Physics Potential of the upgraded detectors at High Luminosity LHC

Mojtaba Mohammadi Najafabadi
School of Particles and Accelerators, IPM

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Outline

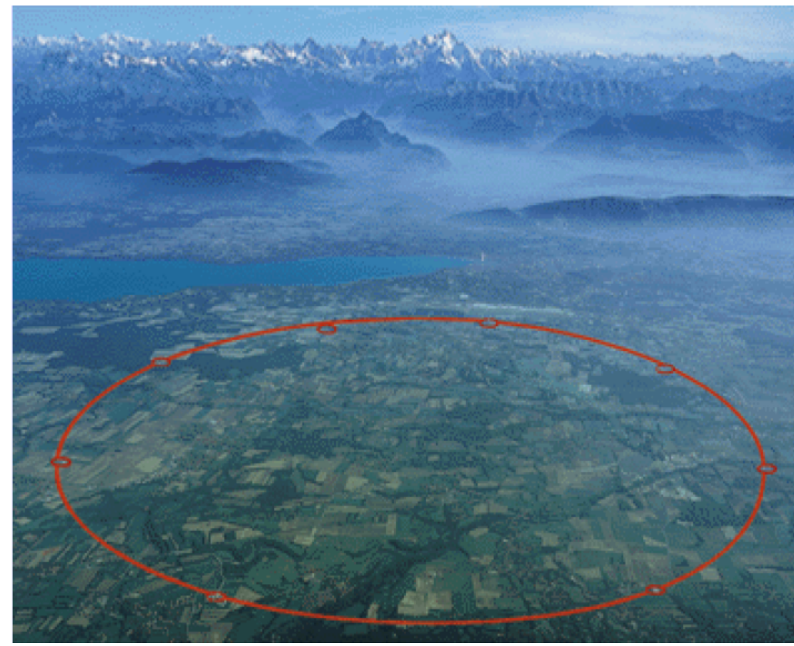
- **Introduction**
- **Detector upgrade**
- **Physics at HL-LHC**

  - Higgs boson physics
  - SM precision measurements
  - Beyond the SM physics

Introduction: LHC

- Proton-proton collider in the former LEP tunnel at CERN (Geneva)

- Highest ever energy per collision 7 TeV in the pp-system
- Conditions as 10^{-13} – 10^{-14} s after the Big Bang
- 4 experiments:
  ATLAS
  CMS
  LHC-B specialised on b-physics
  ALICE specialised for heavy ion collisons
- Constructed in a worldwide collaboration



Proton-Proton Collisions at the LHC

- 2835 + 2835 proton bunches
  separated by 7.5 m

→ collisions every 25 ns
  = 40 MHz crossing rate

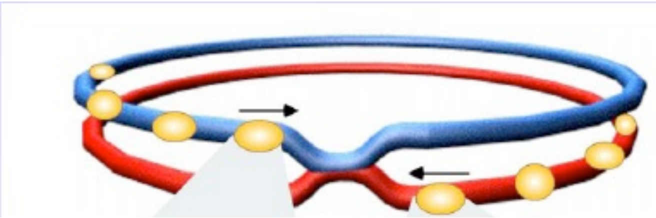
- 10^{11} protons per bunch

- at $(5\text{-}7)\times10^{34}/\text{cm}^2/\text{s}$
  ≈ **140-200 pp interactions per crossing**
  pile-up

→ ≈ **10^9** pp interactions per second !!!

- in each collision
  ≈ 1600 charged particles produced

enormous challenge for the detectors



To maximize the potential for **precise measurements** and **new discoveries** at the LHC, it should deliver as high as possible collision rates.
Therefore, **multiple proton-proton collisions** occur whenever two protons bunches cross.

In addition to high-energy (hard) collisions, there are contamination from several soft, zero-bias events (pile-up).

$$N_{events} = \sigma \times \underbrace{\int \mathcal{L}\, dt}_{\text{Integrated luminosity}} \times \varepsilon_A \times \varepsilon_D$$

Integrated luminosity

Luminosity $$\mathcal{L} = \frac{n_1 n_2}{A} \times \frac{1}{f}$$

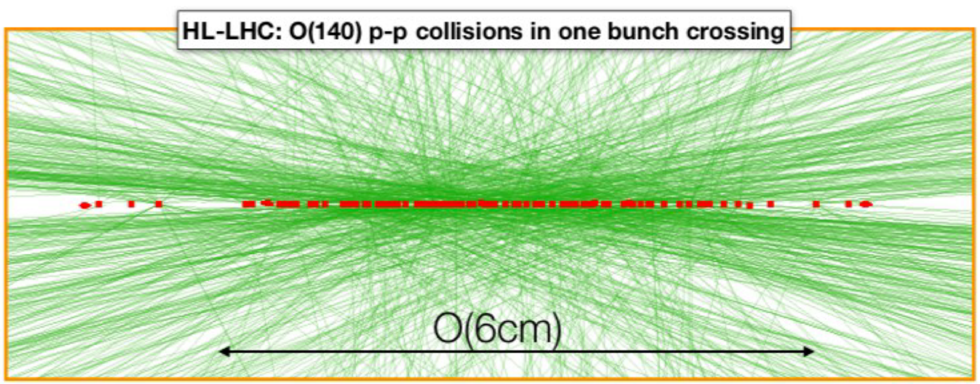
CMS detector in HL-LHC

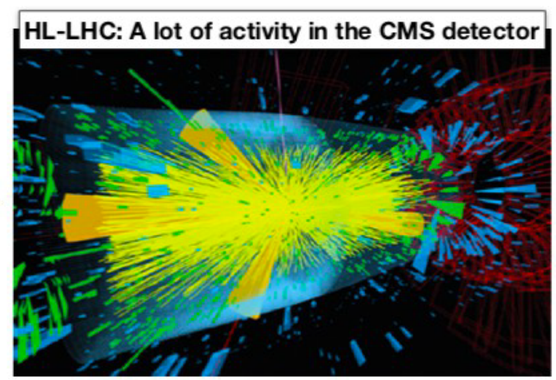
- The current CMS detector was designed for operation at **40-60 collisions** per bunch crossing and up to 500 fb^{-1}

