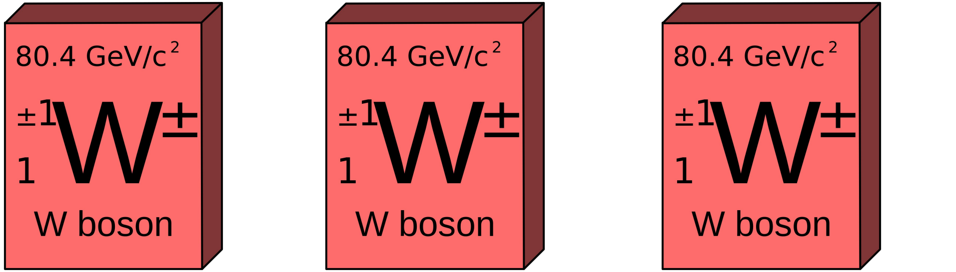
W-Boson Scattering and Interactions at the LHC-CMS experiment and beyond

W-玻色子散射和相互作用的物理研究

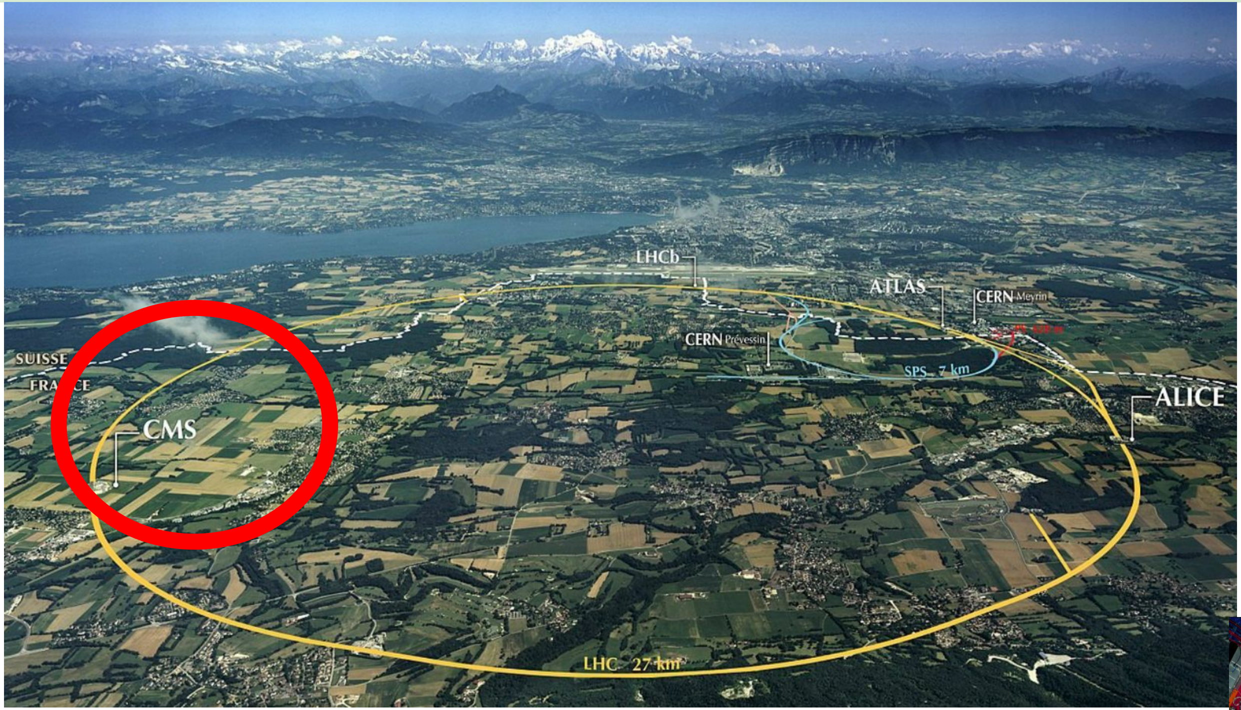
Qiang Li (PKU)

2022/4/14 @THU

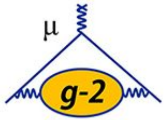
https://WWW.boson.and.friends.bsm



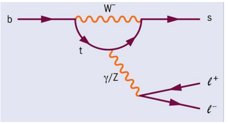
King's Landing: Run3-fell



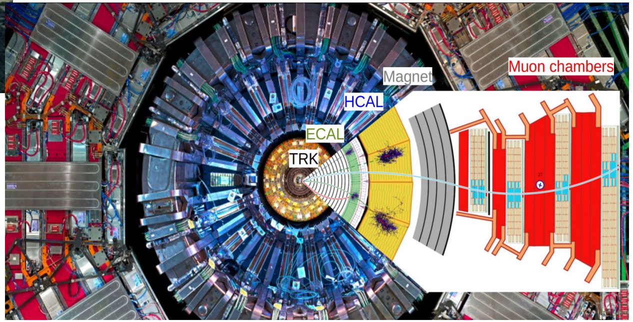
Going Beyond:



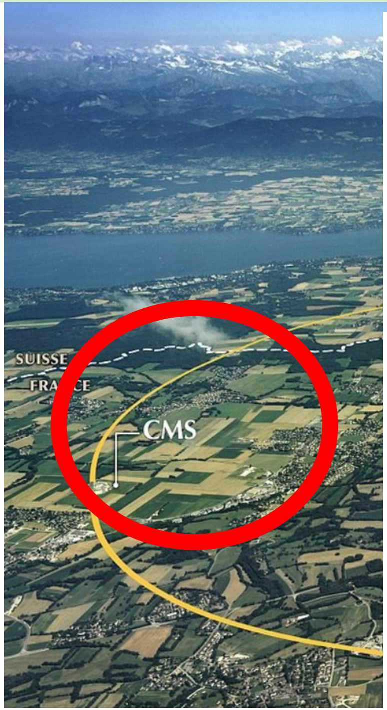
- Dark Matter,
- CP violation,
- Flavor symmetry,
- Fine Tuning,
- *Lepton Flavor Universality Violation*
- *Muon g-2*
- ***W-mass!***



CMS(Compact Muon Solenoid) is one of the large experiments at the LHC, consists of over 3000 scientists, >200 institutes, from 40+ countries. PKU joined CMS in late 1990s.



King's Landing: Run3-fell



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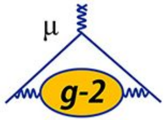
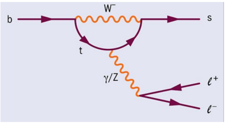
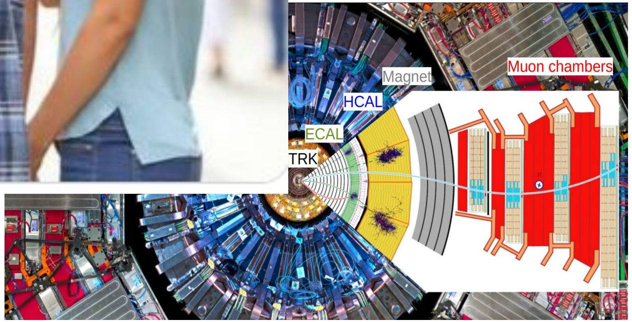
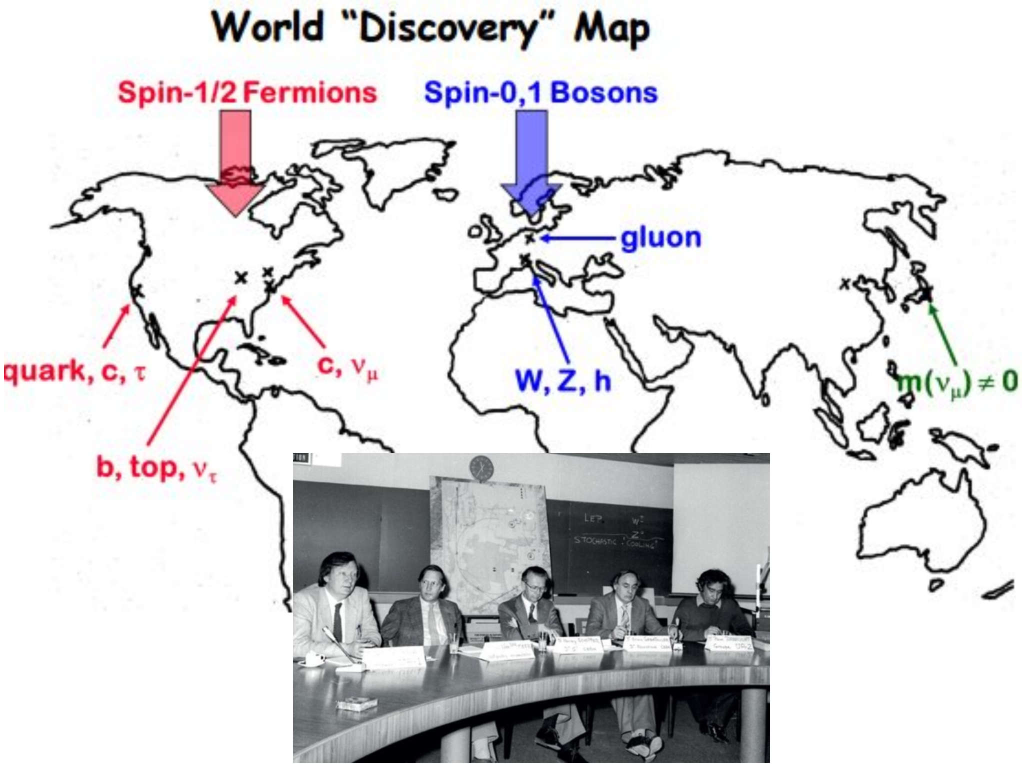


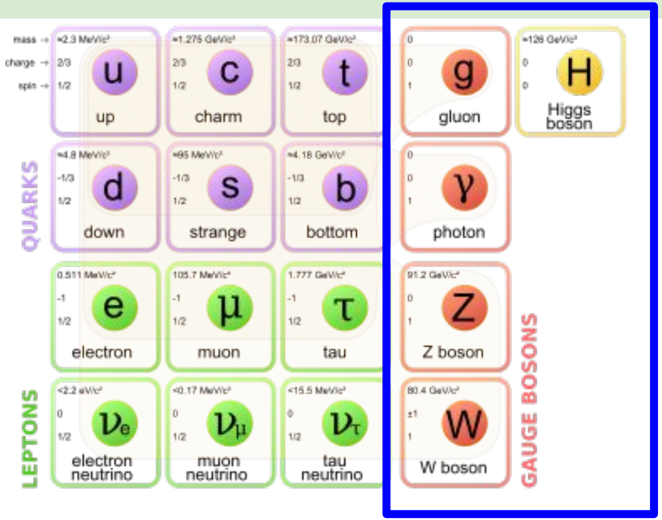


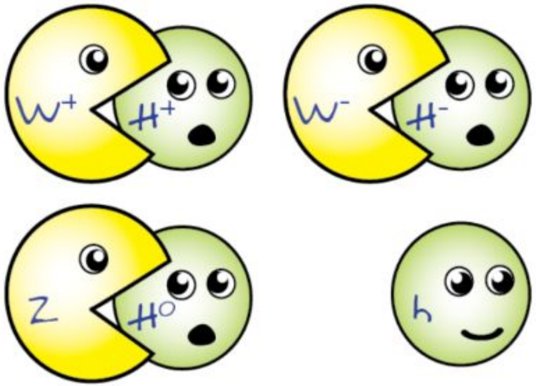


CMS(Compact
large experime
3000 scientists, >200 institutes, from 40+ countries. **PKU joined CMS in late 1990s.**

Boson







The LHC is also a Large Boson Collider

W-mass@CMS

- **Quite challenging analysis**
  - results expected at Moriond2023 (hopefully)
- **Intermediate results**
  - CMS-PAS-SMP-14-007:
    - W-like measurement of the Z boson mass using dimuon events collected in pp collisions at 7TeV
  - Phys. Rev. D 102 (2020) 092012:
    - Measurements of the W boson rapidity, helicity, double-differential cross sections, and charge asymmetry
- **CERN-THESIS-2021-271** thesis of Elisabetta Manca
  - "...of the order of 10 MeV, using the data… in 2016"
- **MiNNLO$_{PS}$** (OR MiNNLO⊗SCETlib, EWK NLO) being investigated
  - consistently combine next-to-next-to-leading order (NNLO) QCD calculations with parton-shower simulations
  - **Several billion events' budget!**

Below I will focus more on W plus friends!

Erratum | Open Access | Published: 04 February 2022

Erratum to: MiNNLO$_{PS}$: a new method to match NNLO QCD to parton showers

Pier Francesco Monni, Paolo Nason, Emanuele Re, Marius Wiesemann & Giulia Zanderighi

Journal of High Energy Physics **2022**, Article number: 31 (2022) | Cite this article

Dear Qiang,
we are pleased to inform you that CMS has decided to award you with a CMS award for your outstanding contributions to offline and computing in CMS over more than ten years.

The CMS award ceremony will take place during the June CMS week. You may want to plan to be at CERN in person for the ceremony. However if you cannot participate in person, you will be able to collect the award at the CMS secretariat after the June CMS week.

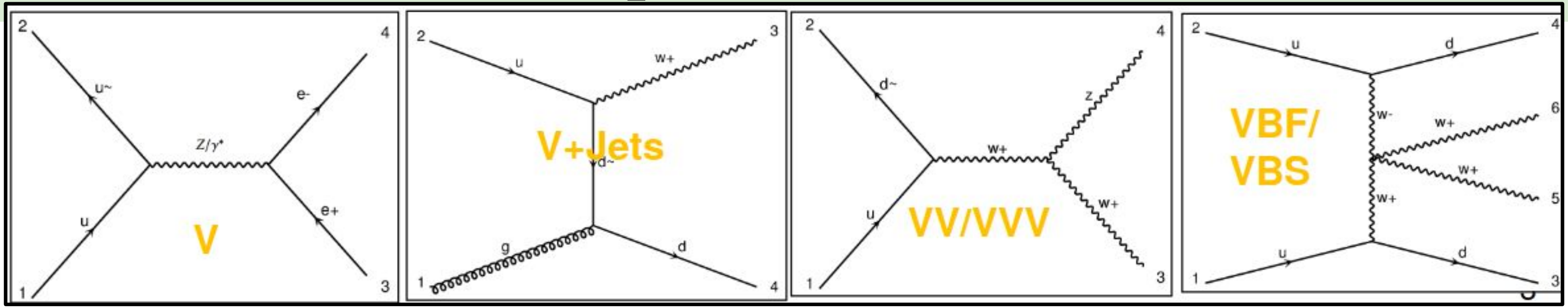
Congratulations,

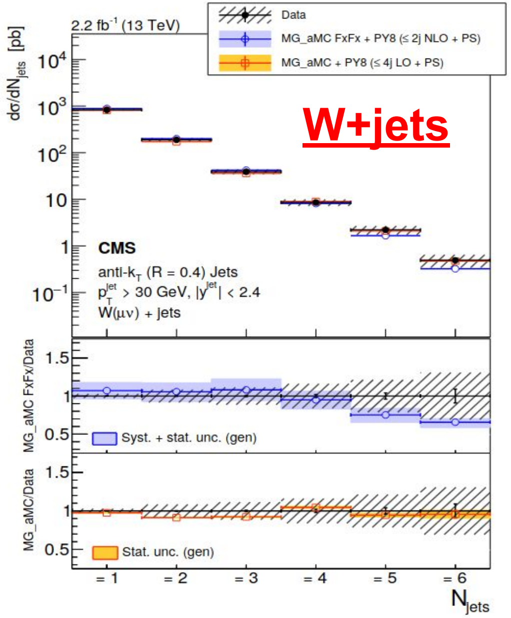
Francesca and Ulrich
for the CMS awards committee

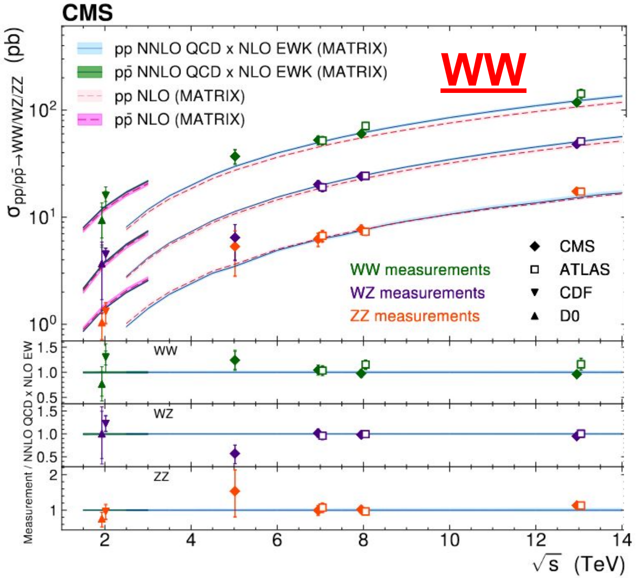
Two CMS Awards

2020-2021 Congqiao Li
2021-2022 Qiang Li
For efficient MC production

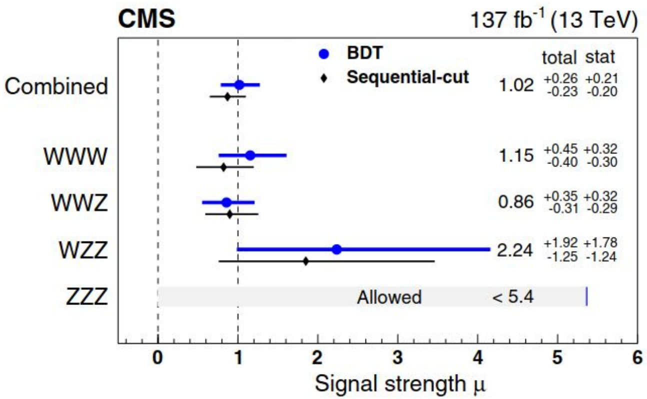
W-boson related topics: not meant to be exhaustive





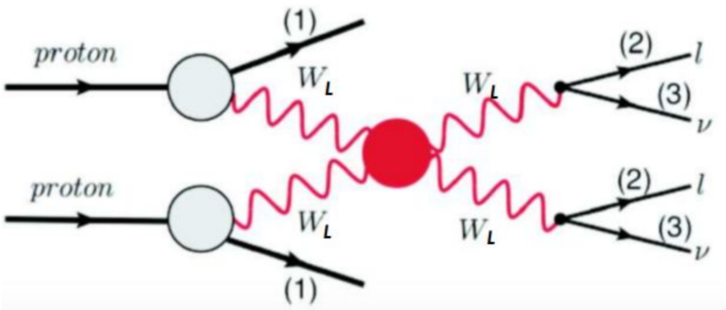


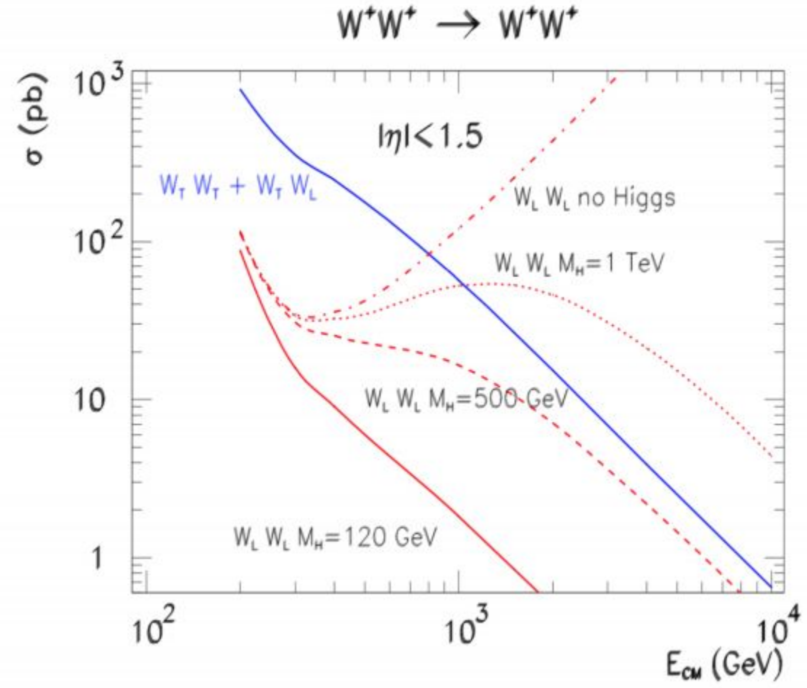
WWW discovery



Boson Scattering and Interactions: only feasible at the LHC

Same-Sign W W-> Polarized scattering, ~200 events (2016-2018)!





