretical predictions match within few % for Φ* < 0.1

Higgs Physics

Constraining total width of Higgs boson



Higgs discovery
H→ ZZ* → 4l

A.Mehta (PU), J..Singh (PU), S.Kumar, KM

CMS PAS/PAPER HIG-14-032
Analysis note: AN-14-192

- Crucial: identification of the nature of the discovered resonance at 125 GeV
- Novel strategy to constrain the natural width

- Measured m_H ~125 GeV, in SM: Γ_H ~ 4 MeV ➔ $\Gamma_H / m_H \sim 10^{-5}$ ➔ narrow peak

$$N \propto \sigma(xx \to \mathrm{H}) \cdot \mathcal{B}(\mathrm{H} \to yy) \propto \frac{\Gamma_{xx}\,\Gamma_{yy}}{\Gamma_{\mathrm{tot}}},$$

$$\sigma * Br \propto g_{xx}^2\, g_{yy}^2 / \Gamma_H$$

g_{ii}: couplings at production & decay vertices

- Rescaling all the couplings by the same factor, say ξ and the total width by ξ^4 the on-shell production rate remains same ➔ there is some degeneracy.

Variation of Higgs boson cross section

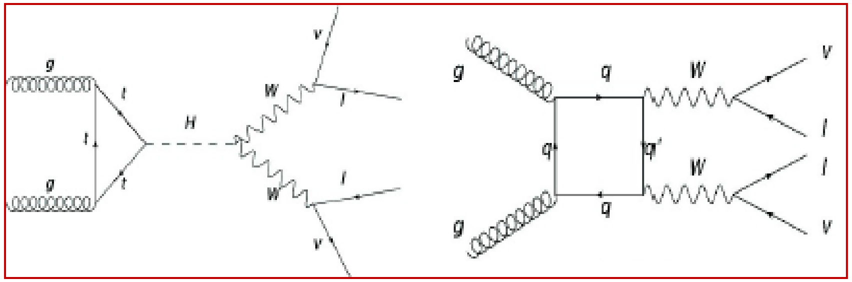
For gg→ H → WW
$$\frac{d\sigma_{gg\to H\to WW}}{dm^2_{WW}} \propto g^2_{ggH} g^2_{HWW} \frac{F(m_{WW})}{(m^2_{WW} - m^2_H)^2 + m^2_H \Gamma^2_H}$$
→ virtual Higgs & Z decay dynamics

At resonance → $\sigma^{on-peak}_{gg\to H\to WW} \propto \frac{g^2_{ggH} g^2_{HWW}}{\Gamma_H}$ and off-shell part → $\sigma^{off-peak}_{gg\to H\to WW} \propto g^2_{ggH} g^2_{HWW}$

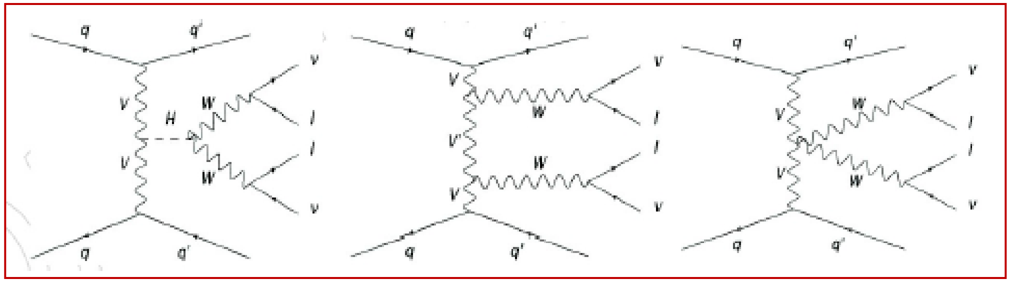
→ off shell part will change with change in coupling

→ **Ratio of on-peak/off-peak cross section ~ Γ_H**

- In the off-sell region interference between resonant and non-resonant processes



Gluon fusion for H production & SM bkg.



Vector boson fusion for H production SM bkg.

- Similar considerations for Vector Boson Fusion (qq→ qqH) production process
- Similar arguments hold for gg→ H → ZZ*

Strategy for experimental analysis

- Do not assume standard model Higgs → introduce scale factors

$r = \Gamma_{\rm H}/\Gamma_{\rm H}^{\rm SM}$

Signal strength = μ to be derived from data, $\mu = 1$ ➔ SM

- In the off-shell region, $M_{WW} > 2M_W$, the shape of mass spectrum ($d\sigma/dm^2$) has 3 components: signal, background and their interference

$$\mathcal{P}_{\rm tot} = \mu r\,\mathcal{P}_{\rm sig} + \sqrt{\mu r}\,\mathcal{P}_{\rm int} + \mathcal{P}_{\rm bkg}$$