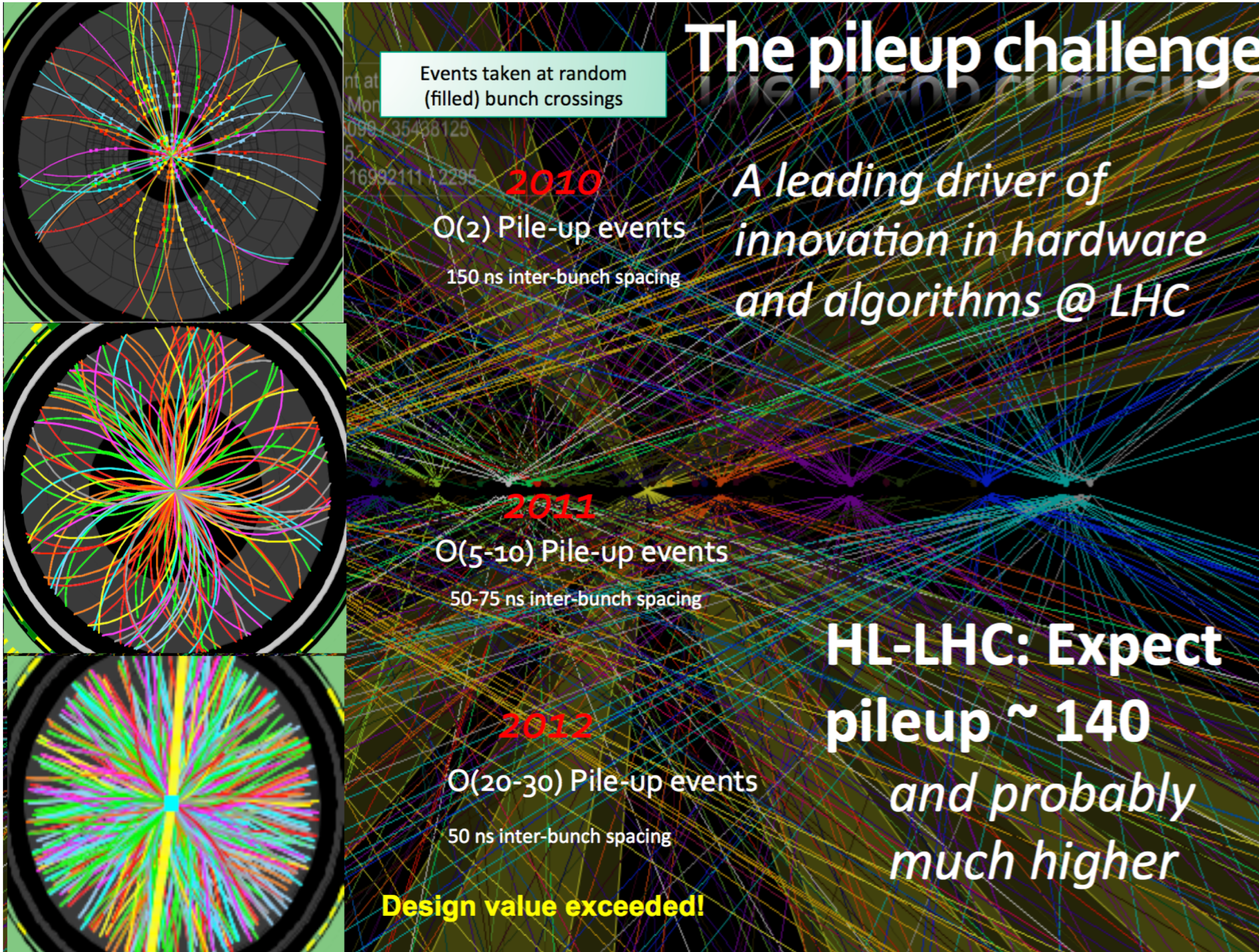
- Integrated luminosity ~ 3000 fb^{-1}@HL-LHC

– 140-200 collisions per bunch crossing
– 3-4 times larger than Run 2!
– Vertices concentrated within a few centimeters

Collisions every 25 ns → Pile-up





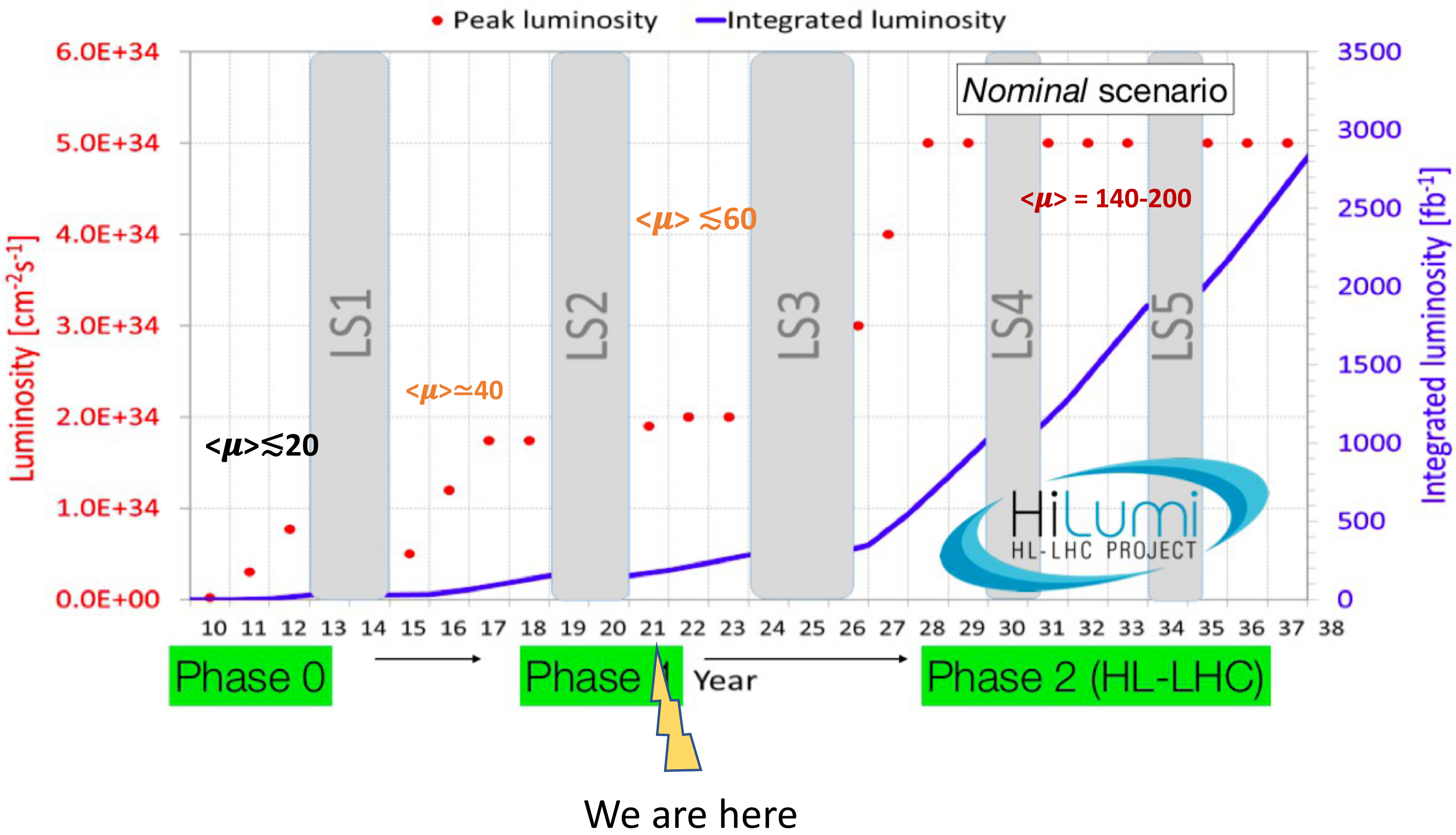


From J. Incandela

HL-LHC

Since 2026, the HL-LHCs instantaneous luminosity:

- will increase by a factor 5 to 7 compared to the LHC Run II
- will result in around 200 collisions per bunch crossing.