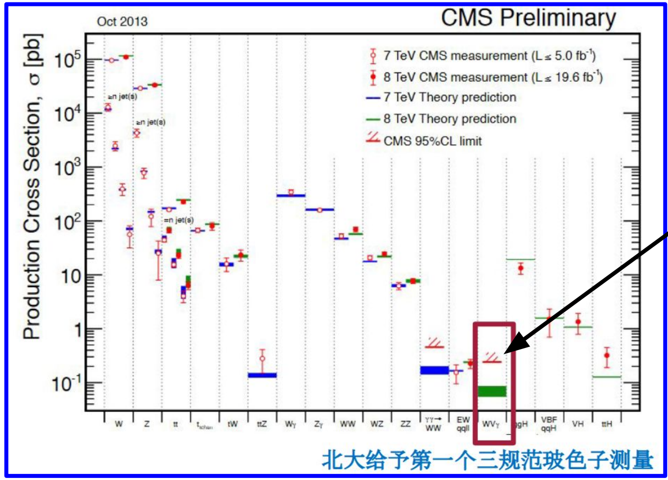
Boson scattering and Interaction

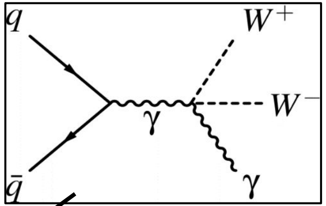
- Yang-Mills Non-Abelian interactions
  Anomalous coupling, EFT
- Electroweak symmetry breaking
  Higgs Unitarization Scheme
- Tev scale new Physics
  Boosted Boson

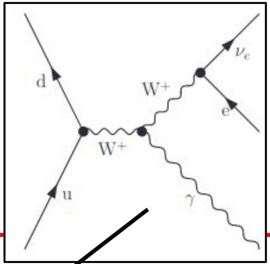
WW->WW behavior
on scattering energy

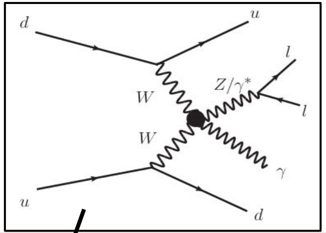
7

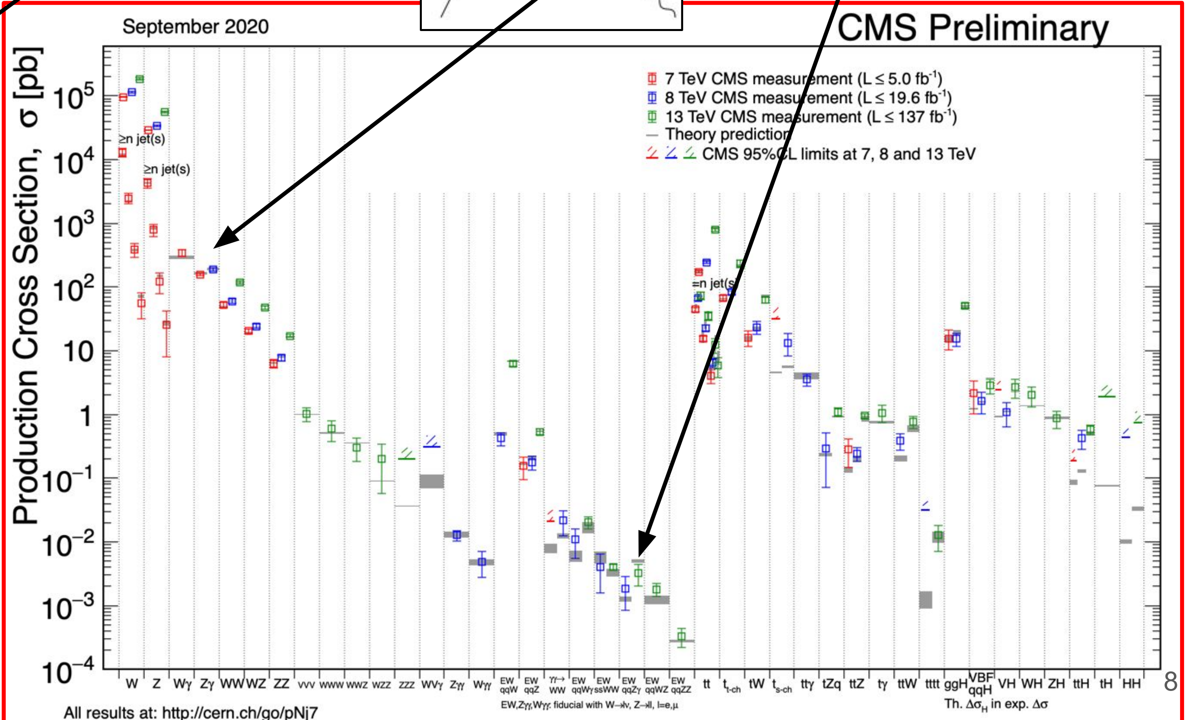
Stair to X: multi-boson road











Enriched CMS measurement summary plot, left plot is the version in 2013 and right the one in 2020.

9 order of magnitudes on XS!

Anomalous Couplings and EFT

EWDim6, SMEFT, aTGC, aQGC...

Sensitive to anomalous coupling

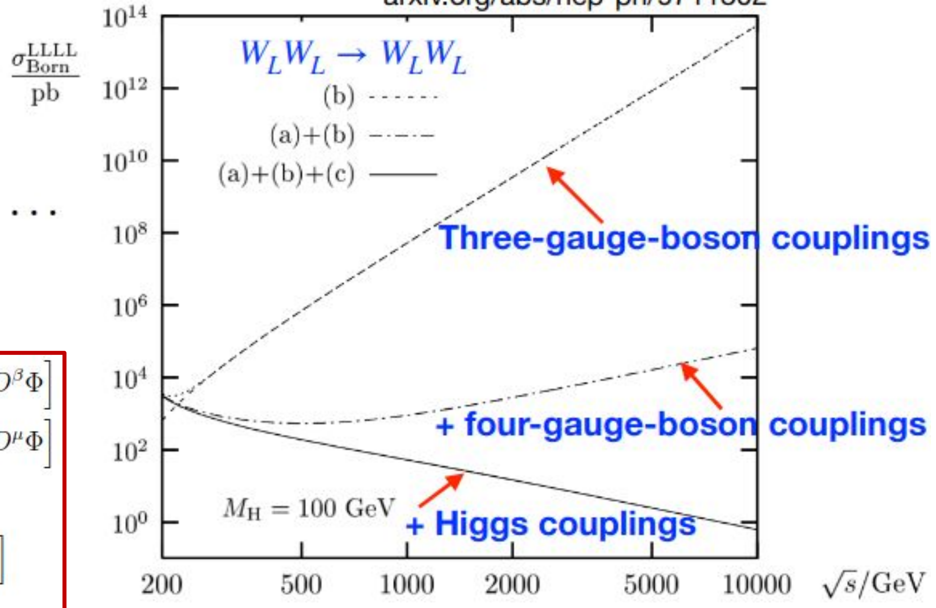
- ☑ Triple and quartic gauge coupling

$$\mathscr{L}_{EFT} = \mathscr{L}_{SM} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathscr{O}^{(6)} + \frac{c_i^{(8)}}{\Lambda^2}\mathscr{O}^{(8)} + \ldots .$$

$$\begin{aligned}
\mathcal{O}_{WWW} &= \mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W^{\mu}_{\rho}], \\
\mathcal{O}_{B} &= (D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi), \\
\mathcal{O}_{W\tilde{W}W} &= \mathrm{Tr}[\tilde{W}_{\mu\nu}W^{\nu\rho}W^{\mu}_{\rho}], \text{ and} \\
\mathcal{O}_{\tilde{W}} &= (D_\mu\Phi)^\dagger \tilde{W}^{\mu\nu}(D_\nu\Phi),
\end{aligned}$$

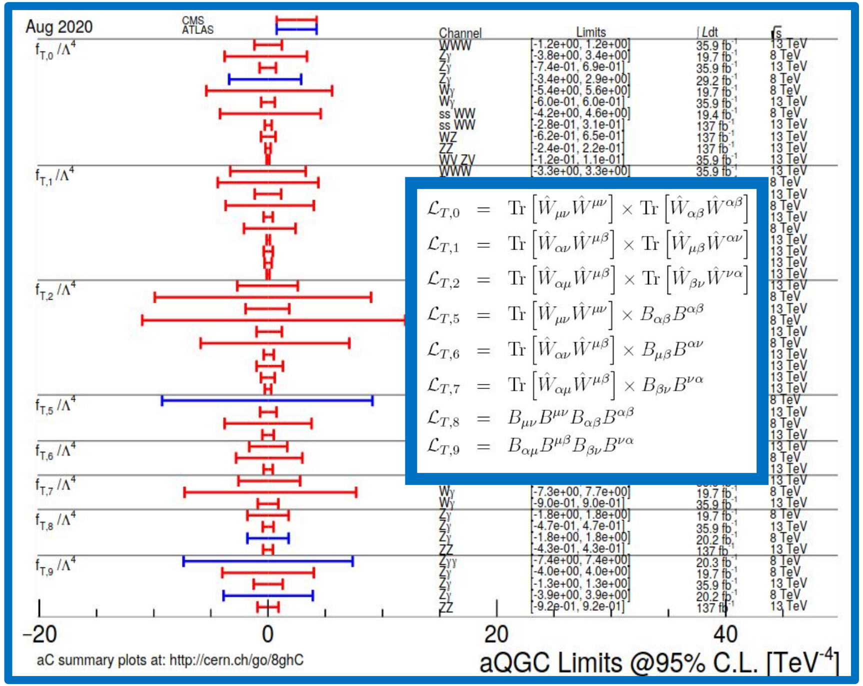
$$\begin{aligned}
\mathcal{L}_{M,0} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \\
\mathcal{L}_{M,1} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \\
\mathcal{L}_{M,2} &= \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \\
\mathcal{L}_{M,3} &= \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \\
\mathcal{L}_{M,4} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\mu\Phi\right] \times B^{\beta\nu} \\
\mathcal{L}_{M,5} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\nu\Phi\right] \times B^{\beta\mu} \\
\mathcal{L}_{M,6} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\nu} D^\mu\Phi\right] \\
\mathcal{L}_{M,7} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu} D^\nu\Phi\right]
\end{aligned}$$

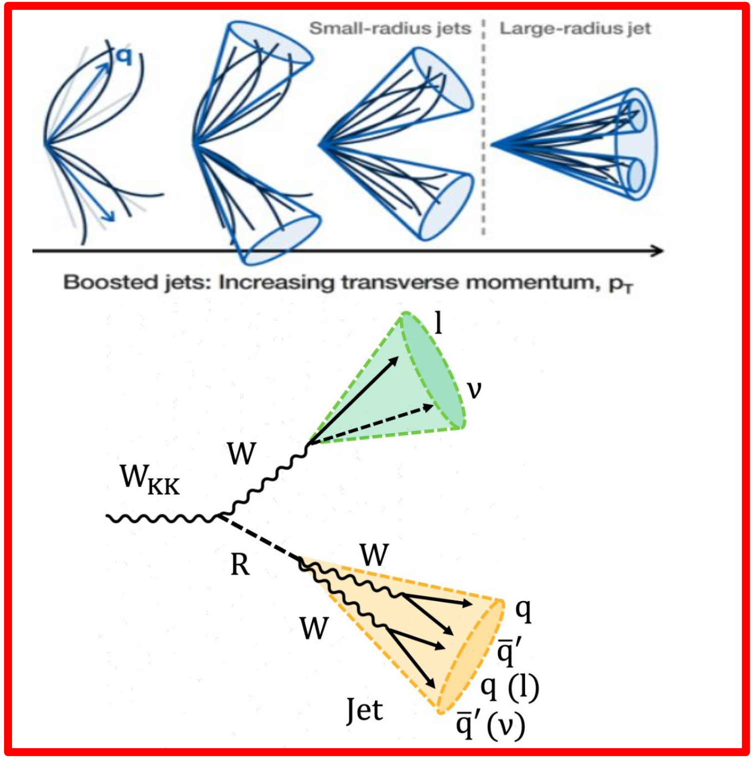
arxiv.org/abs/hep-ph/9711302



$$\begin{aligned}
\mathcal{L}_{S,0} &= \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right] \\
\mathcal{L}_{S,1} &= \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right]
\end{aligned}$$

Indirect and Direct Search for New Physics





The large boson-boson collider Symmetry Magzine

"These heavy boson-boson collisions … provide physicists with a unique view of the subatomic world."

Outline

- **W boson and Photon Associated and Scattering Production**
  - VBS W+γ discovery JHEP 06 (2017) 106, PLB 811 (2020) 135988
  - W+γ precision measurement Phys. Rev. Lett. 126, 252002 (2021)

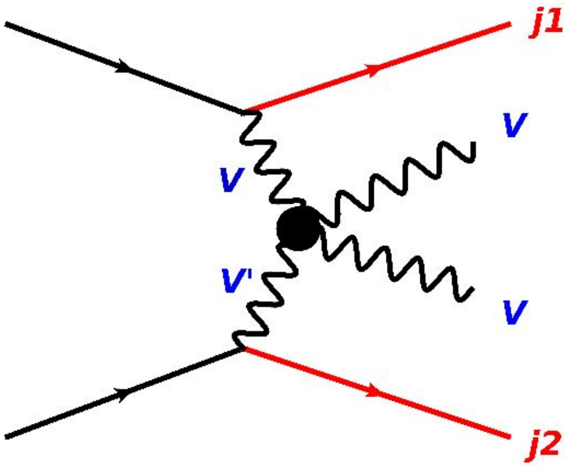
- **Polarized Vector W boson Scattering**
  - First probe at CMS Phys. Lett. B 812 (2020) 136018
  - Projection at a TeV Scale Muon Collider Phys.Rev.D 104 (2021) 9, 093003
  - Heavy Majorana Neutrino and Weinberg Operator
    CMS-PAS-EXO-21-003 to be submitted to PRL

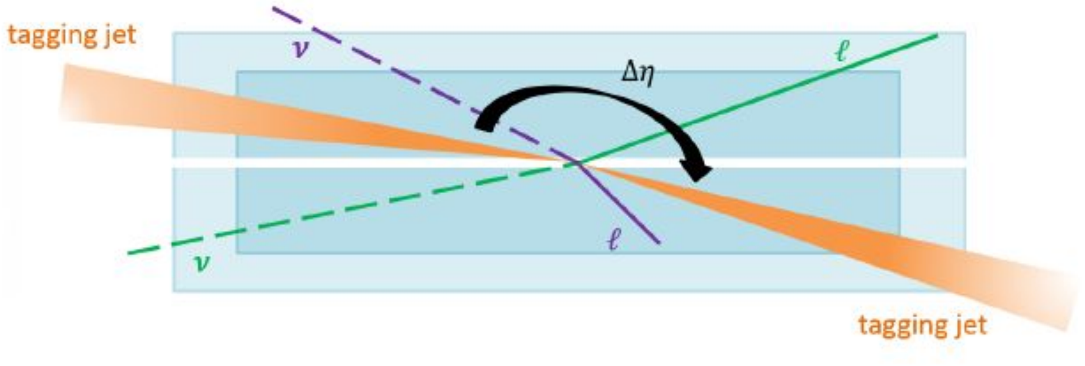
- **Triple W boson Resonance Searches**
  - Deep Learning Tagger JINST 15 (2020) P06005
  - WWW Resonance arXiv:2201.08476 submitted to PRL
    arXiv:2112.13090 submitted to PRD

11

1-1. Vector Boson Scattering

- **Rare & Novel processes (to be) discovered**
- **Clean environment** with less QCD activity
  VBF Jets property measurement;
- **VV scattering sensitive to UV completeness**
- **High Tail enhancements:**
  to probe anomalous Triple (Quartic) Gauge Couplings



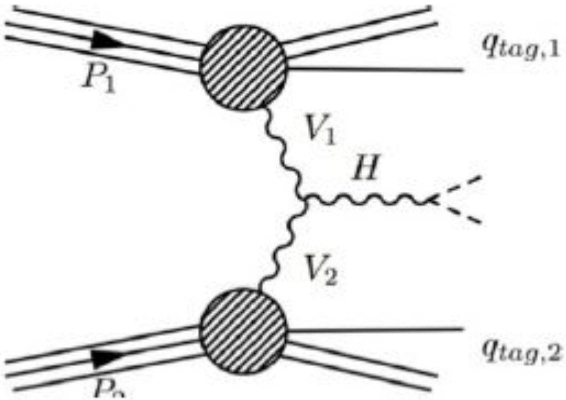


Two VBF Tagged Jets:
    Large mjj and |detajj|
    More quark-like
Lower central hadronic activity:
    More balanced between
    VBF and Central systems

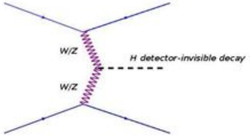
$$y^* = y_Z - \frac{1}{2}(y_{j_1} + y_{j_2})$$

1-2. PKU VBS Roadmap

VBS Invisible Higgs
EPJC 74 (2014) 2980

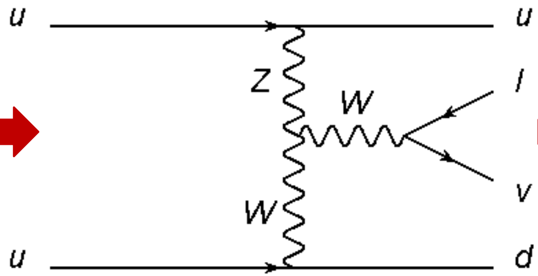


Status of VBF H-> Invisible Study



Qiang Li (Peking University, China)
for the VBF Inv H analysis team
2013/01/15, EXO-Higgs Meeting

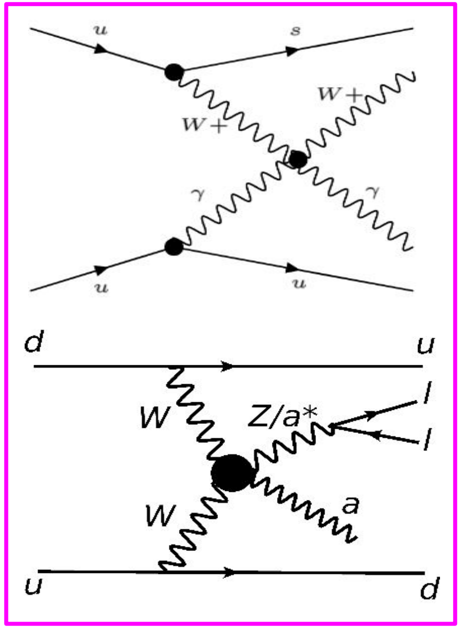
VBF W+2Jets
JHEP 11 (2016) 147



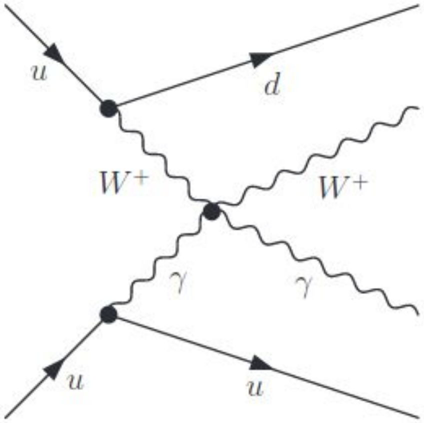
Description	W production with forward jet tagging
Contact Person	Jing Li (PEKING-UNIV)
HN	SMP-13-012

Snapshot of CMS Analysis Page

Let there be light!