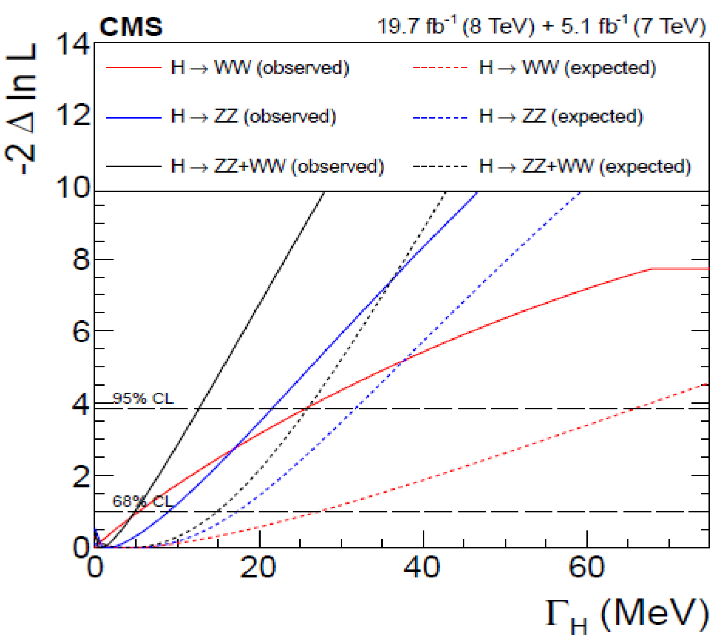
S.Kumar studied these shapes using templates from PHANTOM generator for different values of *r*

In actual analysis use μ value derived from data and fit *r* .

- Experimentally, $m_{ll} < 70$ GeV ➔ on-shell and $m_{ll} > 70$ GeV off-shell regions
- Multivariate analysis discriminates between off-shell Higgs and background
- Probability distributions for on-shell and off-shell regions are used to make a kinematics based likelihood for signal on event-by-event basis

Results on Γ_H

- Perform likelihood scan for all regions of m_{WW} and all event categories of data
- Observed (expected) upper limit at 95% confidence level → **Γ_H < 26 (66) MeV**
- Observed (expected) upper limit on off-shell signal strength
  $\mu_{ggH}^{\text{off-shell}}$ < 3.5 (16.0) and $\mu_{VBF}^{\text{off-shell}}$ < 48.1 (99.2)
- Combine H→ WW* results with existing constraint on Γ_H from H→ ZZ*→ 4l



- **Γ_H < 13 (22.6) MeV**

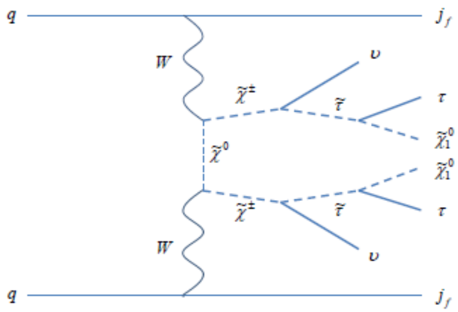
$\mu_{ggH}^{\text{off-shell}}$ < 2.4 (6.2) and $\mu_{VBF}^{\text{off-shell}}$ < 19.3 (34.4)

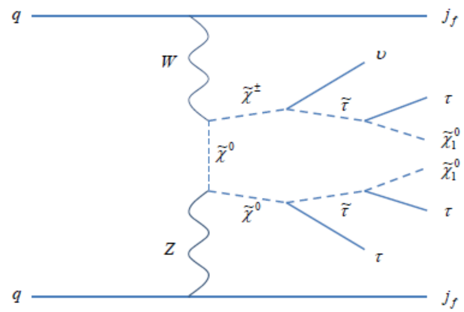
SUSY

Search for Electroweak SUSY particles

- Typically SUSY searches are based on strong production, in the coloured sector → lower mass limits of few TeVs for squarks, gluionos
- Electroweak SUSY particle production cross sections are of much lower rate.
- But if masses of squarks, gluinos are very high, production of electroweakinos Charginos $(\widetilde{\chi}_i^{\pm})$ and neutralinos $(\widetilde{\chi}_i^{0})$ of masses around few hundred GeVs are comparable.
- For compressed mass spectra (mass of lightest SUSY particle only slightly less than other SUSY particles) lower mass limits of electroweakinos are quite soft.
- Sensitivity of searches via $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^{0}$ pair production and leptonic decays limited, depends crucially on the mass difference $m_{\widetilde{\chi}_1^{\pm}} - m_{\widetilde{\chi}_1^{0}}$
- Search in vector boson fusion (VBF) process is complementary.
- Identification of forward-backward jets with VBF topology increases sensitivity, though cross section is low.