Detector Design Aspects

- good measurement of leptons (high p_T)
  muons: large and precise muon chambers
  electrons: precise electromagnetic calorimeter and tracking

- good measurement of photons

- good measurement of missing transverse energy (E_T^{miss})
  requires in particular good hadronic energy measurements
  down to small angles, i.e. large pseudo-rapidities ($\eta \approx 5$, i.e. $\theta \approx 1°$)

- in addition identification of b-quarks and τ-leptons
  precise vertex detectors (Si-pixel detectors)

Very important: radiation hardness
e.g. flux of neutrons in forward calorimeters
10^{17} n/cm^2 in 10 years of LHC operation

Online Trigger

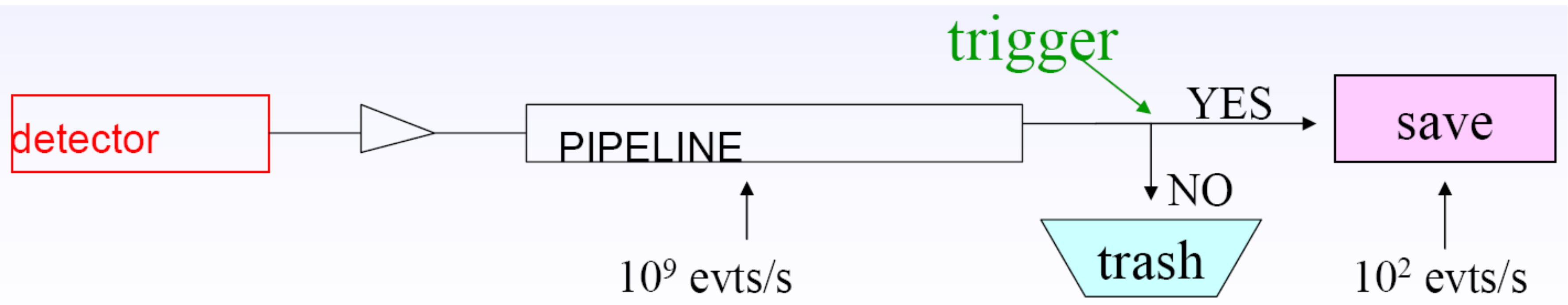
Trigger of interesting events at the LHC is much more complicated than at e^+e^- machines

- interaction rate: ≈ 10^9 events/s
- max. record rate: ≈ 100 events/s   event size ≈ 1 MByte ⇒ 1000 TByte/year of data

⇒ trigger rejection ≈ 10^7

- collision rate is 25 ns   (corresponds to 5 m cable delay)
- trigger decision takes ≈ a few μs

⇒ store massive amount of data in front-end pipelines
while special trigger processors perform calculations



Cross Section of Various SM Processes

⇒ High Luminosity phase

$10^{34}/cm^2/s = 10/nb/s$

approximately

- 10^9 pp interactions
- 10^7 bb events
- 2000 W-bosons
- 500 Z-bosons
- 10 tt-pair

will be produced per second and

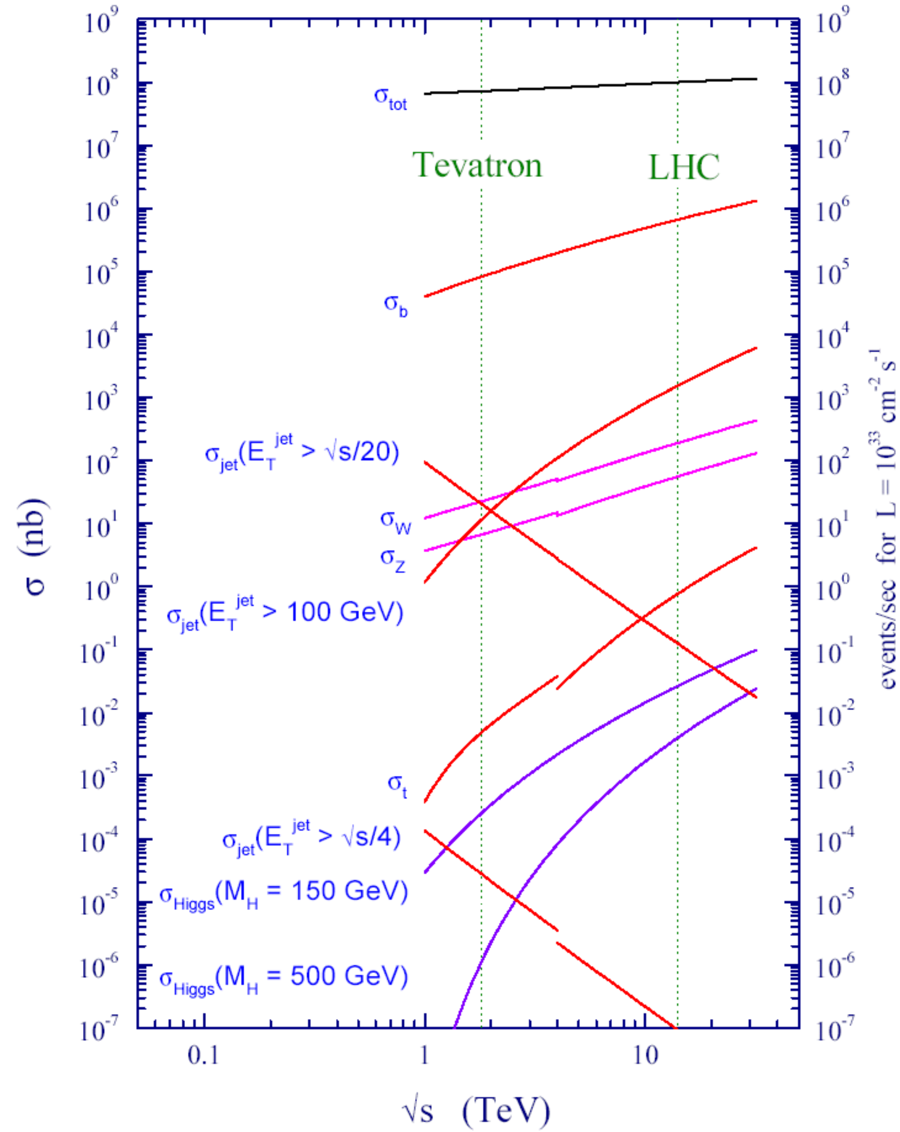
- 10 light Higgs

per minute!