1-3. VBS Wγ Discovery



- First observation of the VBS Wγ production with leptonic final states
- Signal events are extracted from 2D m_{jj}-$m_{l\gamma}$ distribution
  - ☑ Simultaneous fit in the CR and SR
- Signal significance and cross section
  - ☑ Observed (expected) significance 5.3σ (4.8σ) (13 TeV+8TeV)
  - ☑ Fiducial cross section are measured as:

$$\sigma_{EW} = 20.4 \pm 4.5\,\text{fb} \qquad \sigma^{theory}_{EW} = 17.0 \pm 4.1\,\text{fb}$$

$$\sigma_{EW+QCD} = 108 \pm 16\,\text{fb} \qquad \sigma^{theory}_{EW+QCD} = 89.7 \pm 13.9\,\text{fb}$$

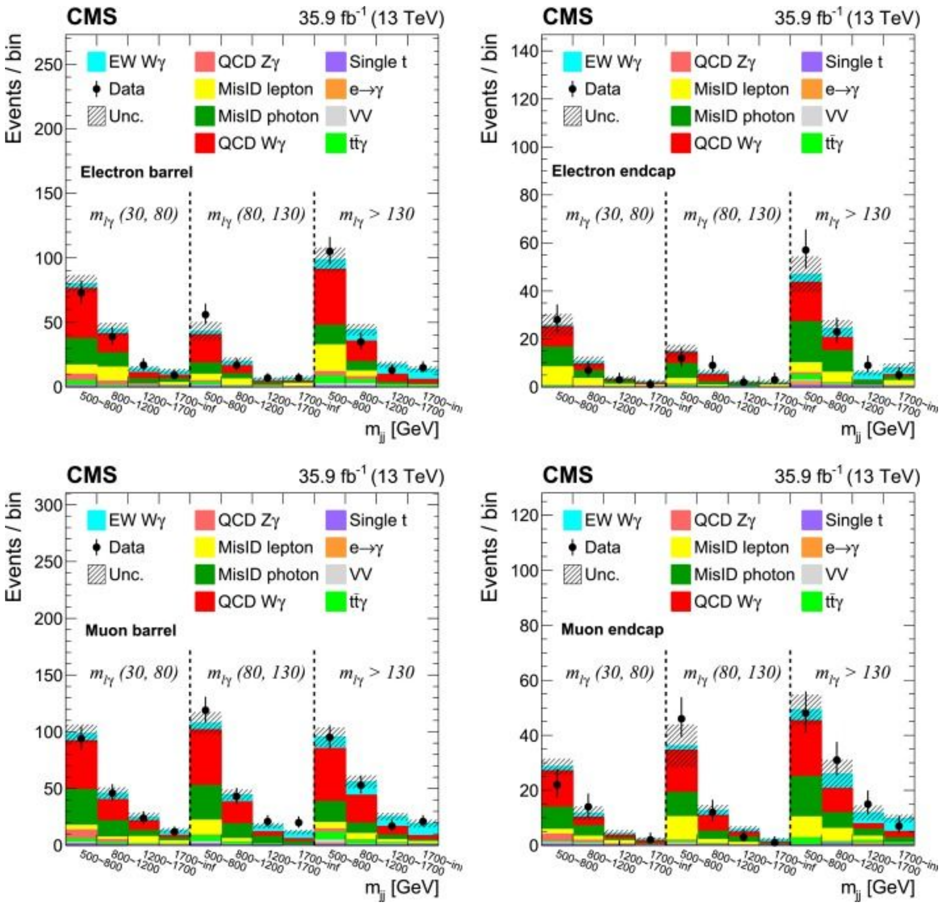
Description	Wgamma + 2 jets production in EWK processes
Contact Person	Daneng Yang (PEKING-UNIV)
HN	SMP-14-011

8TeV JHEP 06 (2017) 106

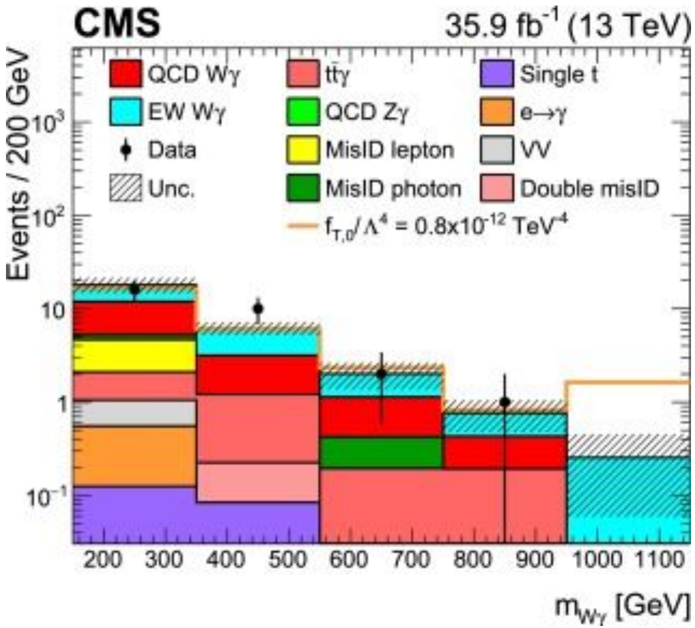
Description	Wgamma vector boson scattering
Contact Person	Qianming Huang (PEKING-UNIV)
HN	SMP-19-008

13TeV, 2016
PLB 811 (2020) 135988

1-4. VBS Wγ Discovery



Misidentified Photon and Lepton estimated from data



most stringent limit for aQGC operator f_{M2-5}, and f_{T6-7}

1-5. Inclusive Wγ

- **Last time measurement was for 7TeV**
- **Wγ fiducial cross section based on fit to mlγ distribution:**
  - σ = 15.44 ±0.05 (stat) ±0.84 (exp) ±0.12 (theory) pb
- **Theoretical cross sections:**
  - MadGraph5_aMC@NLO 0+1 jets at NLO: 15.44 ±1.24 pb
  - POWHEG with “NLO competition” scheme: 22.45 ±3.21 pb
- **Limits on dimension 6 EFT operators based on photon pT distribution**

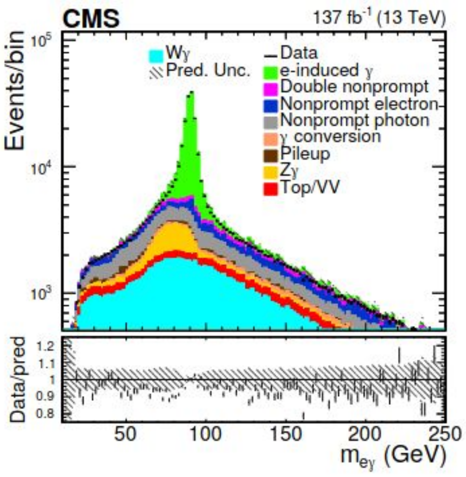
Description	Wgamma cross section
Contact Person	Andrew Michael Levin (PEKING-UNIV)
HN	SMP-19-002

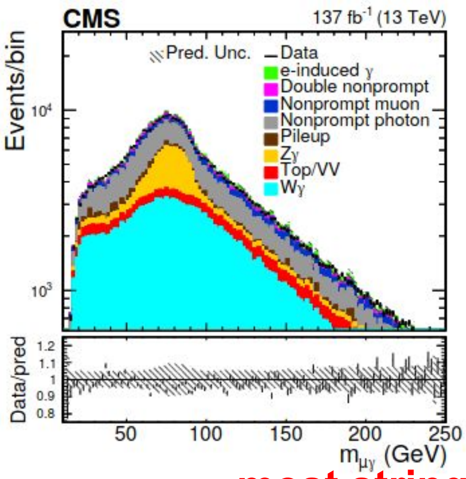
Approval for SMP-19-002 : Wgamma cross section

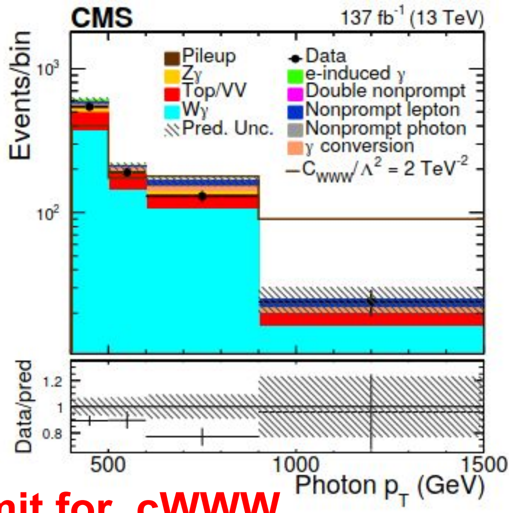
Speaker: Jie Xiao (Peking University (CN))

Full Run2 arXiv:2102.02283

Phys. Rev. Lett. 126, 252002 (2021)

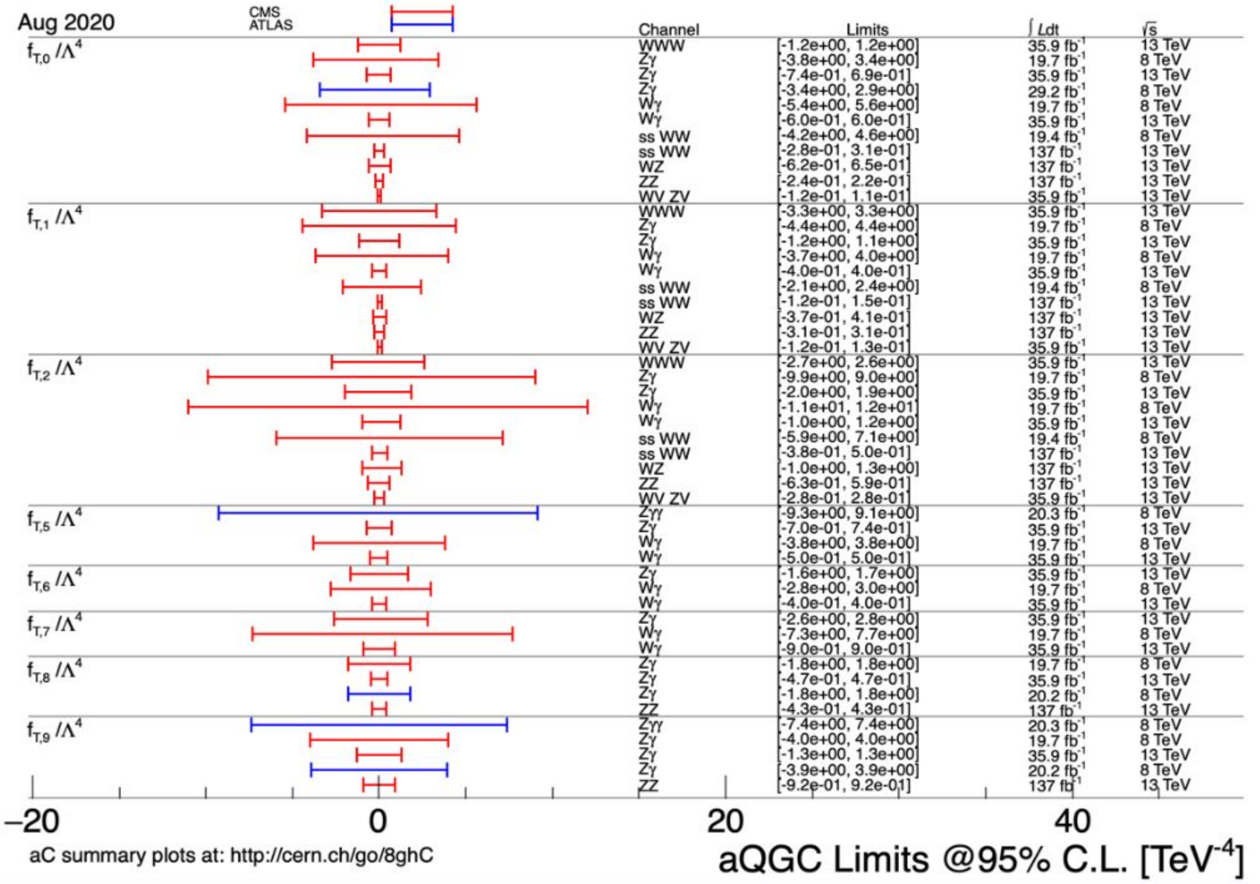


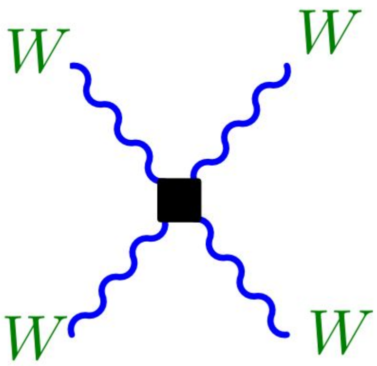


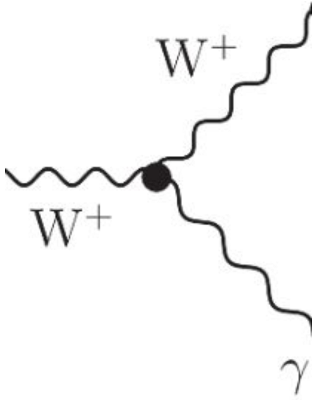


most stringent limit for cWWW

1-6. Best limits on Gauge Boson Self Couplings







https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

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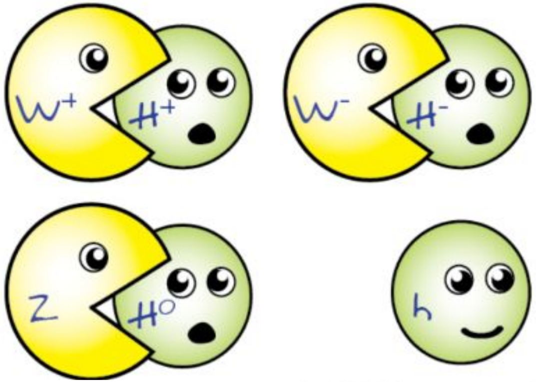
18

2-1. Polarized Vector Boson Scattering



VOLUME 69, NUMBER 18 PHYSICAL REVIEW LETTERS 2 NOVEMBER 1992

On the Precise Formulation of the Equivalence Theorem

Hong-Jian He and Yu-Ping Kuang
CCAST (World Laboratory), P.O. Box 8730, Beijing 100080, China
and Institute of Modern Physics and Department of Physics, Tsinghua University, Beijing 100084, China[a]

Xiaoyuan Li
CCAST (World Laboratory), P.O. Box 8730, and Institute for Theoretical Physics–Academia Sinica, Beijing 100080, China
(Received 19 May 1992)

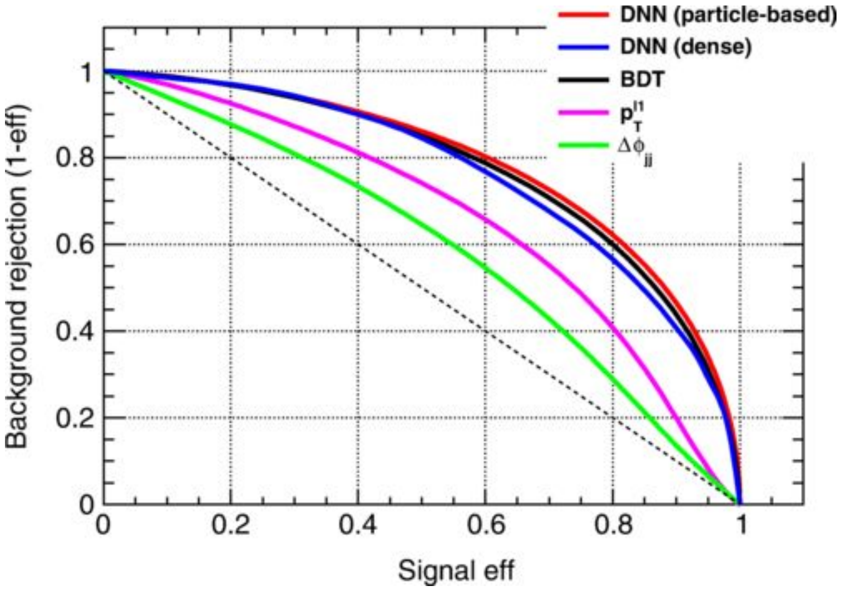
A systematic analysis of renormalization schemes and a general proof of the precise formulation of the equivalence theorem are given in the R_ξ gauge for both the $SU(2)_L$ and the $SU(2)\times U(1)$ theories. The precise formula for the modification factor C_{mod} is obtained, and a convenient particular scheme in which C_{mod} is exactly unity is proposed. C_{mod} in other schemes are discussed up to one loop in the heavy Higgs boson limit.

Longitudinal weak boson scattering… is one of the most important processes to be studied at the Superconducting Super Collider and the CERN Large Hadron Collider. 纵向玻色子散射是LHC待研究的最重要的物理过程。

Small Signal, <10% of VBS

Junho Lee… Q.Li... et.al.,

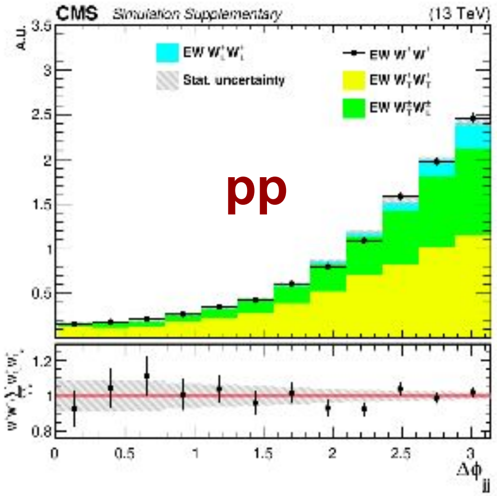
PRD 99, 033004 (2019) ; PRD 100, 116010 (2019)

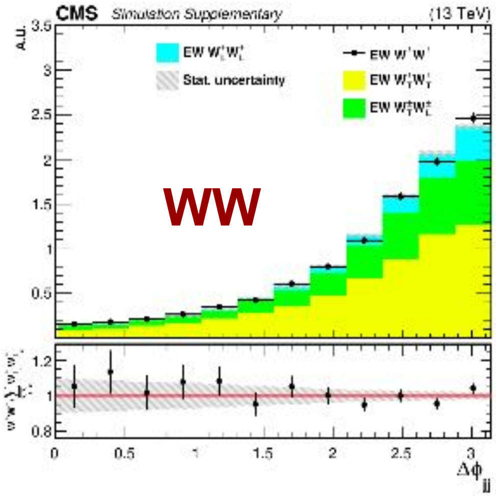


BDT and DNN can help improve the sensitivity. **Although it still needs 3000/fb to reach 4-5 standard deviations.**

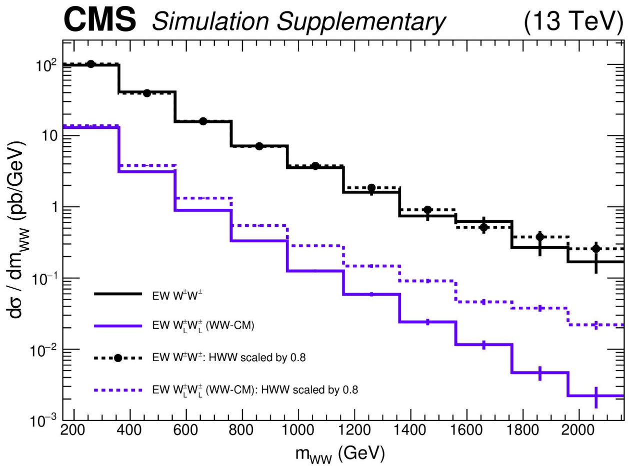
2-2. First Probe from CMS on Polarized VBS