VBF production of charginos & neutrlinos and decay through taus

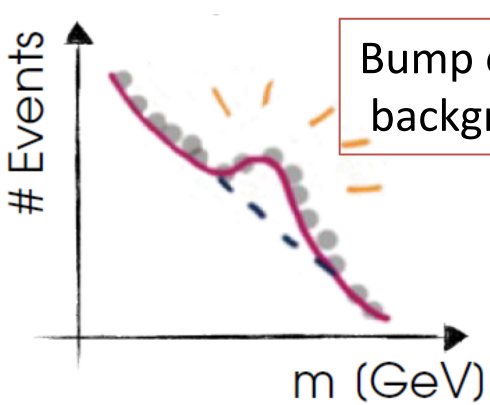




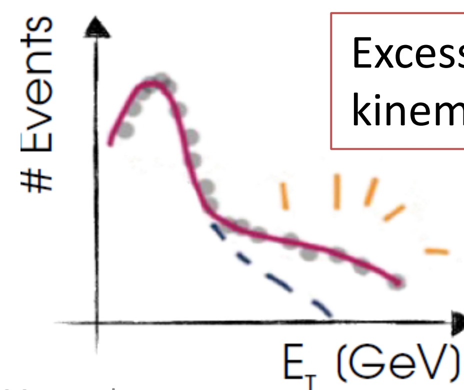
CMS PAS: SUS-12-025
SUS-14-005
arXiv:1508.07628

Amandeep (PU), J.B Singh (PU), N.Dhingra (PU), KM

- If the 1st and 2nd generation sleptons and sneutrinos are heavy (typically with models of large tan β), the electroweakinos decay dominantly via stau ($\tilde{\tau}$)
- Signature: 2 taus in central region, missing transverse energy + 2 tagging jets
- How do you search for such a process ? Understand the background!



Bump over a continuous background



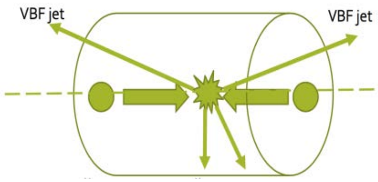
Excess in some kinematic distribution

Main analysis strategy

- Discriminate against background processes :

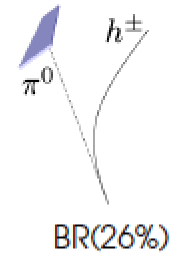
i) Central selection to pick up decay products of taus, E_T^{miss} , no b-jet

ii) VBF selection for tagging jets → positioned in opposite hemispheres, large rapidity gap, large dijet invariant mass



- Search in dominant but difficult final states : $\tau_h\tau_h$ (41%) , $\mu\tau_h$ (23%)

→ Consider only 1-prong hadronic decays of tau: τ_h



- Look for BSM → estimate excess of events in m_{jj} distribution selected with criteria (i) and (ii) and in region of m_{jj} > 250 GeV

- Main backgrounds: QCD multijet, Z (→ $\tau\tau$) + Jets, ..

- Evaluate contribution of dominant backgrounds in signal region (SR) using *data-driven method*

- Use isolated control regions (CR) : *modification of nominal selection criteria*

→ use a correction factor to account for disagreement between simulation and data

Determination of QCD multijet background

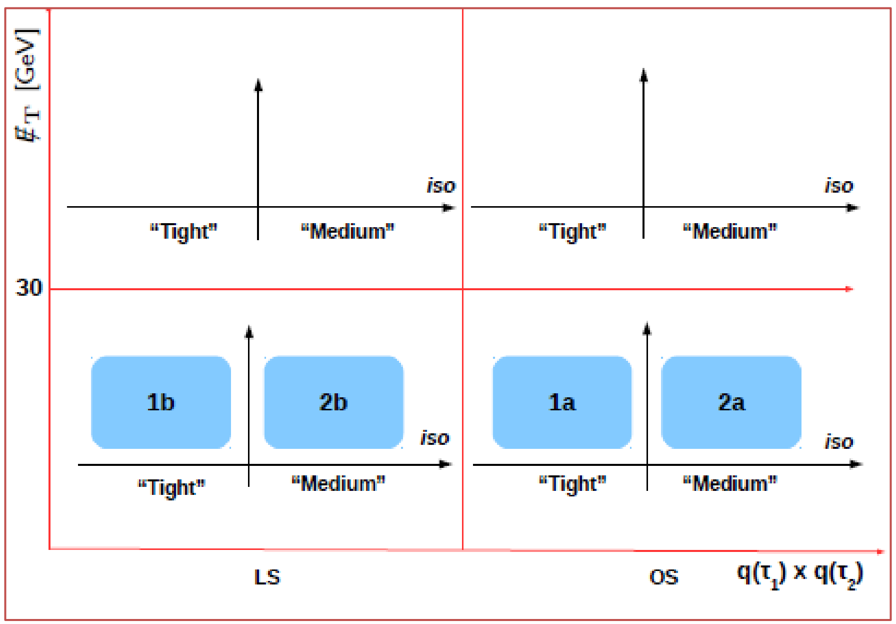
$$N_{\mathrm{OS}}^{\mathrm{QCD}} = N_{\mathrm{OS}}^{\mathrm{Data}} - N_{\mathrm{OS}}^{\overline{\mathrm{QCD}}\ \mathrm{MC}}$$