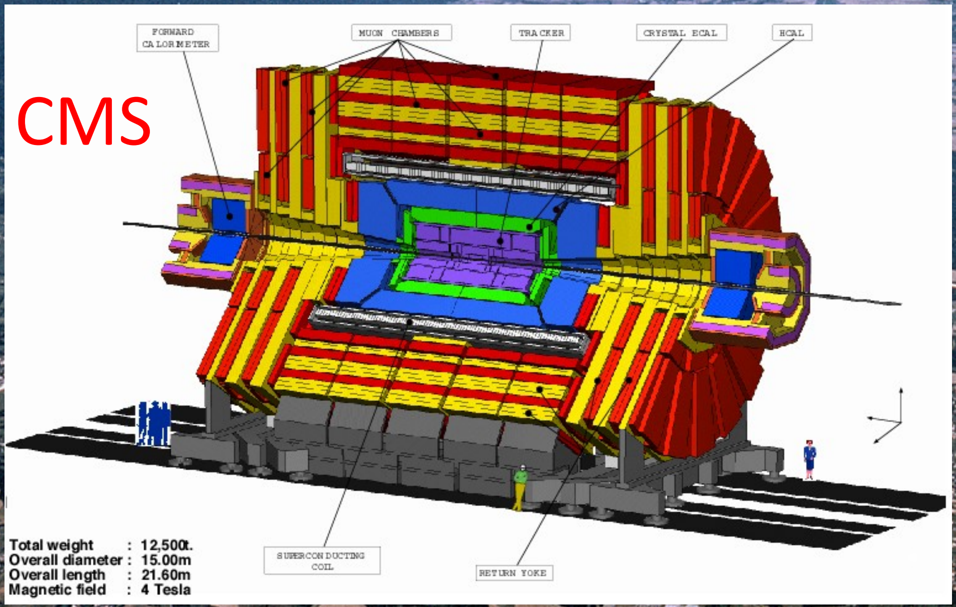
The LHC is a b, W, Z, top, Higgs, … factory!

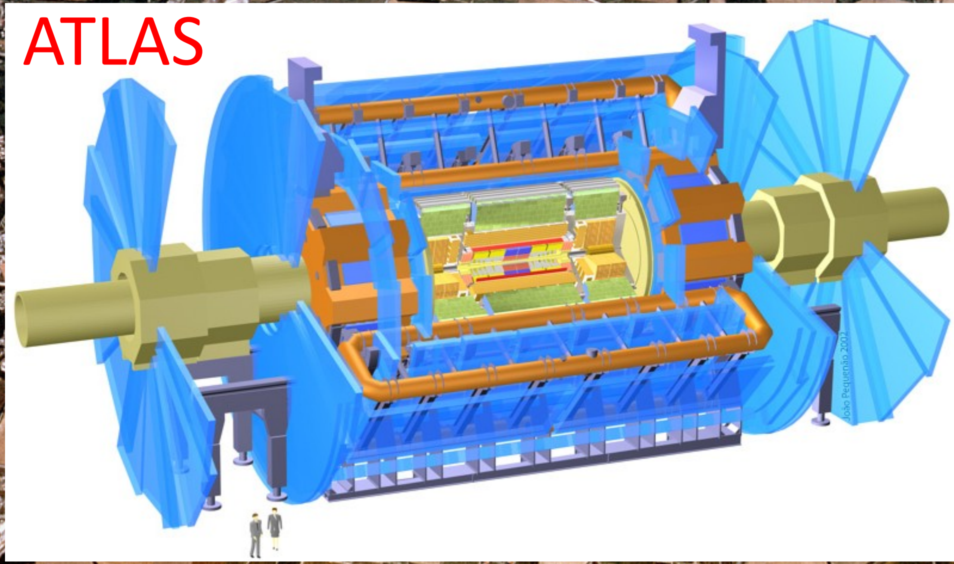
The problem is to detect the events!