- Signal sample simulated in **WW/pp center-of-mass frame**
- Simultaneous fit in bins of two BDT discriminant variables:





MADGRAPH5_aMC@NLO2.7.2



Approval of SMP-20-006 : Measurements of the scattering of polarized same-sign WW bosons

Speakers: Aram Apyan (Fermi National Accelerator Lab. (US)) , Mr Jie Xiao (Peking University (CN))

[Phys. Lett. B 812 (2020) 136018]

2-3. First Probe from CMS on Polarized VBS

Inclusive BDT: **Isolate VBS against non VBS background**

Variables	Definitions
m_{jj}	Dijet mass
$\lvert\Delta\eta_{jj}\rvert$	Difference in pseudorapidity between the leading and subleading jets
$\Delta\phi_{jj}$	Difference in azimuth angles between the leading and subleading jets
p_T^{j1}	p_T of the leading jet
p_T^{j2}	p_T of the subleading jet
$p_T^{\ell_1}$	Leading lepton p_T
$p_T^{\ell\ell}$	Dilepton p_T
$z^*_{\ell_1}$	Zeppenfeld variable of the leading lepton
$z^*_{\ell_2}$	Zeppenfeld variable of the subleading lepton
p_T^{miss}	Missing transverse momentum

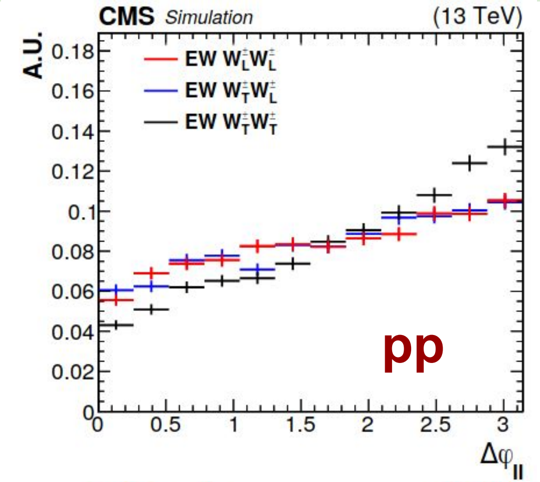
Process	Yields in $W^\pm W^\pm$ SR
$W^\pm_L W^\pm_L$	16.0 ± 18.3
$W^\pm_L W^\pm_T$	63.1 ± 10.7
$W^\pm_T W^\pm_T$	110.1 ± 18.1
QCD $W^\pm W^\pm$	13.8 ± 1.6
Interference $W^\pm W^\pm$	8.4 ± 0.6
WZ	63.3 ± 7.8
ZZ	0.7 ± 0.2
Nonprompt	213.7 ± 52.3
tVx	7.1 ± 2.2
Other background	26.9 ± 9.9
Total SM	522.9 ± 60.7
Data	524

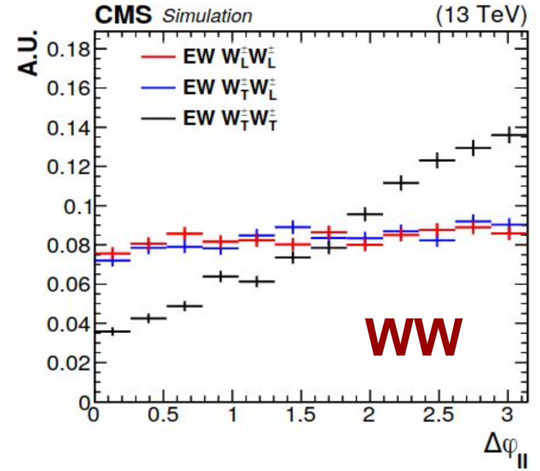
2-4. First Probe from CMS on Polarized VBS

Signal BDTs to improve the sensitivity to polarized scattering

Train LL against (LT+TT) and train (LL+LT) against TT

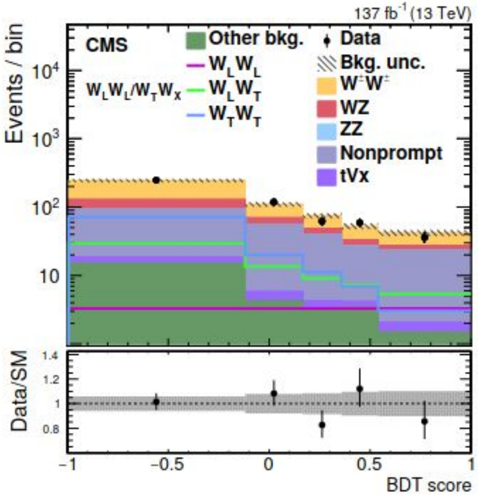
Variables	Definitions
$\Delta\phi_{jj}$	Difference in azimuthal angle between the leading and subleading jets
p_T^{j1}	p_T of the leading jet
p_T^{j2}	p_T of the subleading jet
$p_T^{\ell_1}$	Leading lepton p_T
$p_T^{\ell_2}$	Subleading lepton p_T
$\Delta\phi_{\ell\ell}$	Difference in azimuthal angle between the two leptons
$m_{\ell\ell}$	Dilepton mass
$p_T^{\ell\ell}$	Dilepton p_T
m_T^{WW}	Transverse WW diboson mass
$z^*_{\ell_1}$	Zeppenfeld variable of the leading lepton
$z^*_{\ell_2}$	Zeppenfeld variable of the subleading lepton
$\Delta R_{j1,\ell\ell}$	ΔR between the leading jet and the dilepton system
$\Delta R_{j2,\ell\ell}$	ΔR between the subleading jet and the dilepton system
$(p_T^{\ell_1} p_T^{\ell_2})/(p_T^{j1} p_T^{j2})$	Ratio of p_T products between leptons and jets
p_T^{miss}	Missing transverse momentum

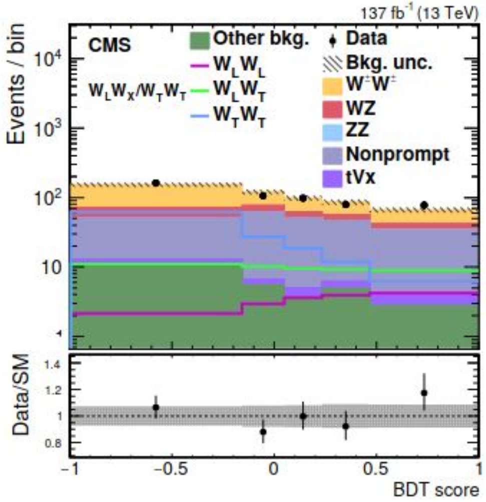


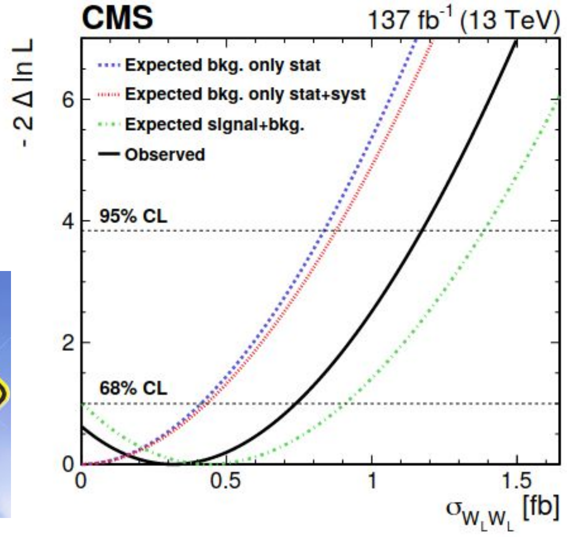


2-5. First Probe from CMS on Polarized VBS

- Simultaneous fit on two BDT discriminant variables:
  - ☑ $W_L^{\pm} W_L^{\pm}$: signal BDT ($W_L^{\pm} W_L^{\pm}$ vs $W_T^{\pm} W_X^{\pm}$) and inclusive BDT (VBS vs Bkg.)
  - ☑ $W_L^{\pm} W_X^{\pm}$: signal BDT ($W_L^{\pm} W_X^{\pm}$ vs $W_T^{\pm} W_T^{\pm}$) and inclusive BDT (VBS vs Bkg.)
  - ☑ Selection and CRs are same as EW W±W± production



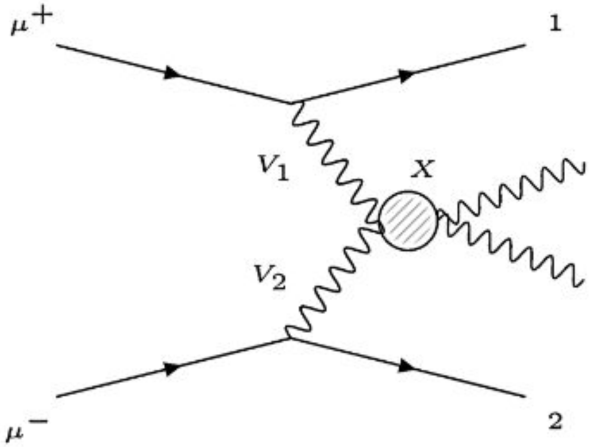




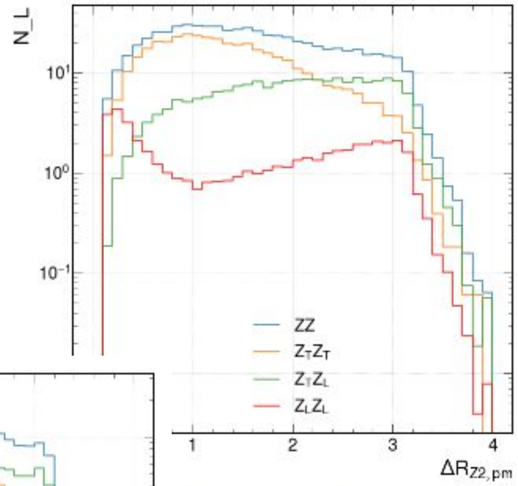
Observed (expected) significance for LL and LT+LL: **0.88 (1.17)σ; 2.3 (3.1)σ**

Process	$\sigma\mathcal{B}$ (fb)	Theoretical prediction (fb)
$W_L^{\pm}W_L^{\pm}$	$0.32^{+0.42}_{-0.40}$	0.44 ± 0.05
$W_X^{\pm}W_T^{\pm}$	$3.06^{+0.51}_{-0.48}$	3.13 ± 0.35
$W_L^{\pm}W_X^{\pm}$	$1.20^{+0.56}_{-0.53}$	1.63 ± 0.18
$W_T^{\pm}W_T^{\pm}$	$2.11^{+0.49}_{-0.47}$	1.94 ± 0.21

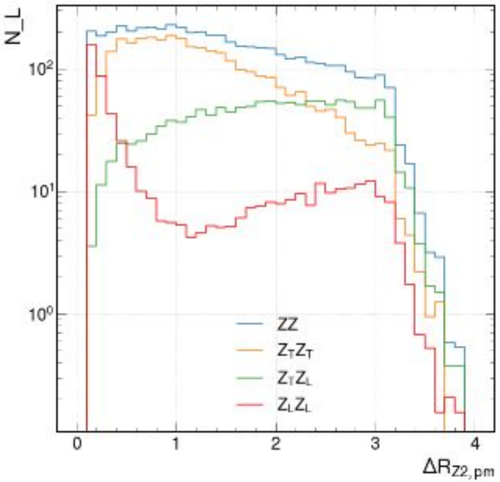
2-6. Polarized VBS at a Muon Collider



Tianyi Yang,... Q.Li…
Phys.Rev.D 104 (2021) 9, 093003



$\Delta R_{Z_2,pm}$, $\sqrt{s} = 6$ TeV



(a) $\Delta R_{Z_2,pm}$, $\sqrt{s} = 14$ TeV

- ~5σ significance can be achieved at 14 TeV muon collider
  - With $3ab^{-1}$ integrated luminosity
- ~2σ significance can be achieved at 6 TeV muon collider
  - With $4ab^{-1}$ integrated luminosity

2-7. Heavy Majorana and Weinberg Operator

Jie Xiao, Sitian (PKU) CMS-PAS-EXO-21-003 **To be submitted to PRL**

Code	Name	Status
EXO-21-003 » | ▲show | ▼CDS | ▼PRL	Search for VBF production of same-sign muons through Majorana neu ...	CWR-ended

EXO-21-003 (*Fri, 8 Apr 2022 08:42:36*)

Name	Search for VBF production of same-sign muons through Majorana neutrinos or the Weinberg operator	**Description**	Search for VBF production of sar neutrinos or the Weinberg operat
Status	CWR-ended	**Contact Person**	Jie Xiao (PEKING-UNIV)
Twiki	EXO-21-003	**HN**	EXO-21-003

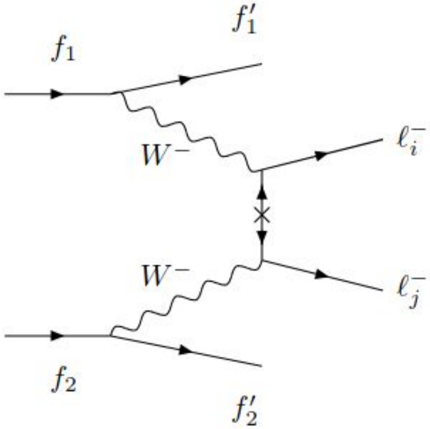
arXiv > hep-ph > arXiv:0901.3589

High Energy Physics - Phenomenology

[Submitted on 23 Jan 2009 (v1), last revised 7 May 2009 (this version, v2)]

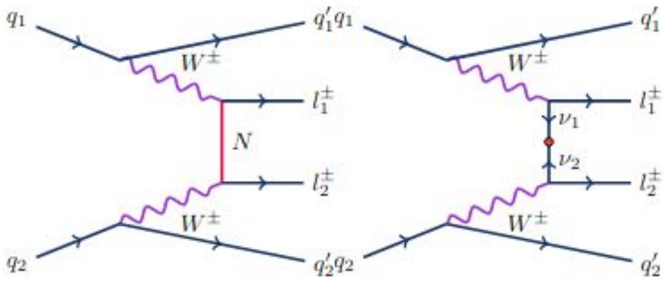
The Search for Heavy Majorana Neutrinos

Anupama Atre, Tao Han, Silvia Pascoli, Bin Zhang



0νμμ experiment

2-8. Heavy Majorana and Weinberg Operator



- Address neutrino mass

✓ Heavy Majorana neutrino HMN (see-saw) → neutrinoless VBF t-channel (high mass sensitivity, new!)

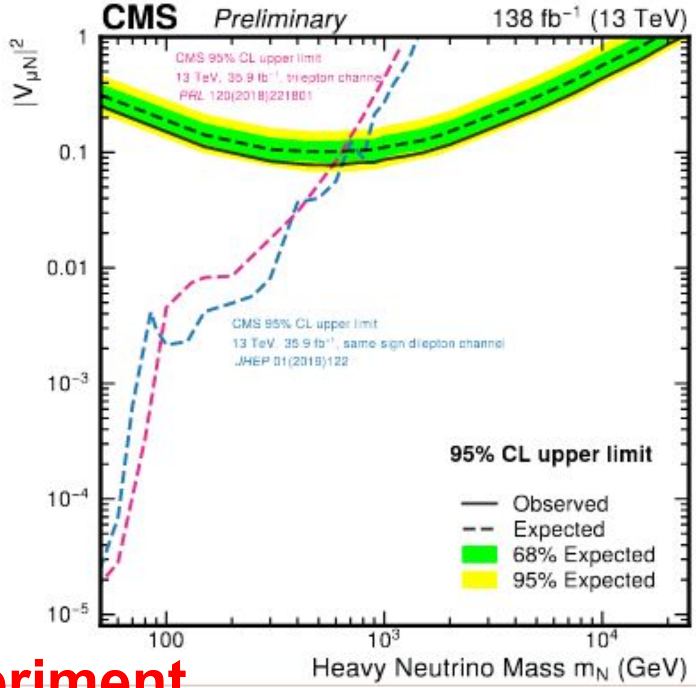
✓ Effective field theory (EFT): dim-5 Weinberg operator (WO) → m_ν with no new fields

→ Analogous to neutrinoless double β decay, but with μ (instead of e)

- Final state: two same sign $\mu\mu$ and VBF jets
- Dedicated studies to identify high-p_T μ

~23TeV!

- Limits exclude
  - HMN up to $m_N = 23$ TeV
  - Effective Majorana mass up to $m_{\ell\ell} = 10.84$ GeV
  - → First constraints for this process!



0νμμ experiment

Outline

- **W boson and Photon Associated and Scattering Production**
  - VBS W+γ discovery — JHEP 06 (2017) 106, PLB 811 (2020) 135988
  - W+γ precision measurement — Phys. Rev. Lett. 126, 252002 (2021)

- **Polarized Vector W boson Scattering**
  - First probe at CMS — Phys. Lett. B 812 (2020) 136018
  - Projection at a TeV Scale Muon Collider — Phys.Rev.D 104 (2021) 9, 093003
  - Heavy Majorana Neutrino and Weinberg Operator
    CMS-PAS-EXO-21-003 to be submitted to PRL

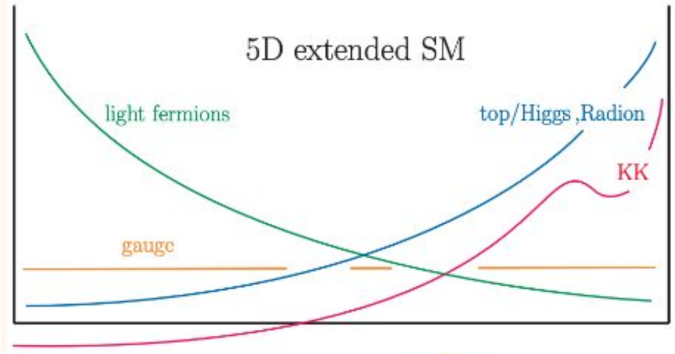
- **Triple W boson Resonance Searches**
  - Deep Learning Tagger — JINST 15 (2020) P06005
  - WWW Resonance — arXiv:2201.08476 submitted to PRL
    arXiv:2112.13090 submitted to PRD

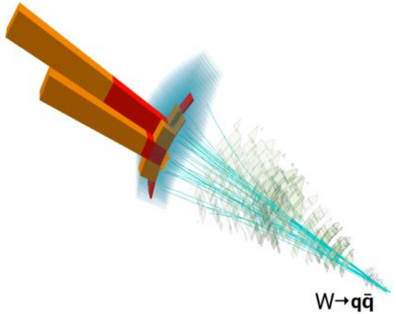
27

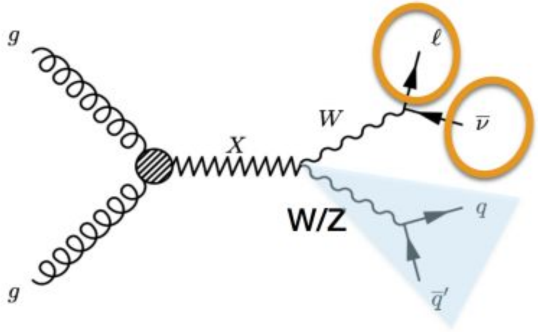
3-1. 'traditional' di-boson Resonance Search

Take Standard (Minimal) Warped ED model as an example

- 2 Branes in Bulk, everything propagates to the same bulk
- motivated by hierarchy problem and flavor structure
- Constrained by LHC searches

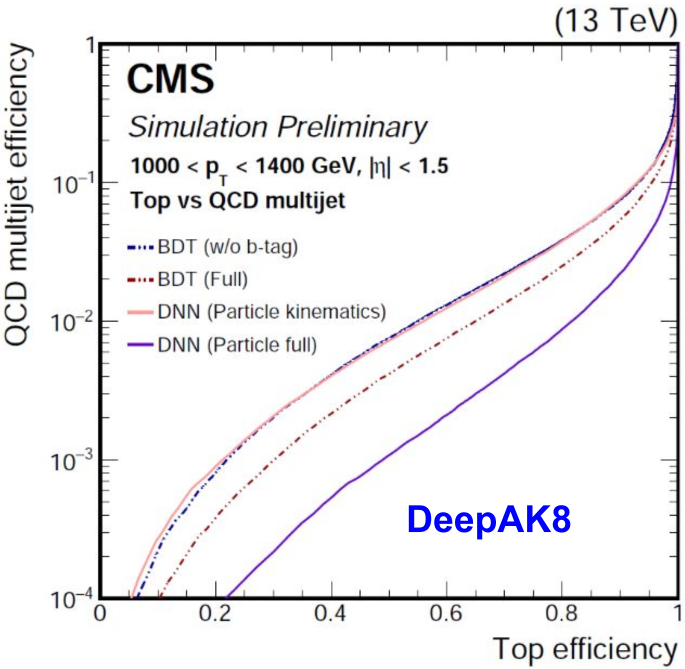






Rich developments and applications of advanced technique on (boosted) jet in last years:
PileUp Per Particle Identification (PUPPI); W/H tagging; Nsubjettiness; Softdrop; Grooming; Deep learning tagger (DeepAK, ParticleNet)

3-2. Deep Tagger in CMS



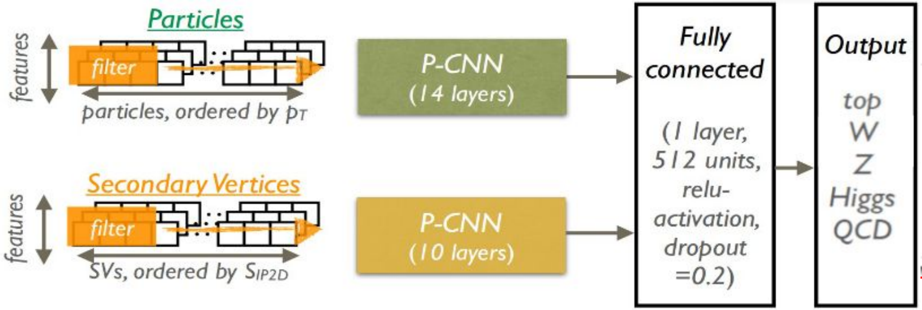
JINST 15 (2020) P06005
CMS_DP-2017-049

DeepAK and ParticleNet becomes CMS standards!