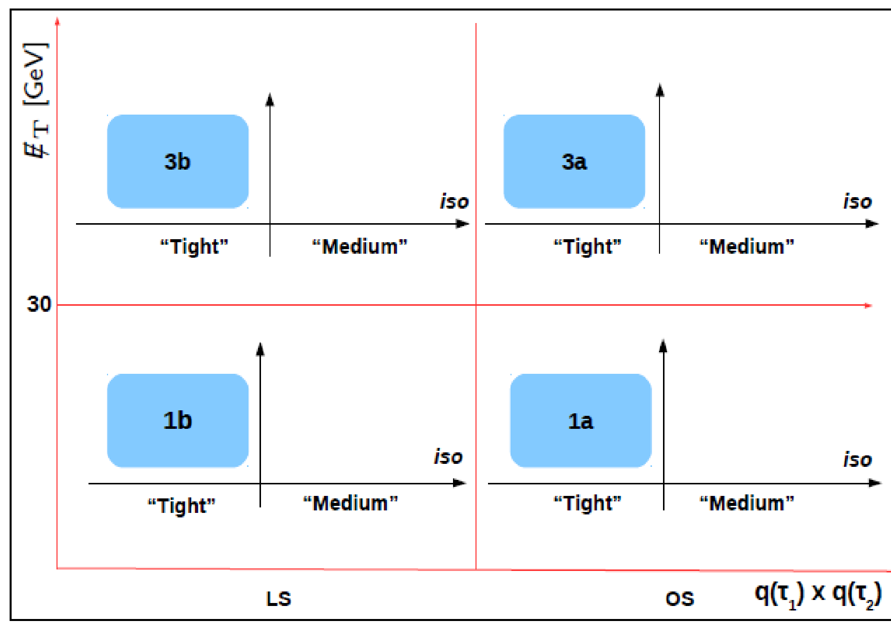
$$N_{\mathrm{LS}}^{\mathrm{QCD}} = N_{\mathrm{LS}}^{\mathrm{Data}} - N_{\mathrm{LS}}^{\overline{\mathrm{QCD}}\ \mathrm{MC}}$$

$$R_{\mathrm{OS/LS}} = N_{\mathrm{OS}}^{\mathrm{QCD}} / N_{\mathrm{LS}}^{\mathrm{QCD}}$$

No. of events with central selection in OS signal region (3a) = $N_{Central}^{QCD} = N_{CR3b}^{QCD} \cdot R_{OS/LS}$

- Control region : low E_T^{miss} region with other central selections same
- Determine $R_{OS/LS}$: 1a (OS) , 1b (LS)
- Validation: 2a (OS) , 2b (LS)





Determination of VBF selection efficiency for tagging jets

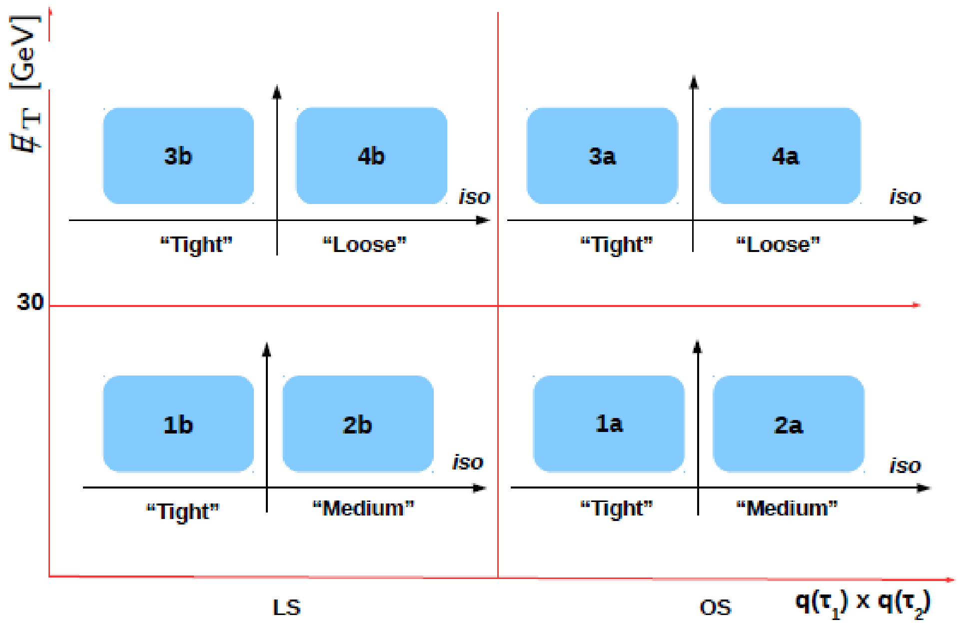
of QCD multijet events in signal region: $N^{\rm QCD}_{\rm Signal} = N^{\rm QCD}_{\rm w/o\ VBF\ cuts} \cdot \epsilon_{\rm VBF}$