proton - (anti)proton cross sections

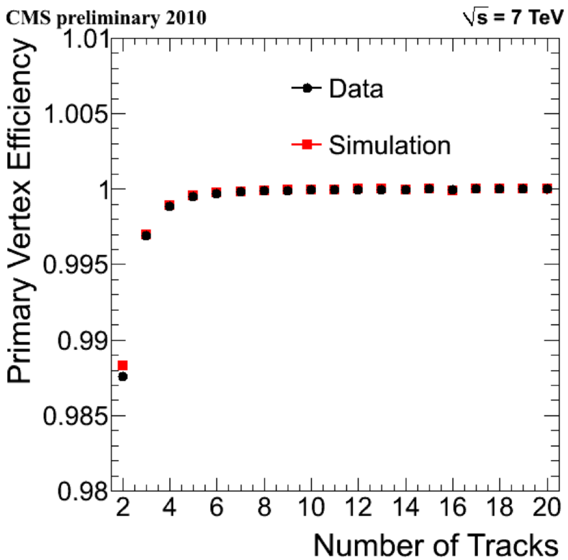


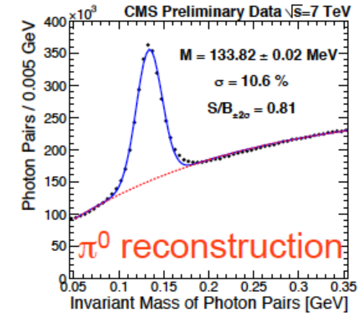
The Large Hadron Collider LHC



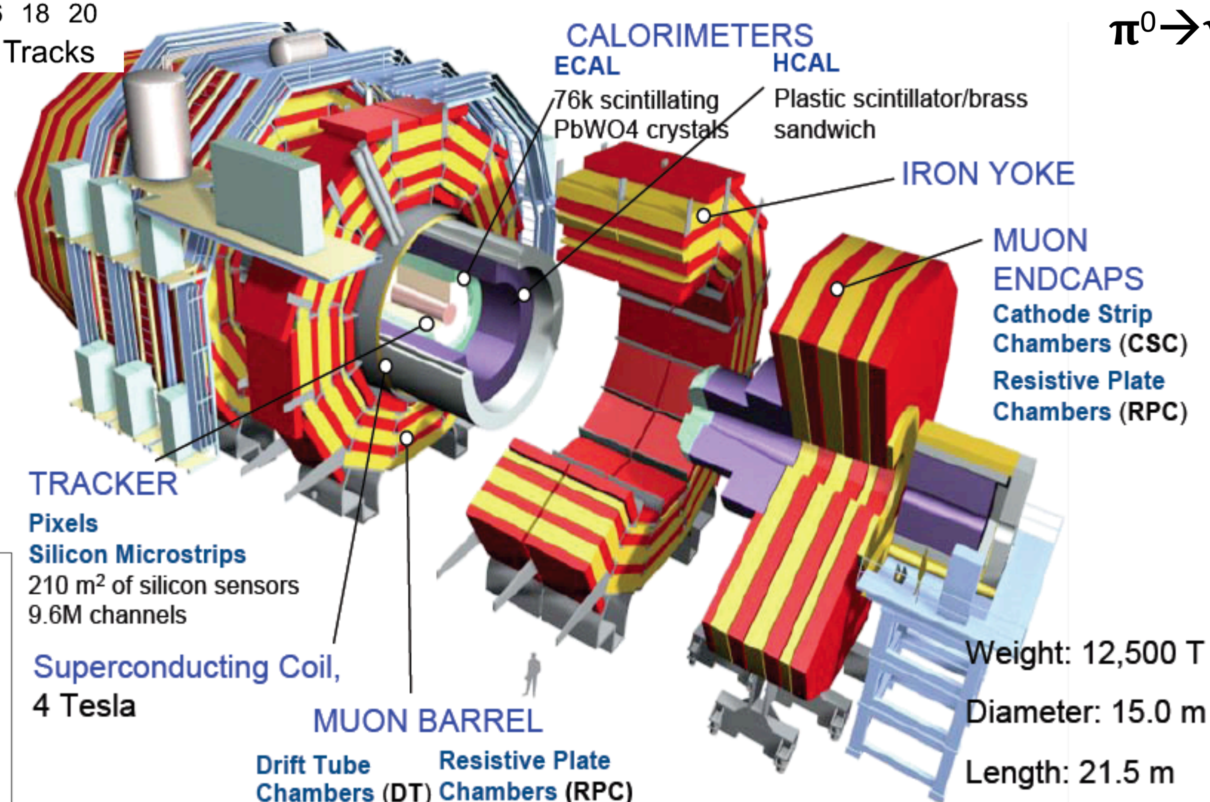


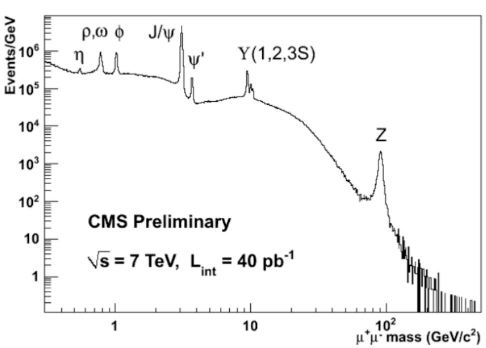
CMS Detector, Phase I





$\pi^0 \rightarrow \gamma\gamma$

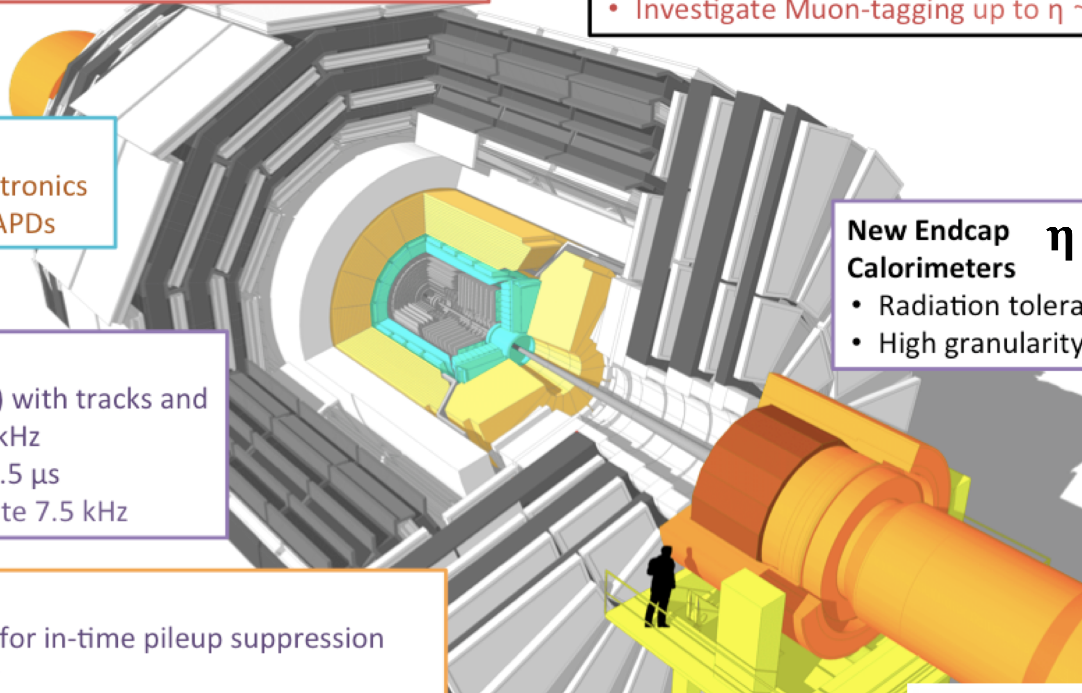




CMS Detector Upgrades

New Tracker
- Radiation tolerant - high granularity - less material
- Tracks in hardware trigger (L1)
- Coverage up to η ~ 4

Muons
- Replace DT FE electronics
- Complete RPC coverage in forward region (new GEM/RPC technology)
- Investigate Muon-tagging up to η ~ 3

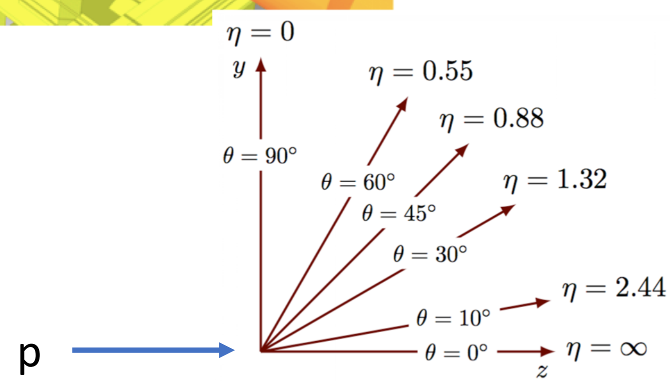


Barrel ECAL
- Replace FE electronics
- Cool detector/APDs

New Endcap Calorimeters $\eta = 3$
- Radiation tolerant
- High granularity

Trigger/DAQ
- L1 (hardware) with tracks and rate up ~ 750 kHz
- L1 Latency 12.5 µs
- HLT output rate 7.5 kHz

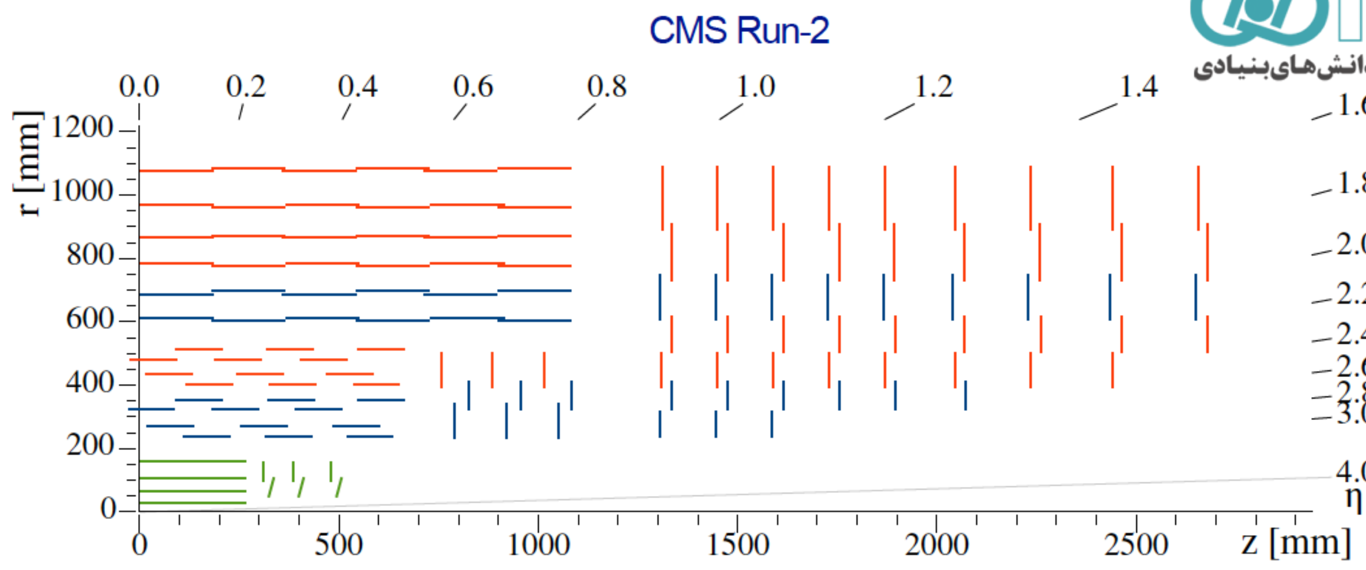
Other R&D
- Fast-timing for in-time pileup suppression
- Pixel trigger