Developed by Dr. Huilin Qu (曲慧麟) + PKU

CERN Fellow, UCSB Ph.D, PKU Under.

new standards



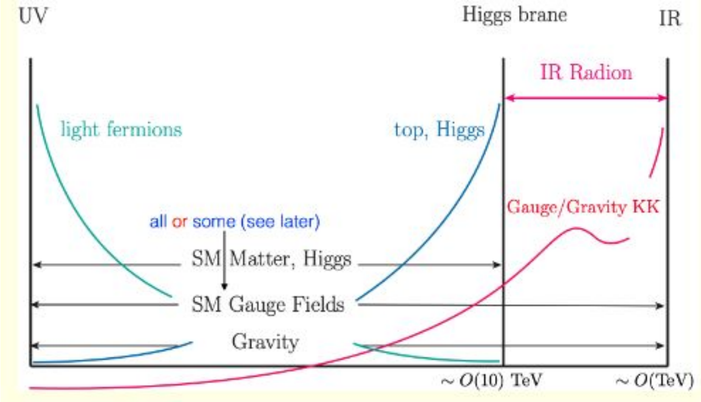
Output

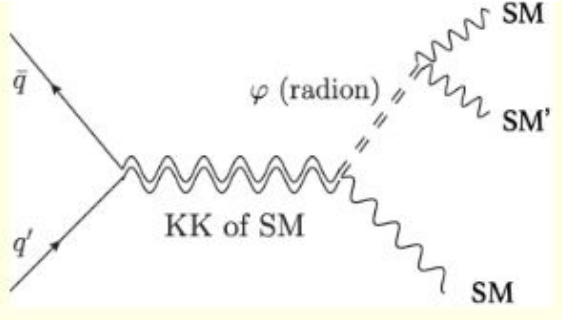
Category	Label
Higgs	H (bb)
	H (cc)
	H (VV*→qqqq)
Top	top (bcq)
	top (bqq)
	top (bc)
	top (bq)
W	W (cq)
	W (qq)
Z	Z (bb)
	Z (cc)
	Z (qq)
QCD	QCD (bb)
	QCD (cc)
	QCD (b)
	QCD (c)
	QCD (others)

3-3. 2+1=3 is not easy

Extended Warped ED model (link1, link2):

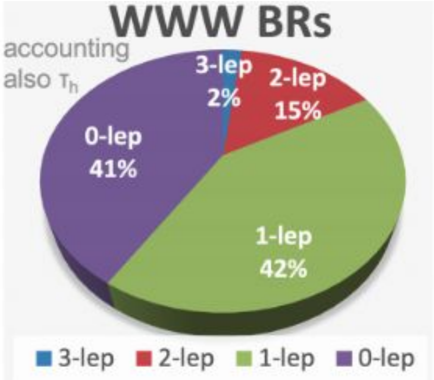
- 3 (or more) branes, 2 (or more) Radions
- Various fields propagate in diff. Regions





Only QCD in extended bulk → dominant: $g_{KK} \to R\, g \to ggg$

Only EW in extended bulk → dominant: $V_{KK} \to R\, V \to VVV$



Moriond EW Wednesday: Moriond EWK - Wednesday: afternoon session

16:00 **Approval of B2G-20-001: Search for resonances decaying into WVV in the single lepton final state**

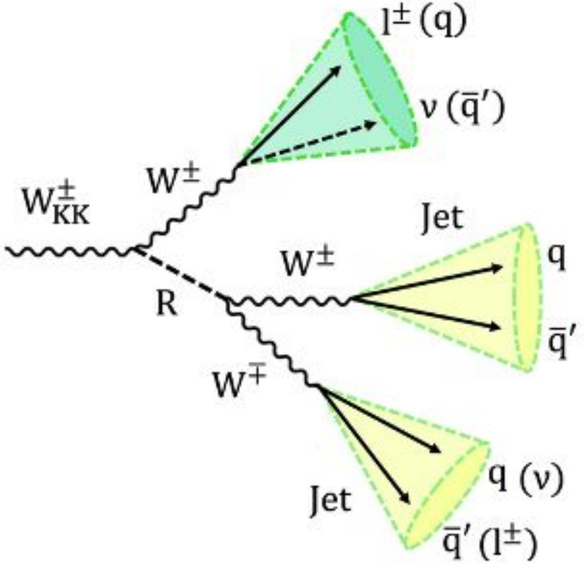
Speakers: Antonis Agapitos (Peking University (CN)) , Qiang Li (Peking University (CN)) , Xudong Lyu (Peking University (CN))

CMS PAS B2G-20-001

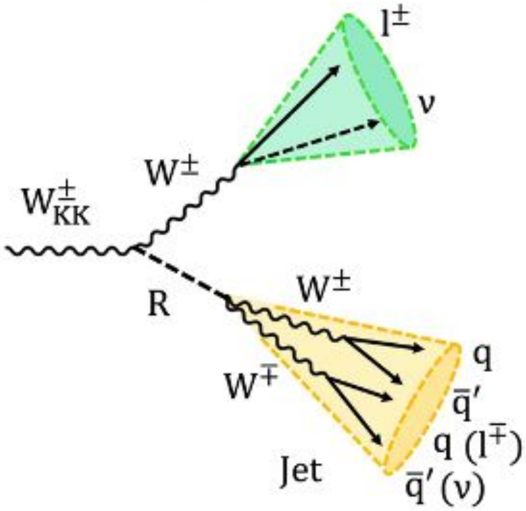
MORIOND @ HOME 2021
21-27 MARCH - 27 MARCH-3 APRIL

3-4. tri-W in 1 lepton channel

B2G-20-001/B2G-21-002 **submitted to PRL/PRD**



Resolved Radion



Merged Radion

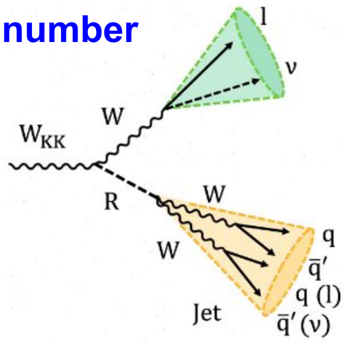
Only through all those challenging improvements it is possible to have three W bosons to study. It is just like what the ancient **Chinese poet *Qu Yuan* 屈原 *(c. 340–278 BC)*** mentioned in his poem *The nine songs: Mountain Spirit*: *"I picked three-bloom asphodel out in the hills, on slopes rough and rocky, through tangles of vines"*.

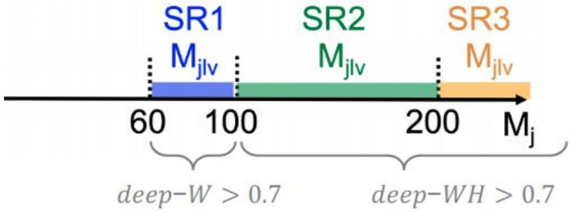
https://cms.cern/news/one-two-three-w-bosons-bloom-spring

3-5. tri-W in 1 lepton channel

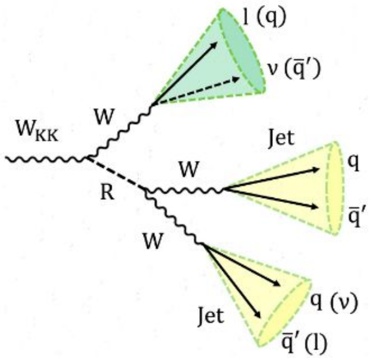
AK8 Jet number

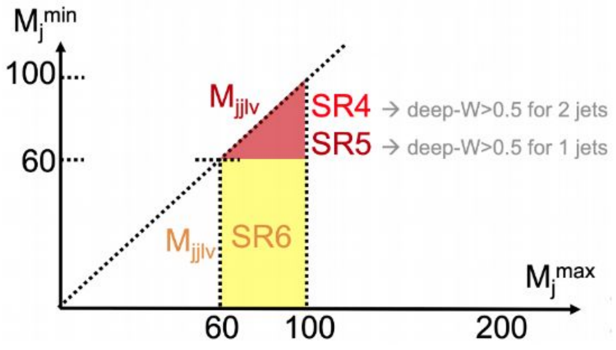
N_j=1





N_j=2





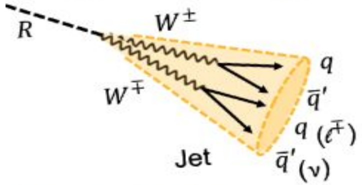
W tagging with "binary" scores

$$\text{deep−W} = \frac{W_{qq,qc}}{QCD_{g,q,b,..} + W_{qq,qc}}$$

Radion tagging with hybrid:

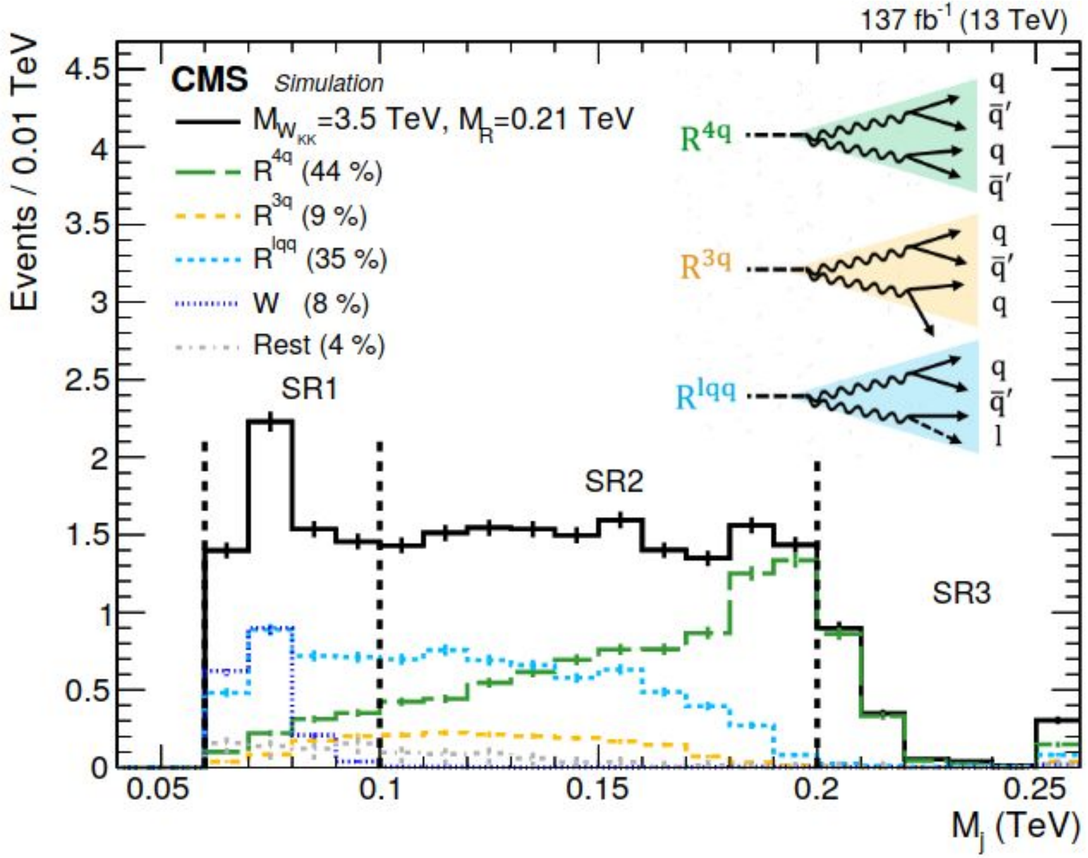
$$\text{deep−WH} = \frac{W_{qq,qc} + H_{4q}}{QCD_{g,q,b,..} + W_{qq,qc} + H_{4q}}$$

$R \approx R^{4q} + R^{3q} + R^{lqq}$



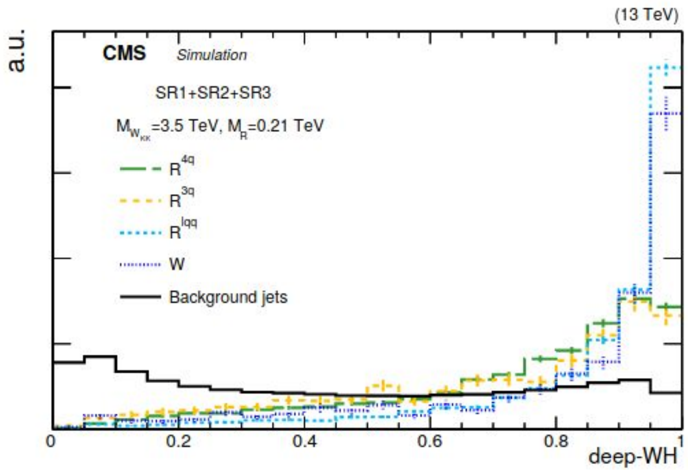
We do NOT have standard candle in SM to calibrate all these

3-6. tri-W in 1 lepton channel



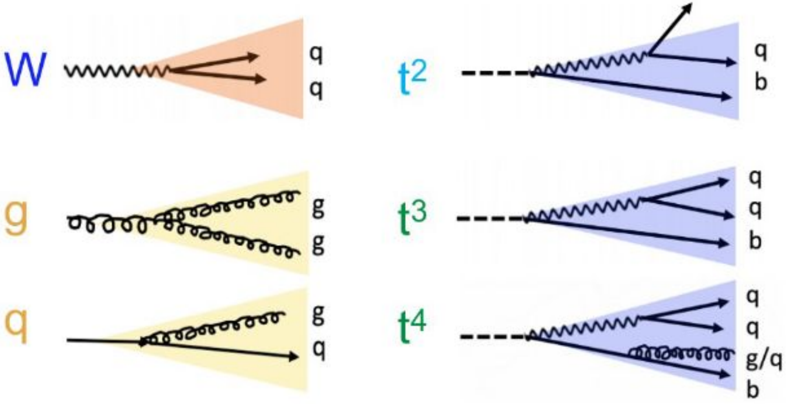
Signal Regions 1-3 for merged Radion scenario

Very complicated and wide Radio-jet compositions and distributions!



"Radion jets"! Beyond the usual top/W/Z/Higgs tagging.

3-7. tri-W in 1 lepton channel



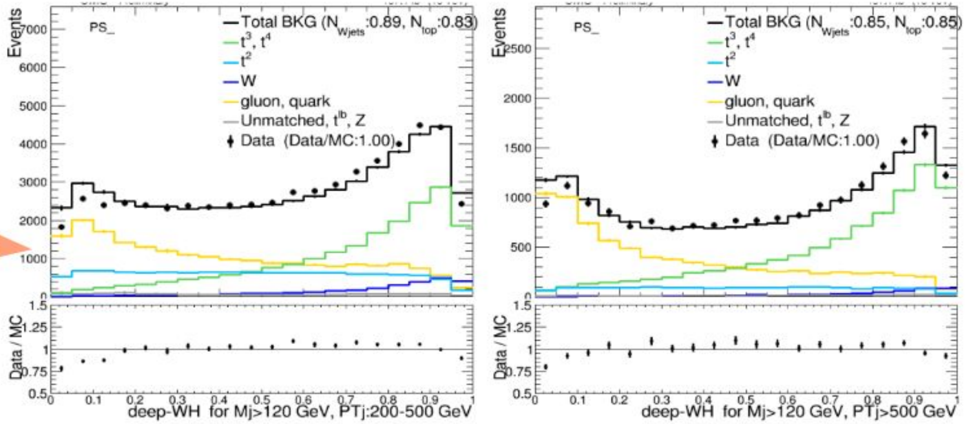
Used as a proxy for 4q Radion jet (with ***large*** systematics)