- VBF selection efficiency of QCD jets are not biased by charge or isolation

➔ apply lenient isolation (control regions 4a, 4b and 1b)

ε_{VBF} = 0.35% ± 0.0079% (stat) ± 0.028% (iso) ± 0.048 (sign) ± 0.011% (E_T^{miss})

$N^{\rm QCD}_{\rm w/o\ VBF\ cuts} = 1807.97 \pm 86.7({\rm stat}) \pm 56.0({\rm systematic:\ OS/LS\ ratio\ of\ 3.1\%})$

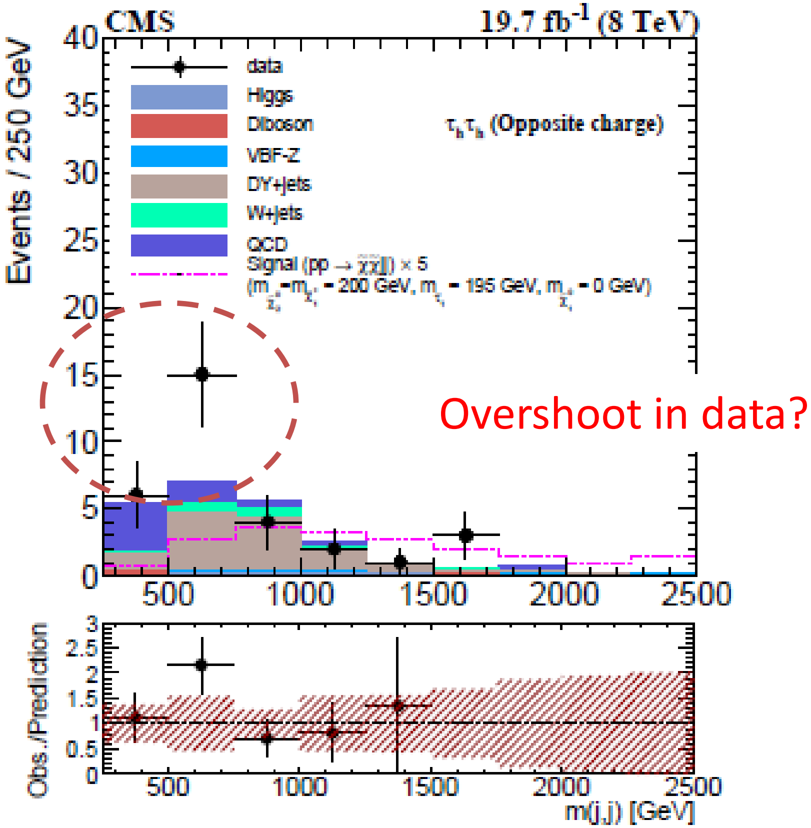


$N^{\rm QCD}_{\rm Signal} = 6.33 \pm 1.79$

Results for opposite sign di-tau hadronic events

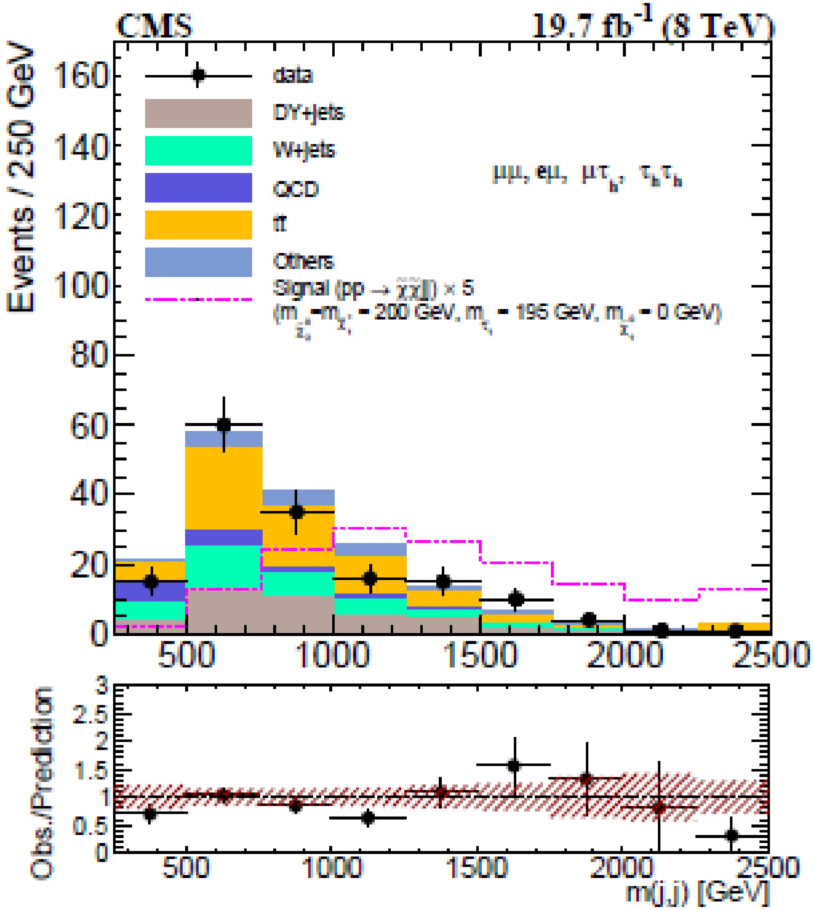
Final Yields for OS $\tau_h \tau_h$

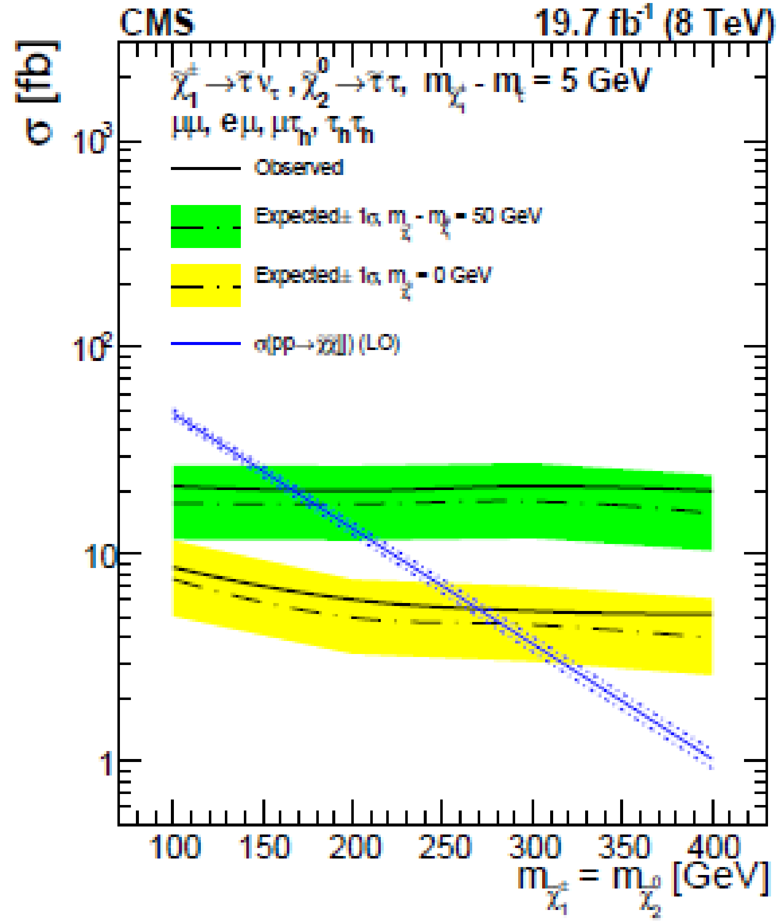
Sample	Event Rate
Data	31
$Z \rightarrow \ell\ell + jets$	$12.25 \pm 2.66(stat) \pm 3.06(sys)$
QCD	6.33 ± 1.79
$t\bar{t}$	–
$W + Jet$	1.988 ± 1.693
WZ	0.1299 ± 0.0424
WW	0.0818 ± 0.0700
ZZ	0.2643 ± 0.1675
$VBFHiggs$	1.1423 ± 0.0575
$WWjj$	0.0466 ± 0.0198
$VBF\ Z$	0.7007 ± 0.1438
Total MC	$22.9336 \pm 3.6339(stat)$



- Overshooting got compensated by some deficiency in $\mu\tau_h$ final state!
- Put 95% CL upper limit on the cross section as a function $m_{\tilde{\chi}_2^0} = m_{\tilde{\chi}_1^\pm}$

Results from all channels





In the compressed spectra scenario with $m_{\widetilde{\chi}_1^{\pm}} - m_{\widetilde{\chi}_1^0}$ = 50 GeV lower mass limit of neutralino_2 and Chargino_1 is 170 GeV

Thank you!