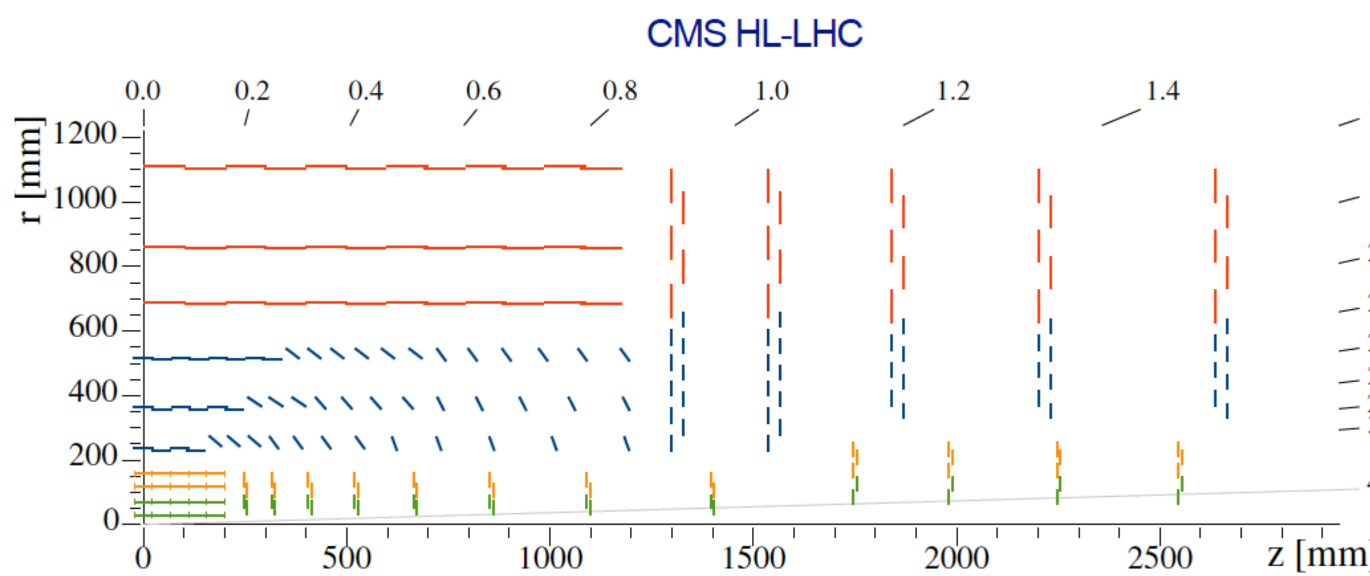


$\eta = 4$
$\theta = 2$ deg.

$$N_{events} = \sigma \times \int \mathcal{L}\, dt \times \varepsilon_A \times \varepsilon_D$$

Tracker upgrade





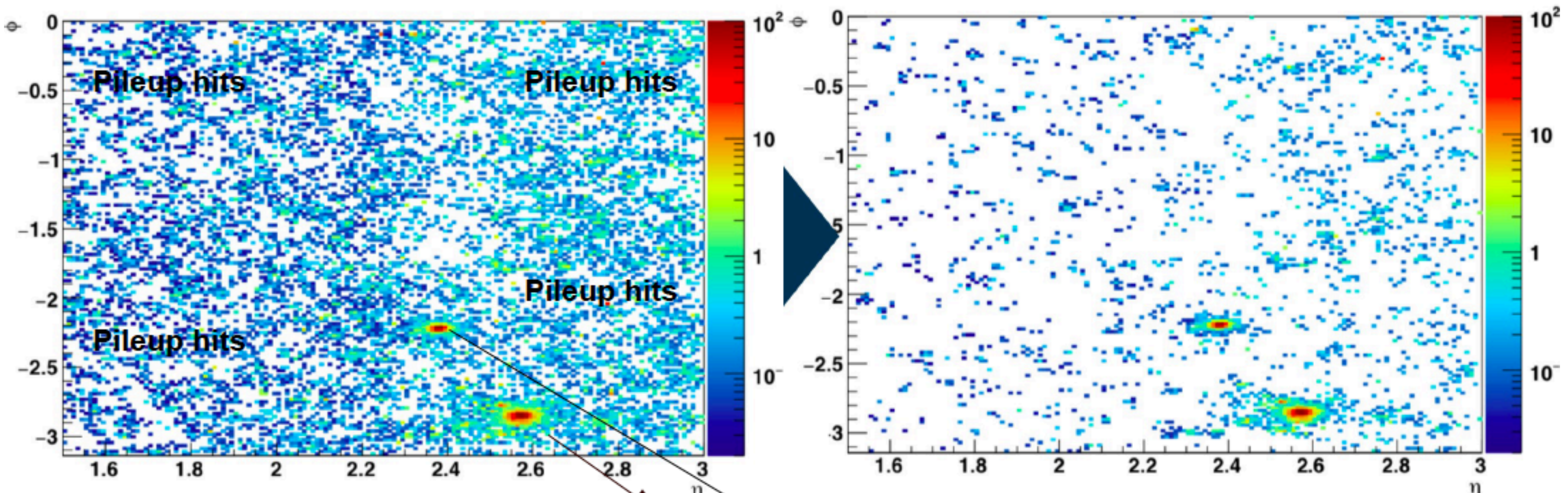
Much larger acceptance: |η| < 4
less detector material and better resolution

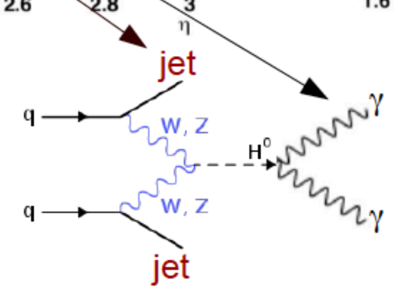
HGCAL Timing capability

-Possibility for imaging of showers with timing.