deep−WH @ Mj > 120

PTj: 200-500

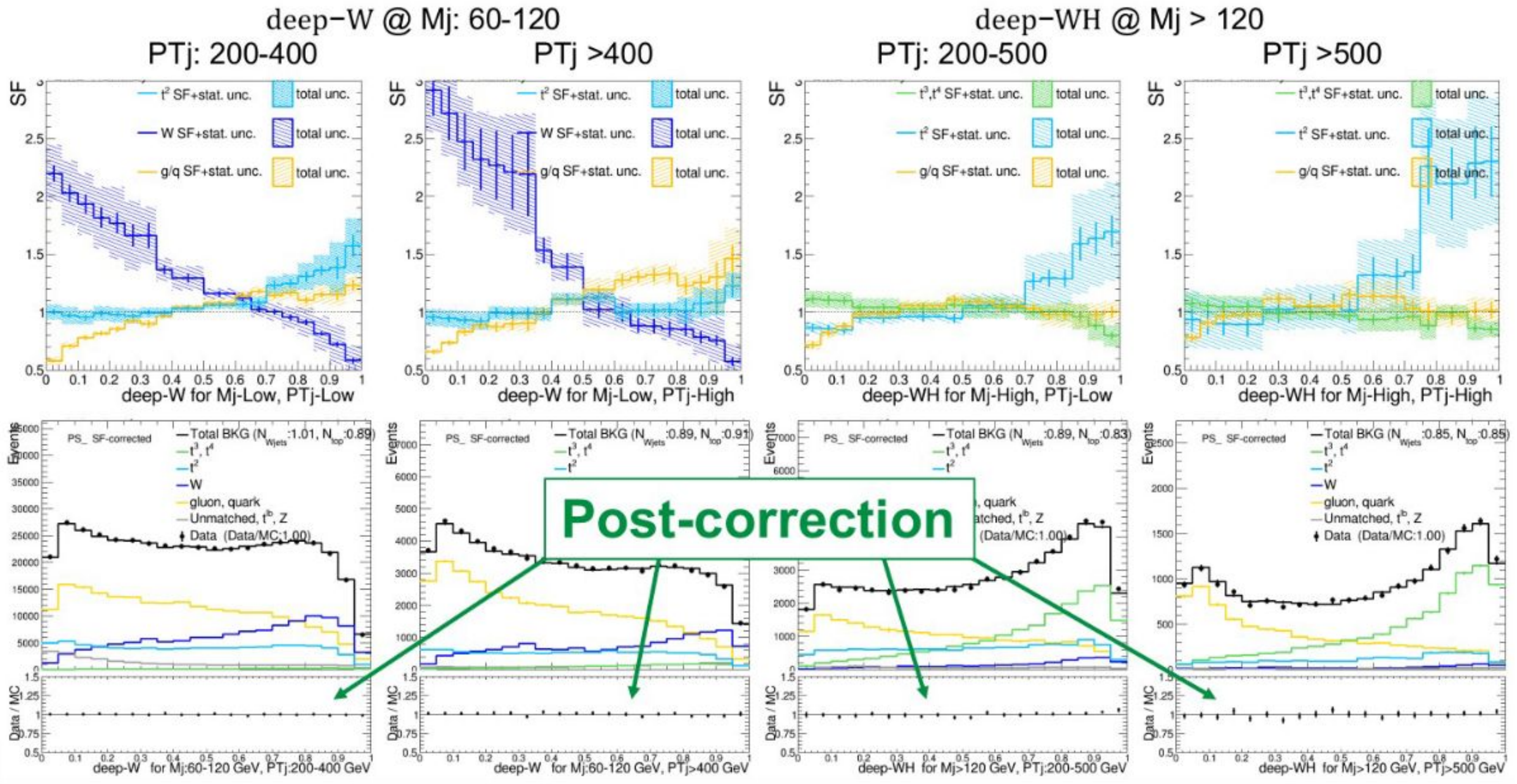
PTj >500

- Correct MC shapes, bin by bin

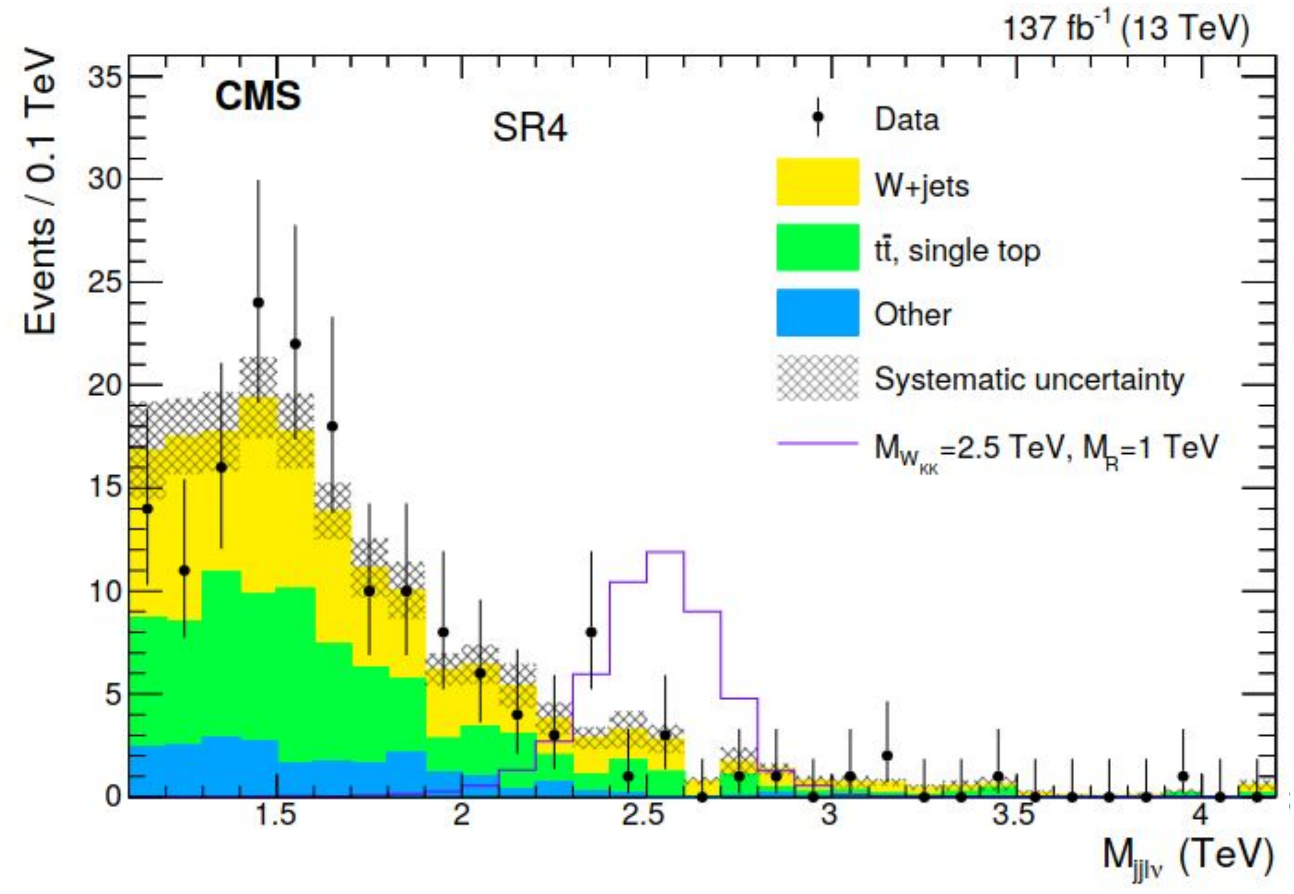


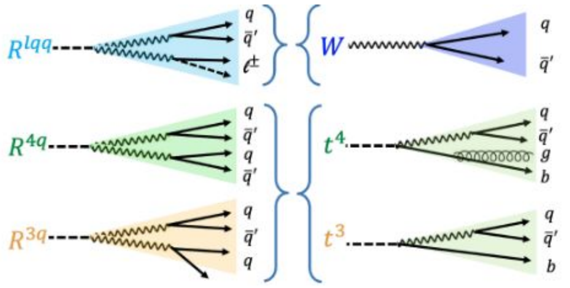
3-8. tri-W in 1 lepton channel

All SFs derived for all 4 bins (2 Mj , 2 pTj bins) and for all types of jets W, t^2, $t^{3,4}$, g/q



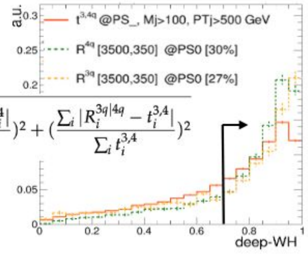
3-9. tri-W in 1 lepton channel



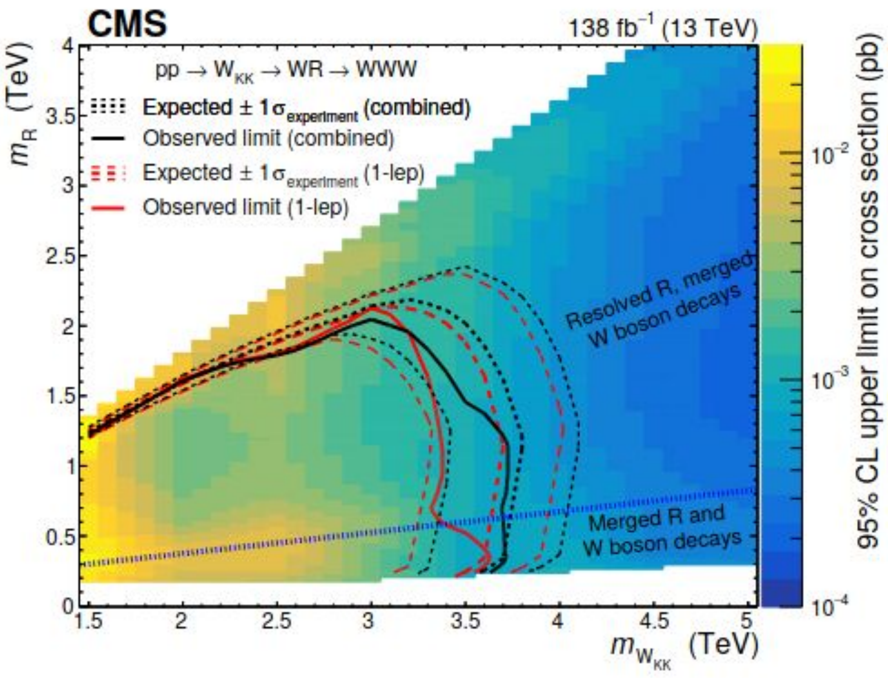


Proxy-unc. Accounts for differences between $R^{4q/3q}$(R^{lqq}) and SM proxy: $t^{3,4}$(W). Compare normalized deep-W(WH) spectra to **evaluate % diff. above the cut** with metric:

$$\text{Proxy unc.}=\sqrt{\left(\frac{\sum_i |t_i^3 - t_i^4|}{\sum_i t_i^4}\right)^2 + \left(\frac{\sum_i |R_i^{3q|4q} - t_i^{3,4}|}{\sum_i t_i^{3,4}}\right)^2}$$

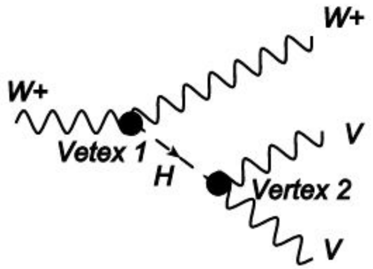


3-10. tri-W resonance search results



B2G-20-001 arXiv:2201.08476
submitted to PRL [1lep+0lep Channels]
B2G-21-002 arXiv:2112.13090
Submitted to PRD [Full Hadronic Channel]

Inspired also by Prof. Kuang's idea!



[13] Y.-P. Kuang, H.-Y. Ren, and L.-H. Xia, "Further investigation of the model-independent probe of heavy neutral Higgs bosons at LHC Run 2", *Chin. Phys. C* **40** (2016) 023101, doi:10.1088/1674-1137/40/2/023101, arXiv:1506.08007.

[14] H.-Y. Ren, L.-H. Xia, and Y.-P. Kuang, "Model-independent probe of anomalous heavy neutral Higgs bosons at the LHC", *Phys. Rev. D* **90** (2014) 115002, doi:10.1103/PhysRevD.90.115002, arXiv:1404.6367.

邝宇平 <ypkuang@mail.tsinghua.edu.cn>
to Xin, 陈国明, me

28 Jan 2016

陈新、国明、李强：

我们在CPC的文章终于在线刊登出来了，见附件。

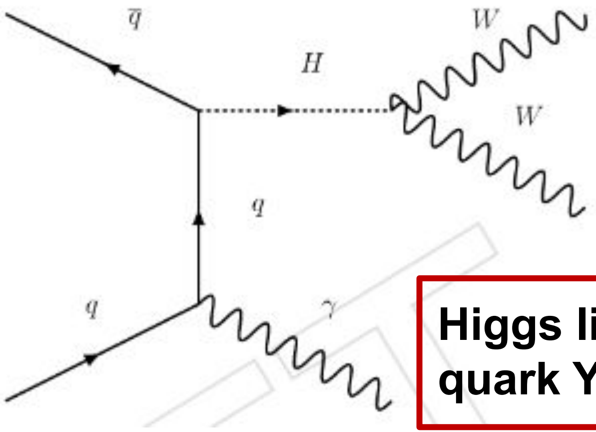
邝宇平

Summary

(W) Boson scattering and Interaction

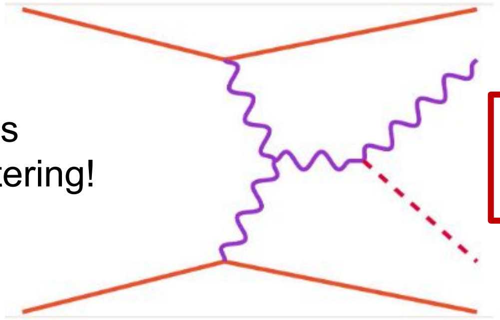
- Yang-Mills Non-Abelian interactions
  Anomalous couplings, EFT
- Electroweak symmetry breaking
  Higgs Unitarization Scheme
- Tev scale new Physics
  Boosted Boson
- Future: Run3, novel ideas
  (Electron) Muon Collider

WINE AND MORE

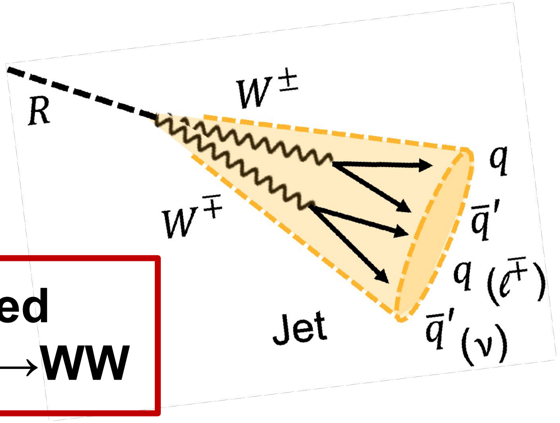


Higgs light quark Yukawa

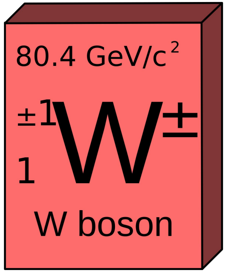
Higgs scattering!



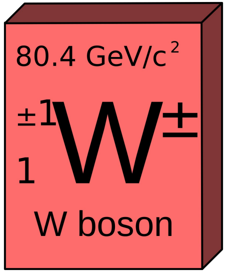
$$\lambda_{WZ} = \frac{\kappa_W}{\kappa_Z}$$



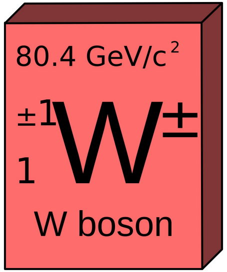
Boosted Higgs→WW



here do we come from?



hat are we?



here are we going?

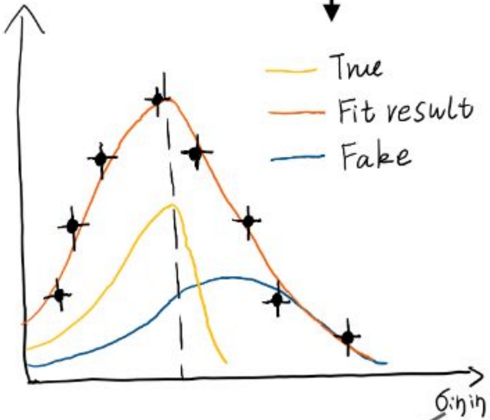

P
+
BACKUP

A5. VBS Zγ with 2016-2018 dataset

From Data

$$n_{fake}^{weighted} = n_{tot} \times \epsilon = N_{fake}^{unweighted} \times weights$$

Fake photon enriched sample by inverting one of cut in the photon WP with data



A shower shape variable

True photon is from QCD Zγ with medium photon WP and matched to generator-level

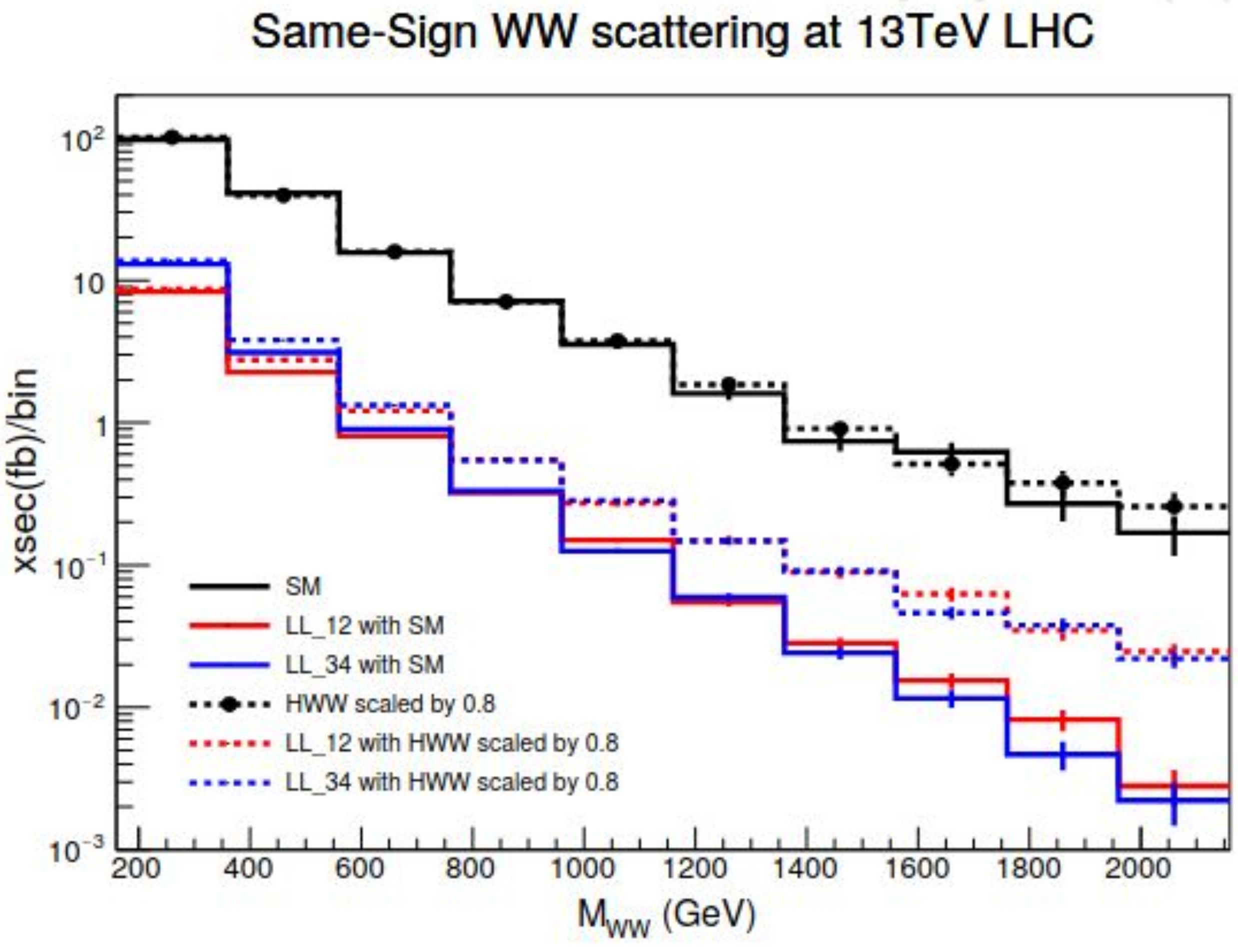
Fake photon is from data by inverting charged isolation with an appropriate sideband.