Event yields in various final states

OS leptons

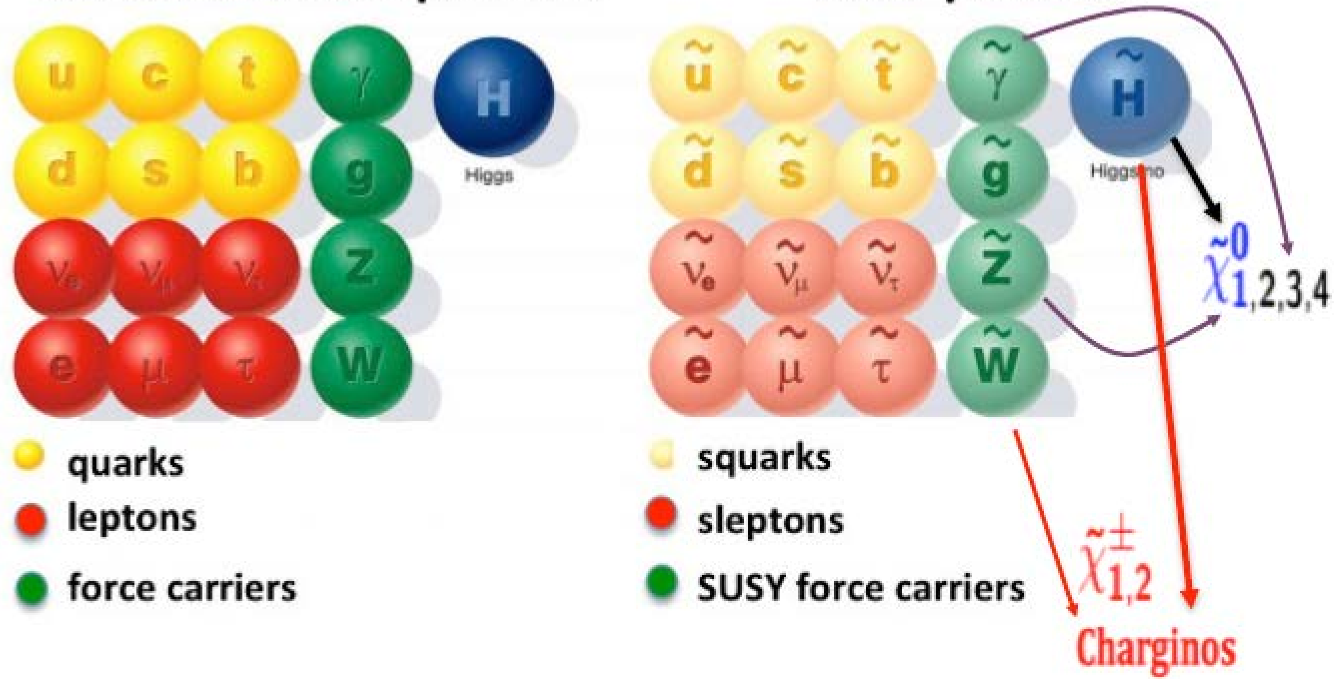
Process	$\mu^{\pm}\mu^{\mp}jj$	$e^{\pm}\mu^{\mp}jj$	$\mu^{\pm}\tau_h^{\mp}jj$	$\tau_h^{\pm}\tau_h^{\mp}jj$
Z+jets	4.3 ± 1.7	$3.7^{+2.1}_{-1.9}$	19.9 ± 2.9	12.3 ± 4.4
W+jets	<0.1	$4.2^{+3.3}_{-2.5}$	17.3 ± 3.0	2.0 ± 1.7
VV	2.8 ± 0.5	3.1 ± 0.7	2.9 ± 0.5	0.5 ± 0.2
$t\bar{t}$	24.0 ± 1.7	$19.0^{+2.3}_{-2.4}$	11.7 ± 2.8	–
QCD	—	—	—	6.3 ± 1.8
Higgs boson	1.0 ± 0.1	1.1 ± 0.5	—	1.1 ± 0.1
VBF Z	—	—	—	0.7 ± 0.2
Total	32.2 ± 2.4	$31.1^{+4.6}_{-4.1}$	51.8 ± 5.1	22.9 ± 5.1
Observed	31	22	41	31