- time resolution (**30 ps for clusters with p_T > 5 GeV**)

-Simulation of VBF H (γγ) event in HGCAL with and without timing selection (timing cut |Δt| < 90 ps)



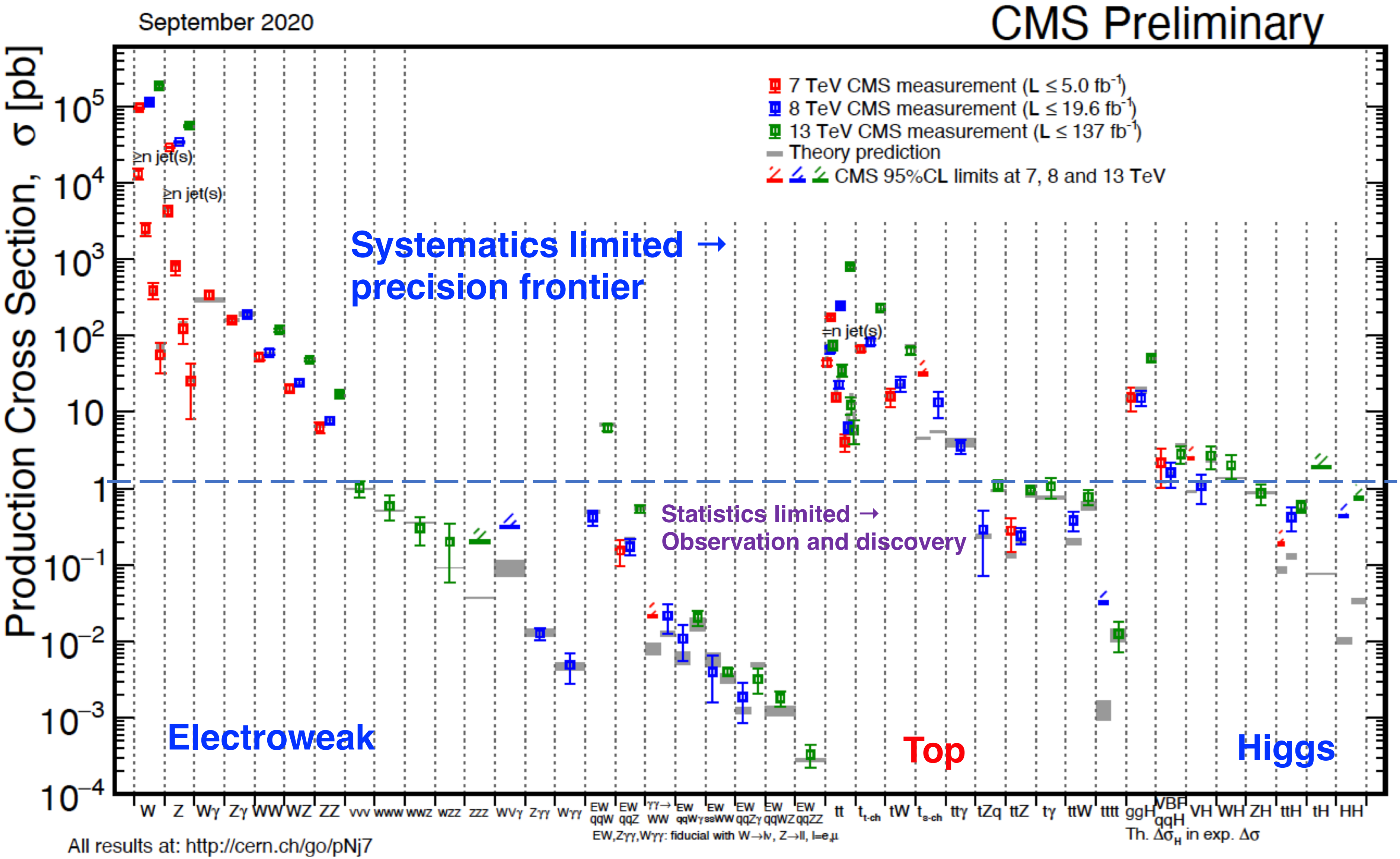


• Plots show cells with Q > 12fC (~3.5 MIPs @300μm - threshold for timing measurement) projected to the front face of the endcap calorimeter.

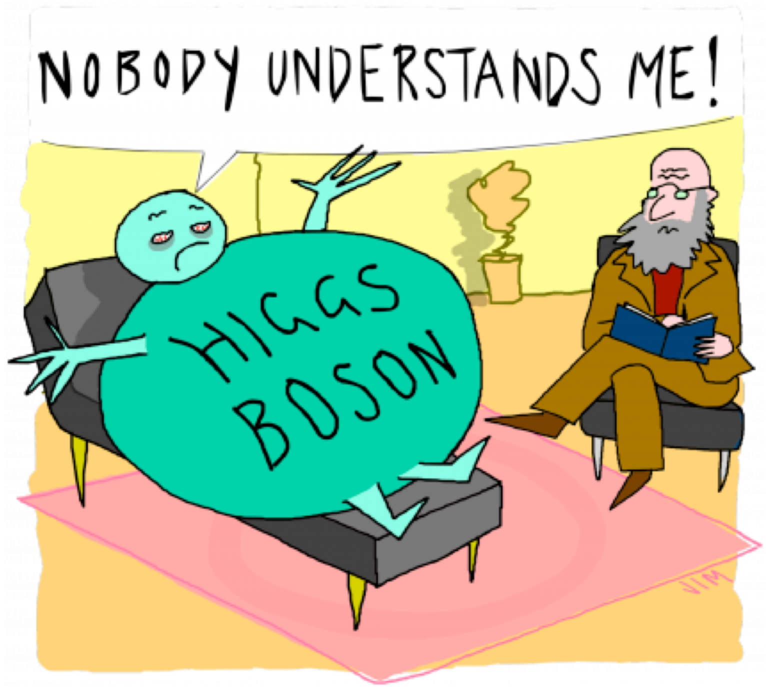
• Concept: identify high-energy clusters, then make timing cut to retain hits of interest

Current CMS SM Measurements

CMS SM Results



Higgs Boson

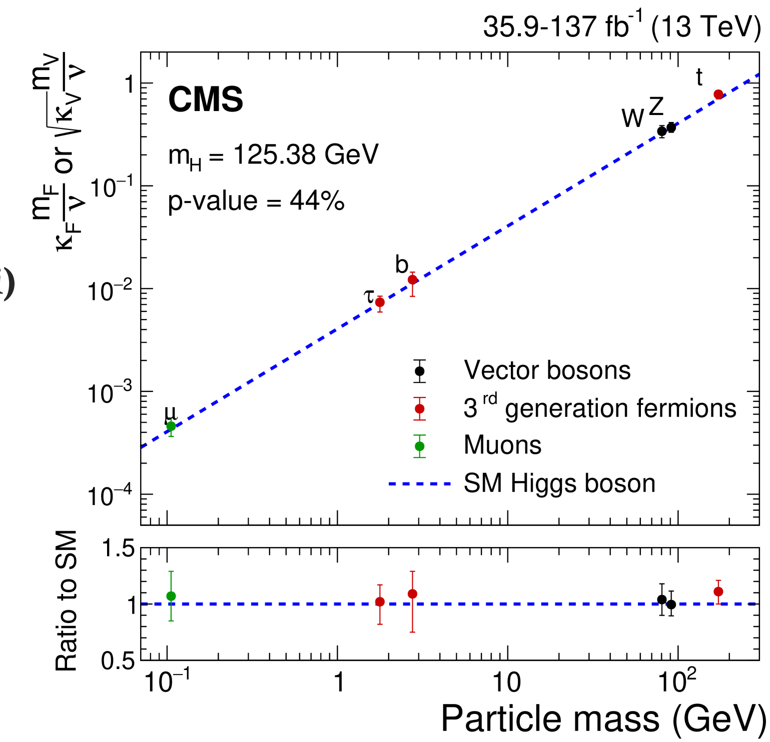


-Precise Measurements of Properties and Couplings for Higgs
-Completing the unknown part of Higgs boson