Closure test was done to select a best charged isolation sideband

Data is from data with medium photon WP

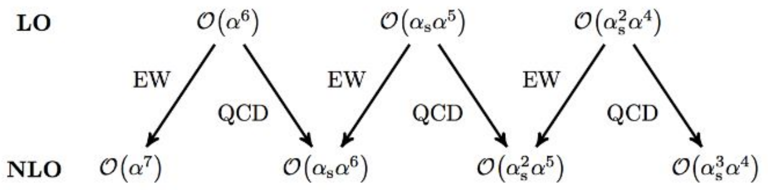
$$\textbf{weight}(p_T^\gamma) = \frac{n_{data}(p_T^\gamma)}{N_{fake}^{unweighted}(p_T^\gamma)} \times \textbf{FakeFraction}(p_T^\gamma)$$

7


Same-Sign WW scattering at 13TeV LHC
xsec(fb)/bin
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
200
400
600
800
1000
1200
1400
1600
1800
2000
M_{WW} (GeV)
SM
LL_12 with SM
LL_34 with SM
HWW scaled by 0.8
LL_12 with HWW scaled by 0.8
LL_34 with HWW scaled by 0.8

Higher order corrections

- Full NLO computation have been done for same-sign unpolarized WW process



1708.00268

B. Biedermann
A. Denner
M. Pellen

All contributing orders at both LO and NLO

Order	$\mathcal{O}(\alpha^7)$	$\mathcal{O}(\alpha_s\alpha^6)$	$\mathcal{O}(\alpha_s^2\alpha^5)$	$\mathcal{O}(\alpha_s^3\alpha^4)$	Sum
$\delta\sigma_{NLO}$ [fb]	−0.2169(3)	−0.0568(5)	−0.00032(13)	−0.0063(4)	−0.2804(7)
$\delta\sigma_{NLO}/\sigma_{LO}$ [%]	−13.2	−3.5	0.0	−0.4	−17.1

Jie Xiao
VBSCAN 2020

- NLO EW and QCD [$\mathcal{O}(\alpha^7)$, $\mathcal{O}(\alpha_s\alpha^6)$] corrections are considered
- EW corrections are large and negative (~-15%) in the fiducial region and increasing with dijet and dilepton masses
- NLO corrections for the polarized samples are not known (α_s corrections expected to be the same for the 3 modes. α corrections expected to be small for the longitudinal modes).
  - Apply α_s corrections on LL, LT, and TT
  - Apply α corrections for TT
  - Take the size of α corrections as uncertainty for LL and LT

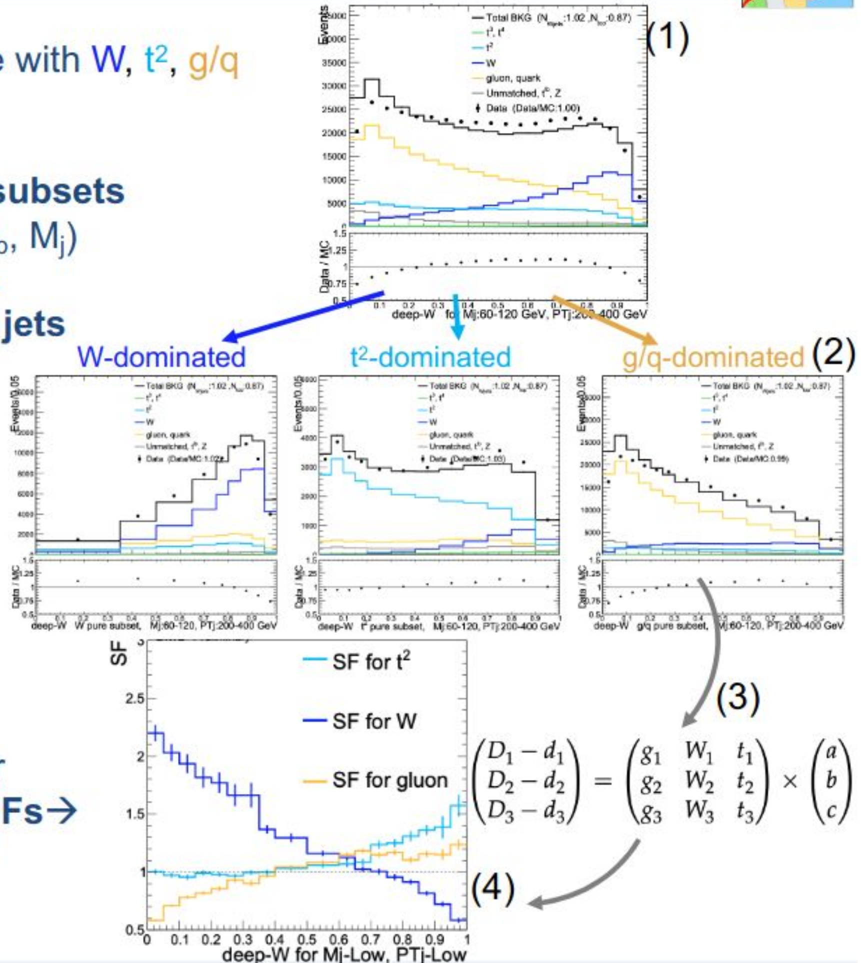
deep-taggers Calibration with Matrix Method

1. Focus at low-Mj, low-PTj sample with W, t^2, g/q (first column of last slide)

2. **Split the samples into 3 pure subsets** (applying cuts on τ_{ij}, deep-x/y, N_b, M_j) **in a way where each subset is dominated by a single type of jets** → mismodeling revealed:

3. Demand:
   Data = scaled sum of yields
   $D_1 = ag_1 + bW_1 + ct_1 + d_1$
   Define system of 3 equations, 1 per each subset, and per tagger score bin

4. **Solve a 3x3 system** for SFs per each tagger score bin and **get SFs→**
   - **Known** yields: D, W, t, g/q, d
   - **Unknown** SFs: a, b, c



$$\begin{pmatrix} D_1 - d_1 \\ D_2 - d_2 \\ D_3 - d_3 \end{pmatrix} = \begin{pmatrix} g_1 & W_1 & t_1 \\ g_2 & W_2 & t_2 \\ g_3 & W_3 & t_3 \end{pmatrix} \times \begin{pmatrix} a \\ b \\ c \end{pmatrix}$$

4-1. electron-muon Collider

Electron-muon collider is a VBS machine with low bkg!

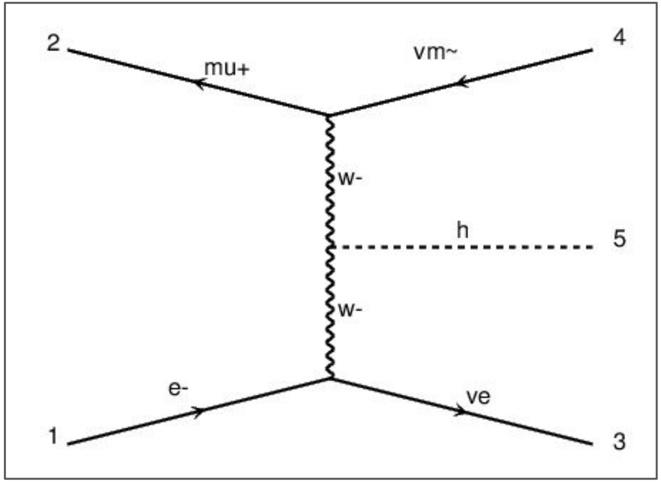
Would be interesting to check this option, considering muon anomalies (LHCb LFUV, muon g-2...)

The Physics Case for an Electron-Muon Collider

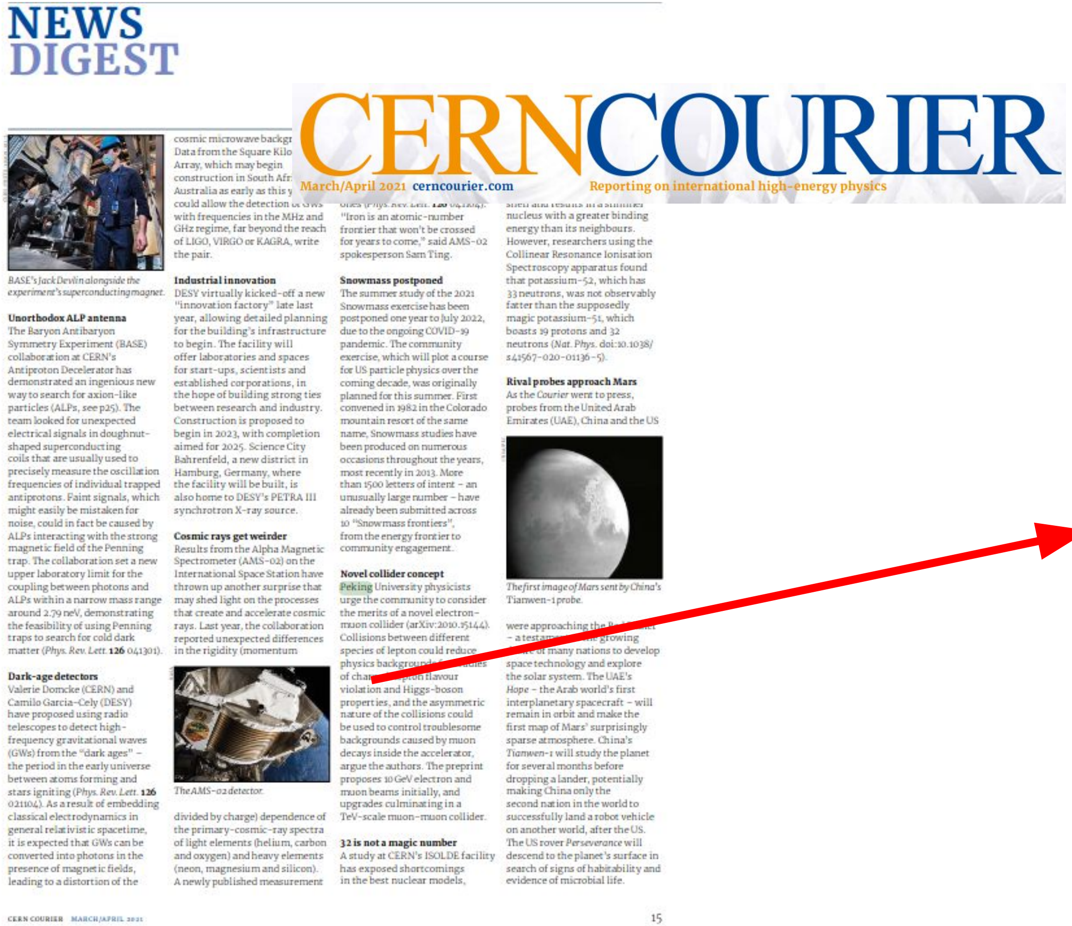
Meng Lu,[1] Andrew Michael Levin,[1] Congqiao Li,[1] Antonios Agapitos,[1] **Qiang Li**,[1] Fanqiang Meng,[1] Sitian Qian,[1] Jie Xiao,[1] and Tianyi Yang[1]
Show more

Academic Editor: Mariana Frank

Received	Accepted	Published
10 Dec 2020	08 Feb 2021	26 Feb 2021



4-2. electron-muon Collider



NEWS DIGEST

March/April 2021 cerncourier.com Reporting on international high-energy physics

BASE's Jack Devlin alongside the experiment's superconducting magnet.

Unorthodox ALP antenna
The Baryon Antibaryon Symmetry Experiment (BASE) collaboration at CERN's Antiproton Decelerator has demonstrated an ingenious new way to search for axion-like particles (ALPs, see p25). The team looked for unexpected electrical signals in doughnut-shaped superconducting coils that are usually used to precisely measure the oscillation frequencies of individual trapped antiprotons. Faint signals, which might easily be mistaken for noise, could in fact be caused by ALPs interacting with the strong magnetic field of the Penning trap. The collaboration set a new upper laboratory limit for the coupling between photons and ALPs within a narrow mass range around 2.79 neV, demonstrating the feasibility of using Penning traps to search for cold dark matter (*Phys. Rev. Lett.* **126** 041301).

Dark-age detectors
Valerie Domcke (CERN) and Camilo Garcia-Cely (DESY) have proposed using radio telescopes to detect high-frequency gravitational waves (GWs) from the "dark ages" – the period in the early universe between atoms forming and stars igniting (*Phys. Rev. Lett.* **126** 021104). As a result of embedding classical electrodynamics in general relativistic spacetime, it is expected that GWs can be converted into photons in the presence of magnetic fields, leading to a distortion of the cosmic microwave backgr... Data from the Square Kilo... Array, which may begin construction in South Afr... Australia as early as this y... could allow the detection of GWs with frequencies in the MHz and GHz regime, far beyond the reach of LIGO, VIRGO or KAGRA, write the pair.

Industrial innovation
DESY virtually kicked-off a new "innovation factory" late last year, allowing detailed planning for the building's infrastructure to begin. The facility will offer laboratories and spaces for start-ups, scientists and established corporations, in the hope of building strong ties between research and industry. Construction is proposed to begin in 2023, with completion aimed for 2025. Science City Bahrenfeld, a new district in Hamburg, Germany, where the facility will be built, is also home to DESY's PETRA III synchrotron X-ray source.

Cosmic rays get weirder
Results from the Alpha Magnetic Spectrometer (AMS-02) on the International Space Station have thrown up another surprise that may shed light on the processes that create and accelerate cosmic rays. Last year, the collaboration reported unexpected differences in the rigidity (momentum

The AMS-02 detector.

divided by charge) dependence of the primary-cosmic-ray spectra of light elements (helium, carbon and oxygen) and heavy elements (neon, magnesium and silicon). A newly published measurement

... ones (*Phys. Rev. Lett.* **126** 041104). "Iron is an atomic-number frontier that won't be crossed for years to come," said AMS-02 spokesperson Sam Ting.

Snowmass postponed
The summer study of the 2021 Snowmass exercise has been postponed one year to July 2022, due to the ongoing COVID-19 pandemic. The community exercise, which will plot a course for US particle physics over the coming decade, was originally planned for this summer. First convened in 1982 in the Colorado mountain resort of the same name, Snowmass studies have been produced on numerous occasions throughout the years, most recently in 2013. More than 1500 letters of intent – an unusually large number – have already been submitted across 10 "Snowmass frontiers", from the energy frontier to community engagement.

Novel collider concept
Peking University physicists urge the community to consider the merits of a novel electron–muon collider (arXiv:2010.15144). Collisions between different species of lepton could reduce physics backgrounds for studies of charged-lepton flavour violation and Higgs-boson properties, and the asymmetric nature of the collisions could be used to control troublesome backgrounds caused by muon decays inside the accelerator, argue the authors. The preprint proposes 10 GeV electron and muon beams initially, and upgrades culminating in a TeV-scale muon–muon collider.

32 is not a magic number
A study at CERN's ISOLDE facility has exposed shortcomings in the best nuclear models, ...

... shell and results in a similar nucleus with a greater binding energy than its neighbours. However, researchers using the Collinear Resonance Ionisation Spectroscopy apparatus found that potassium-52, which has 33 neutrons, was not observably fatter than the supposedly magic potassium-51, which boasts 19 protons and 32 neutrons (*Nat. Phys.* doi:10.1038/s41567-020-01136-5).

Rival probes approach Mars
As the *Courier* went to press, probes from the United Arab Emirates (UAE), China and the US

The first image of Mars sent by China's Tianwen-1 probe.

were approaching the Red Planet – a testament to the growing ... of many nations to develop space technology and explore the solar system. The UAE's *Hope* – the Arab world's first interplanetary spacecraft – will remain in orbit and make the first map of Mars' surprisingly sparse atmosphere. China's *Tianwen-1* will study the planet for several months before dropping a lander, potentially making China only the second nation in the world to successfully land a robot vehicle on another world, after the US. The US rover *Perseverance* will descend to the planet's surface in search of signs of habitability and evidence of microbial life.

CERN COURIER MARCH/APRIL 2021 15

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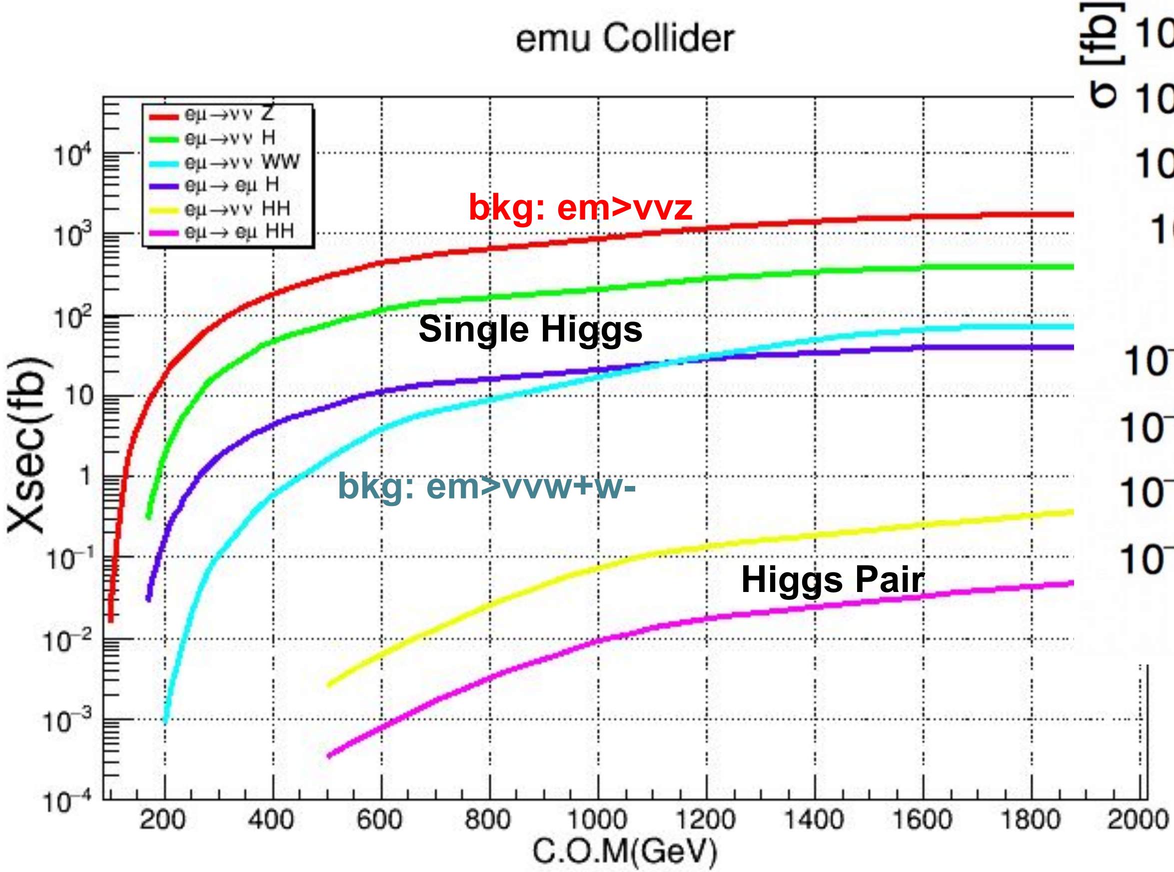
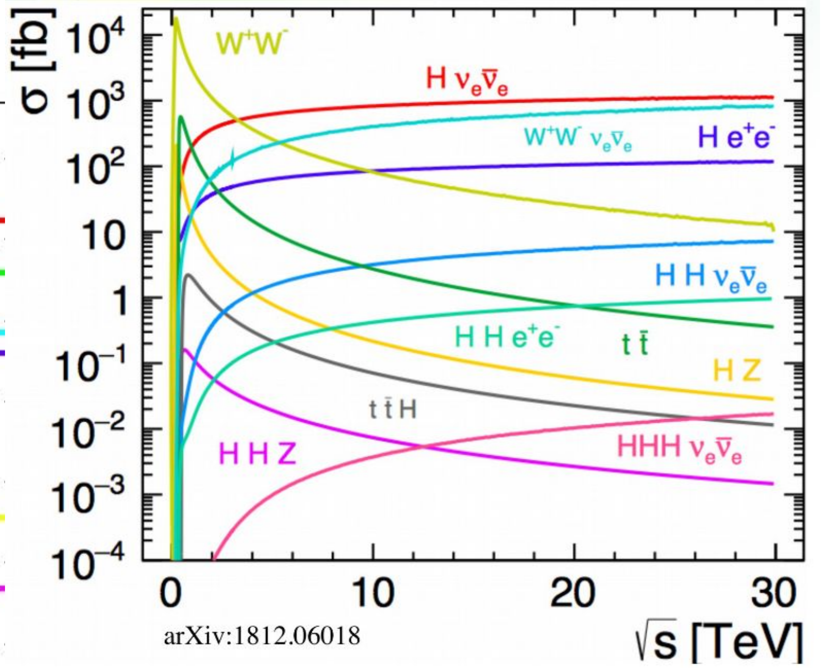
4-3. Xsec plot @ emu and mumu collider