LS leptons

Process	$\mu^{\pm}\mu^{\pm}jj$	$e^{\pm}\mu^{\pm}jj$	$\mu^{\pm}\tau^{\pm}_{\tau_h}jj$	$\tau^{\pm}_{\tau_h}\tau^{\pm}_{\tau_h}jj$
Z+jets	<0.1	$0^{+1.7}_{-0}$	0.5 ± 0.2	<0.1
W+jets	<0.1	$0^{+3.0}_{-0}$	9.3 ± 2.3	0.5 ± 0.1
VV	2.1 ± 0.3	$1.9^{+0.4}_{-0.2}$	1.1 ± 0.2	$0.1 \pm 6.5 \times 10^{-2}$
$t\bar{t}$	3.1 ± 0.1	$3.5^{+0.7}_{-0.9}$	6.7 ± 2.8	$0.1 \pm 1.2 \times 10^{-2}$
Single top	—	—	—	<0.1
QCD	—	—	—	7.6 ± 0.9
Higgs boson	—	—	—	<0.1
Total	5.4 ± 0.3	$5.4 \pm^{3.5}_{0.9}$	17.6 ± 3.8	8.4 ± 0.9
Observed	4	5	14	9

The known world of Standard Model particles

The hypothetical world of SUSY particles



Other academic activities

Analyses review committee (ARC: FSQ-15-006, HIG-16-009
Institutional review: FSQ-13-008

Systematic uncertainties in f* measurement

Components considered:

- ID/ISO and Trigger efficiency
- Electron/muon energy/momentum scale and resolution
- Background
- MC statistics
- Unfolding, systematics due to model dependence
- Pile-up
- Modeling of final state radiation (FSR) in simulation.
  < 0.08% for absolute and < 0.04% for normalized
- Parton Distribution function (PDF)
- Luminosity: Only for the absolute distribubition. a flat rate of 2.6%

All uncertainties are propagated through the unfolding

Templates and event distribution

Same sign chargino production: rate few fb

- Signal, background, interference templates are not available separately.

VBF process rate independent of mass of chargino_1

Decays with Br 1/6 to stau or staunu

- Generate total amplitudes with 3 values of r, say, r = 1, 9, 25

$$\begin{pmatrix} p_1 \\ p_9 \\ p_{25} \end{pmatrix} = A \cdot \begin{pmatrix} S \\ I \\ B \end{pmatrix}, \; A = \begin{pmatrix} 1 & 1 & 1 \\ 9 & 3 & 1 \\ 25 & 5 & 1 \end{pmatrix}$$

- Extract 3 components from matrix eqn.

Likelihood of each event :

$$\mathcal{L}_i = N_{gg\to ZZ}\left[\mu r \times \mathcal{P}^{gg}_{\rm sig} + \sqrt{\mu r}\times \mathcal{P}^{gg}_{\rm int} + \mathcal{P}^{gg}_{\rm bkg}\right] + N_{\rm VBF}\left[\mu r \times \mathcal{P}^{VBF}_{\rm sig} + \sqrt{\mu r}\times \mathcal{P}^{VBF}_{\rm int} + \mathcal{P}^{VBF}_{\rm bkg}\right] + N_{q\bar{q}\to ZZ}\mathcal{P}^{q\bar{q}}_{\rm bkg} + \ldots$$

Probability distribution for on-shell region

$$\mathcal{P}^{\text{on-shell}}_{\rm tot}(\vec{x}) = \mu_{\rm ggH}\times\left[\mathcal{P}^{\rm gg}_{\rm sig}(\vec{x}) + \mathcal{P}^{\rm t\bar{t}H}_{\rm sig}(\vec{x})\right] + \mu_{\rm VBF}\times\left[\mathcal{P}^{\rm VBF}_{\rm sig}(\vec{x}) + \mathcal{P}^{\rm VH}_{\rm sig}(\vec{x})\right] + \mathcal{P}^{q\bar{q}}_{\rm bkg}(\vec{x}) + \mathcal{P}^{\rm gg}_{\rm bkg}(\vec{x}) + \ldots$$

Probability distribution for off-shell region

$$\mathcal{P}^{\text{off-shell}}_{\rm tot}(\vec{x}) = \left[\mu_{\rm ggH}\times(\Gamma_{\rm H}/\Gamma_0)\times\mathcal{P}^{\rm gg}_{\rm sig}(\vec{x}) + \sqrt{\mu_{\rm ggH}\times(\Gamma_{\rm H}/\Gamma_0)}\times\mathcal{P}^{\rm gg}_{\rm int}(\vec{x}) + \mathcal{P}^{\rm gg}_{\rm bkg}(\vec{x})\right] + \left[\mu_{\rm VBF}\times(\Gamma_{\rm H}/\Gamma_0)\times\mathcal{P}^{\rm VBF}_{\rm sig}(\vec{x}) + \sqrt{\mu_{\rm VBF}\times(\Gamma_{\rm H}/\Gamma_0)}\times\mathcal{P}^{\rm VBF}_{\rm int}(\vec{x}) + \mathcal{P}^{\rm VBF}_{\rm bkg}(\vec{x})\right] + \mathcal{P}^{q\bar{q}}_{\rm bkg}(\vec{x}) + \ldots$$

Γ_H / Γ_0 = scale factor r