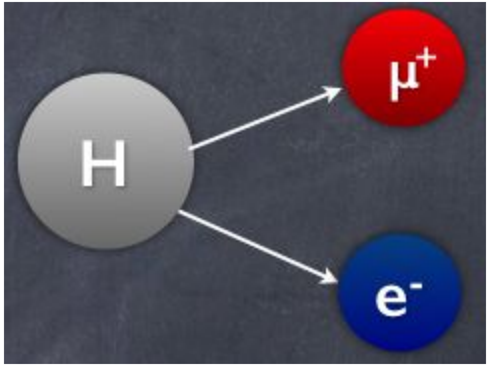


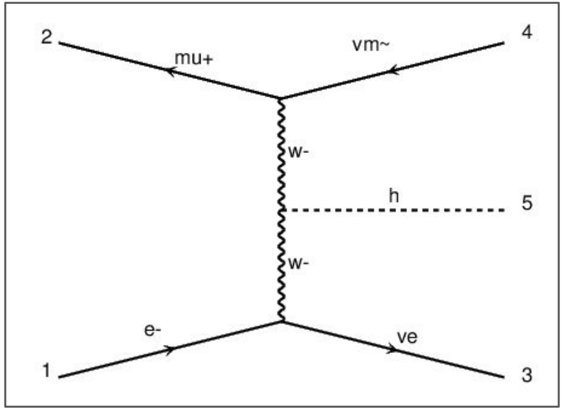


mu-mu collider

A vector boson scattering/fusion machine

4-4. physics@electron-muon collider





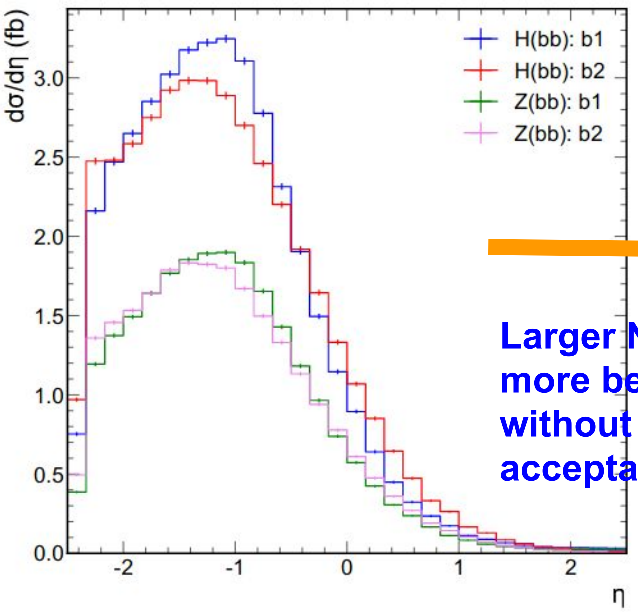
- A novel kind of collider from 0 -> 1
  - low to high collision energy
  - linear/circular/hybrid
  - various beam combinations:
    $e^-\mu^+$, $e^+\mu^-$, $e^+\mu^+$, $e^-\mu^-$, polarization
- An important intermediate step
  - between e-e and mu-mu
  - Robust under muon beam induced background
- Rich physics with economical budget
  - Charged Lepton Flavor violation
  - Higgs precision measurement
  - Muon anomaly, majorana neutrino, heavy lepton
  - ~ 1-2 billion $ in total

Flexibility to extend to various options!

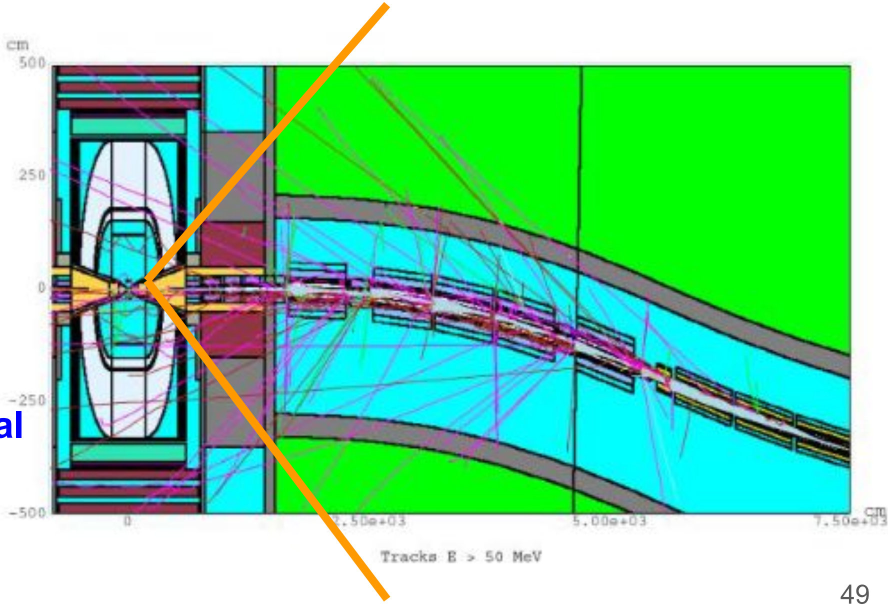
4-5. Asymmetric collision arXiv:2010.15144

- Take 50-1000/100-3000 GeV benchmark as examples
- Higgs produced through VBS, ~60fb
- Main background is VBS Z production
- Using MG+Pythia+Delphes (Muon Collider Card)

require the leading and sub-leading b-tagged jets with $p_T > 40$ GeV and $-2.5 < \eta < 1$ (corresponding to a 40.4° shielding nozzle in muon beam side, compared with a commonly taken value at muon collider studies as around 10–20° [11]). Fig. 4 shows the invariant mass distribution

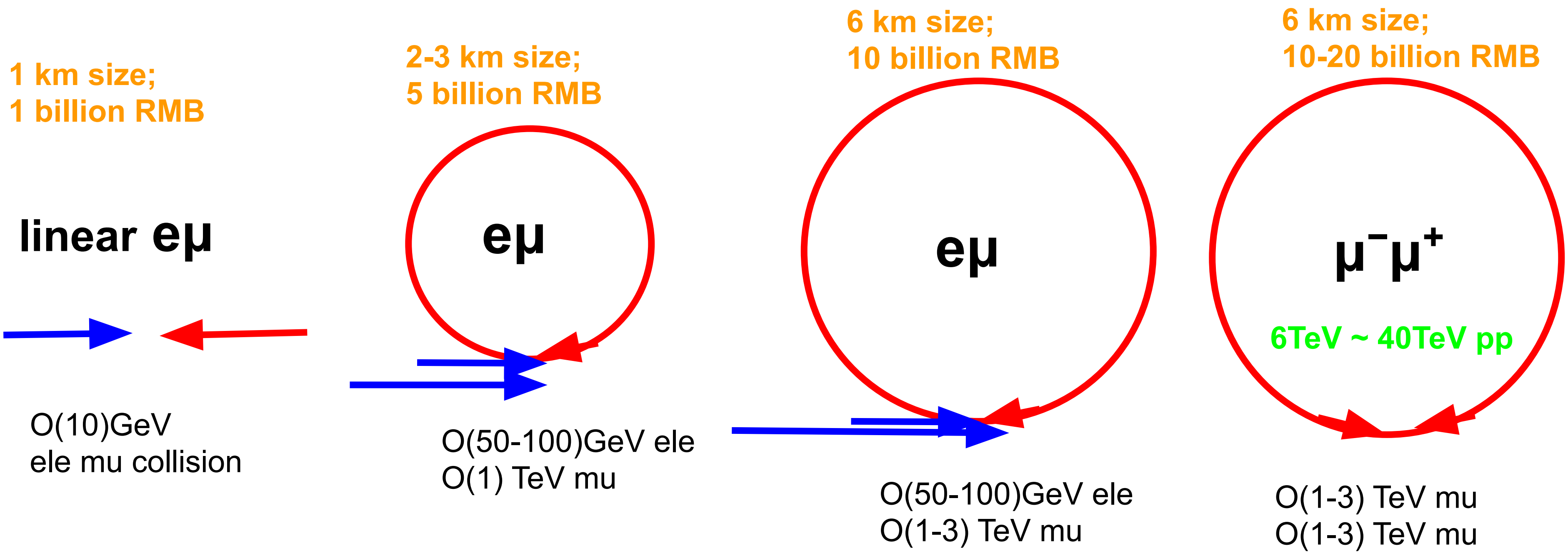


Larger Nozzle to suppress more beam background, without much loss on signal acceptance.



4-6. Lepton complex: eμ || same-charge || $\mu^-\mu^+$ || mu-source

New World/Virgin land

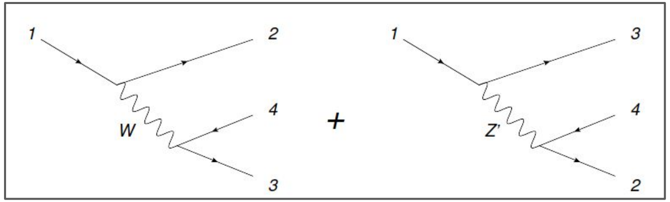


LFV, Higgs, majorana neutrino ....

~10-20 billion RMB in total to reach physics hopefully ~ CEPC + half-SPPC

Lepton Flavor Violation arXiv:2003.03997

- **Many specific and well motivated BSM models including LFV can be found in literature.**
- A simple model where LFV transitions are mediated by a generic heavy neutral boson (Z')
  - Z' as a gauge singlet, SU(2)L invariance
  - No assumption on the couplings of the Z' with quarks



$$g_{ij}^{eL}\bar{e}_i Z' P_L e_j + g_{ij}^{eR}\bar{e}_i Z' P_R e_j + g_{ij}^{\nu L}\bar{\nu}_i Z' P_L \nu_j + g_{ij}^{\nu R}\bar{\nu}_i Z' P_R \nu_j$$

Low energy bounds on Z' couplings

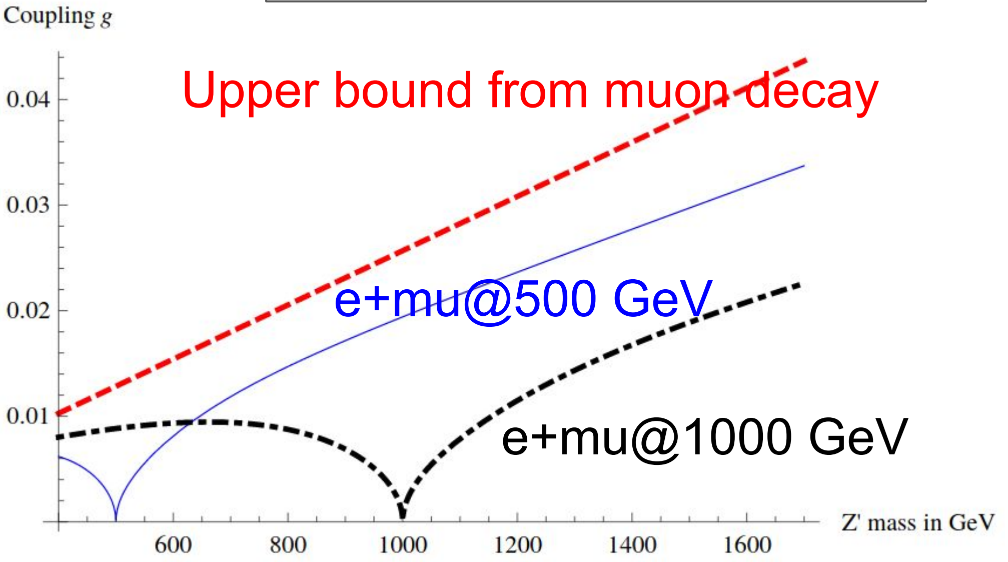
$$\frac{\Gamma_\mu}{m_\mu^5} = \frac{G_F^2}{192\pi^3} - \frac{4\sqrt{2}}{1536\pi^3}\frac{G_F(g_{\mu e}^L)^2}{M_{Z'}^2} + \frac{[(g_{\mu e}^L)^2 + (g_{\mu e}^R)^2][(g_{\mu e}^L)^2 + (g_{\nu_\mu \nu_e}^R)^2]}{1536\pi^3 M_{Z'}^4}$$

$$|BR(\mu^- \to e^-\bar{\nu}_e\nu_\mu) - BR(\mu^- \to e^-\bar{\nu}_e\nu_\mu)_{SM}| \leq 4\times 10^{-5}$$

$$\Gamma(\mu^- \to e^- e^+ e^-) = m_\mu^5 \frac{(g_{ee}g_{\mu e})^2}{384\pi^3 M_{Z'}^4}$$

$$\mathrm{Br}(\mu \to eee) < 1.0\cdot 10^{-12}, \quad 90\%\mathrm{CL}.$$

SINDRUM Collaboration



e+ mu- > e- mu+ double LFV

Higgs property measurement arXiv:2010.15144

$$\sigma = \sigma(\nu\nu\mathrm{H}) \cdot BR(\mathrm{H} \to \mathrm{b\bar{b}}) = \frac{g^2_{\mathrm{HWW}} g^2_{\mathrm{Hbb}}}{\Gamma_\mathrm{H}}$$

$$\frac{\Delta g_{\mathrm{Hbb}}}{g_{\mathrm{Hbb}}} = \frac{1}{2}\sqrt{\left(\frac{\Delta\sigma}{\sigma}\right)^2 + \left(\frac{\Delta \frac{g^2_{\mathrm{HWW}}}{\Gamma_\mathrm{H}}}{\frac{g^2_{\mathrm{HWW}}}{\Gamma_\mathrm{H}}}\right)^2}.$$

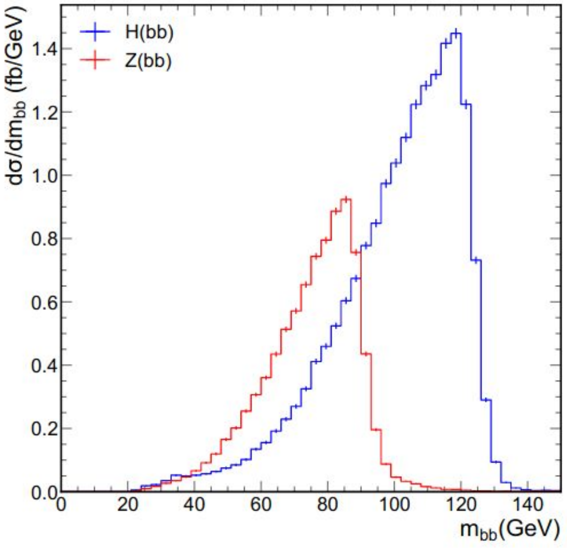


TABLE I: Summary of the parameters used in the estimation of the Higgs boson coupling to b-quarks in different collision schemes. The uncertainty on $g^2_{\mathrm{HWW}}/\Gamma_\mathrm{H}$ is set to 3% in all collision schemes. $\sqrt{s} = 447.2(1095.3)$ GeV corresponds to a 50(100) GeV electron beam and a 1(3) TeV muon beam. The ISR effect is not included as its effect is validated to be small.

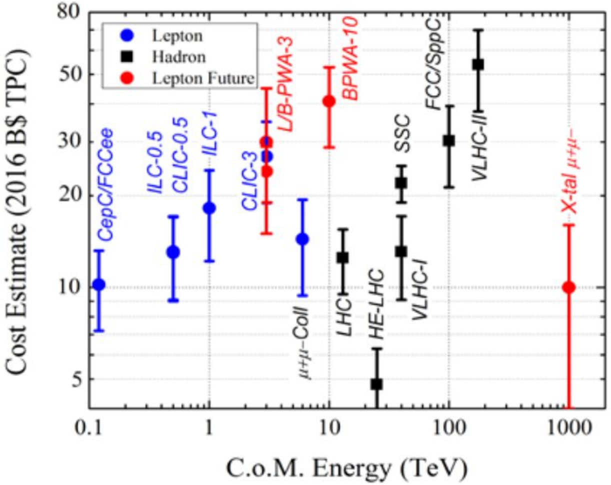
$\mathcal{L}_{\mathrm{int}}[ab^{-1}]$	$\sqrt{s}$[GeV]	$\frac{\Delta\sigma}{\sigma}$[%]	$\frac{\Delta \frac{g^2_{\mathrm{HWW}}}{\Gamma_\mathrm{H}}}{\frac{g^2_{\mathrm{HWW}}}{\Gamma_\mathrm{H}}}$[%]	$\frac{\Delta g_{\mathrm{Hbb}}}{g_{\mathrm{Hbb}}}$[%]
0.5	447.2	2.5	3	2.0
	1095.4	1.4		1.7
1.5	447.2	1.4	3	1.7
	1095.4	0.8		1.6
2.0	447.2	1.2	3	1.6
	1095.4	0.7		1.6

The measured precision of gHbb in the electron-muon collider can reach to a few percent level with order ab−1 of data and is dominated by the uncertainty on gHWW.

Facility and cost estimation

<u>**Total Project Cost (TPC) model**</u> in US accounting (EU accounting might be 2-3 times lower):
"civil construction", "accelerator components", "site power infrastructure"

$$TPC \approx \alpha \times (Length/10km)^{1/2} + \beta \times (Energy/TeV)^{1/2} + \gamma \times (Power/100MW)^{1/2} \;, \quad (1)$$



CEPC:
2B$*(50km/10km)^0.5+2B$*(0.25)^0.5+2B$*(500MW/100MW)^0.5~10B$
or
2B$*(**100**km/10km)^0.5+2B$*(0.25)^0.5+2B$*(500MW/100MW)^0.5~12B$

3 times larger

The ambitious 30-billion-yuan (US$4.3-billion) facility, known as the Circular Electron–Positron Collider (CEPC), is the brainchild of IHEP's director, Wang Yifang. He has spearheaded the project since the discovery of the elementary particle called the Higgs boson at the LHC in 2012.

https://www.nature.com/articles/d41586-018-07492-w

Facility and cost estimation

Total Project Cost (TPC) model in US accounting (EU accounting might be 2-3 times lower):

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$$TPC \approx \alpha \times (Length/10km)^{1/2} + \beta \times (Energy/TeV)^{1/2} + \gamma \times (Power/100MW)^{1/2} \quad , \qquad (1)$$

1TeV Muon beam:

2B$*(4km/10km)^0.5+2B$*(2)^0.5+2B$*(100MW/100MW)^0.5~6B$

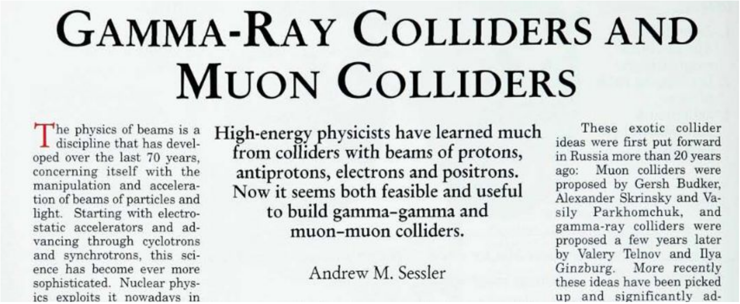
(3TeV Muon ~8B $)

If 3 times larger

2B$ in total

Note:

- **electron part cost is relatively small**
- **O(100)GeV e-mu collider cost much less**



GAMMA-RAY COLLIDERS AND MUON COLLIDERS

The physics of beams is a discipline that has developed over the last 70 years, concerning itself with the manipulation and acceleration of beams of particles and light. Starting with electrostatic accelerators and advancing through cyclotrons and synchrotrons, this science has become ever more sophisticated. Nuclear physics exploits it nowadays in

High-energy physicists have learned much from colliders with beams of protons, antiprotons, electrons and positrons. Now it seems both feasible and useful to build gamma-gamma and muon-muon colliders.

Andrew M. Sessler

These exotic collider ideas were first put forward in Russia more than 20 years ago: Muon colliders were proposed by Gersh Budker, Alexander Skrinsky and Vasily Parkhomchuk, and gamma-ray colliders were proposed a few years later by Valery Telnov and Ilya Ginzburg. More recently these ideas have been picked up and significantly ad-

Physics Today 51, 3, 48 (1998)

"But the result might well be a machine that is less expensive than an ee linear collider with the same final energy, though a TeV muon collider would still be a **billion-dollar** undertaking."