thewordofthemonth

Higgs couplings to SM fields: current status

- Couplings to gauge bosons at 8-12%
- Couplings to 3rd generation fermions at 15-20%. For the muon: ~ 40%



k_i=(Higgs coupling to particle i)/(SM Higgs coupling to particle i)

- Gauge invariance of SM requires ***k***=1
- Simple rescaling; no momentum dependence
- We are just getting to the interesting regime: Generically expect deviations:

$$\delta\kappa \sim \frac{v^2}{\Lambda^2} \sim 6\% \left(\frac{1000\ TeV}{\Lambda}\right)^2$$

Higgs - τ
Summer 2017

Higgs - b
Summer 2018

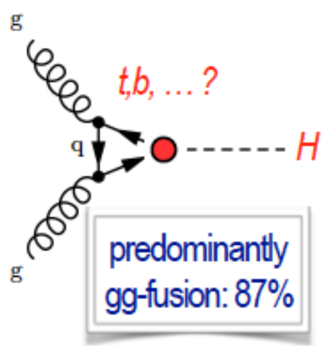
Higgs - top
Spring 2018

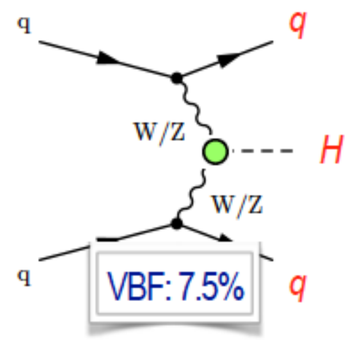
Higgs-μ
Summer 2020

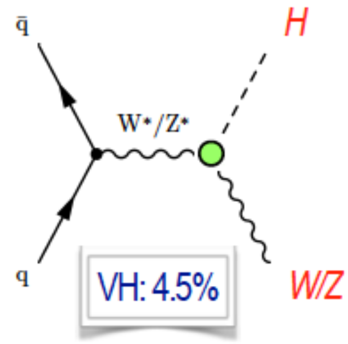
Err. 40%

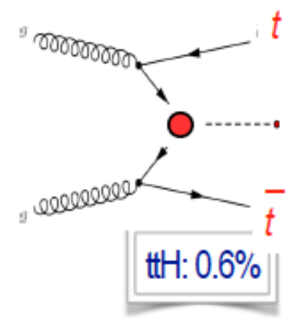
CMS-PAS-HIG-19-006

Higgs Production at the LHC





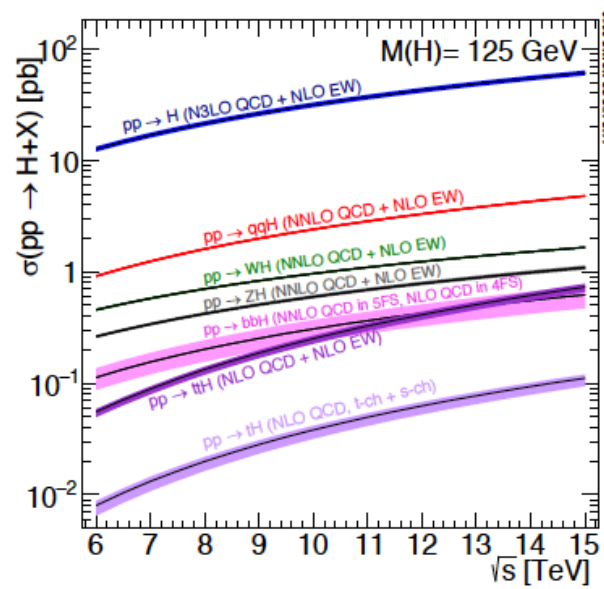


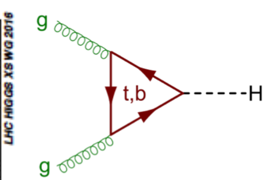


■ We know SM Higgs rates at NLO+EW in perturbation theory.

■ **High statistics** from **future LHC** runs allows for precision measurement of distributions.

– Need NLO (and higher) for both signal and background.
– Need to understand (and reduce) theoretical uncertainties.



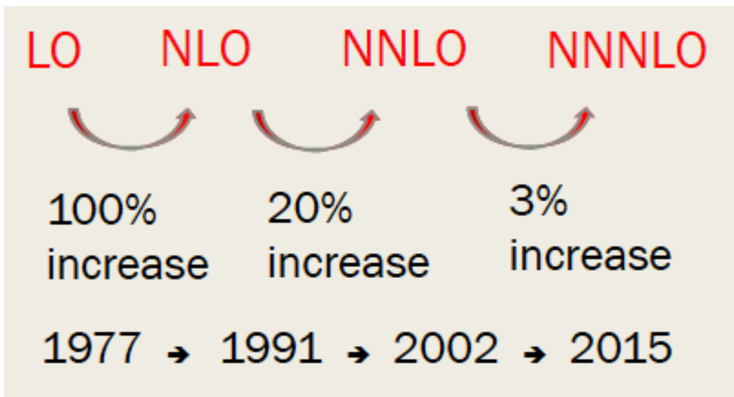


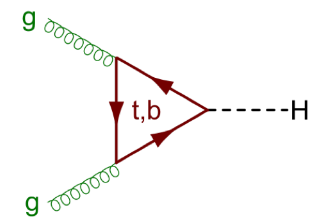
Gluon fusion is largest Higgs rate

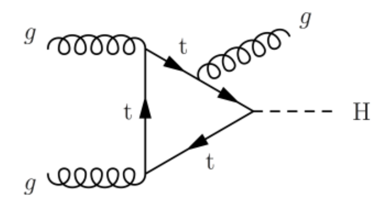
Calculation of Higgs production to NNNLO required:

– Advanced analytic techniques
– New computational techniques

– Surprisingly large corrections to gluon fusion production:





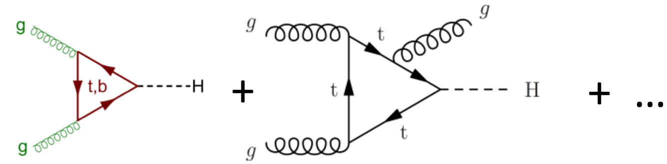


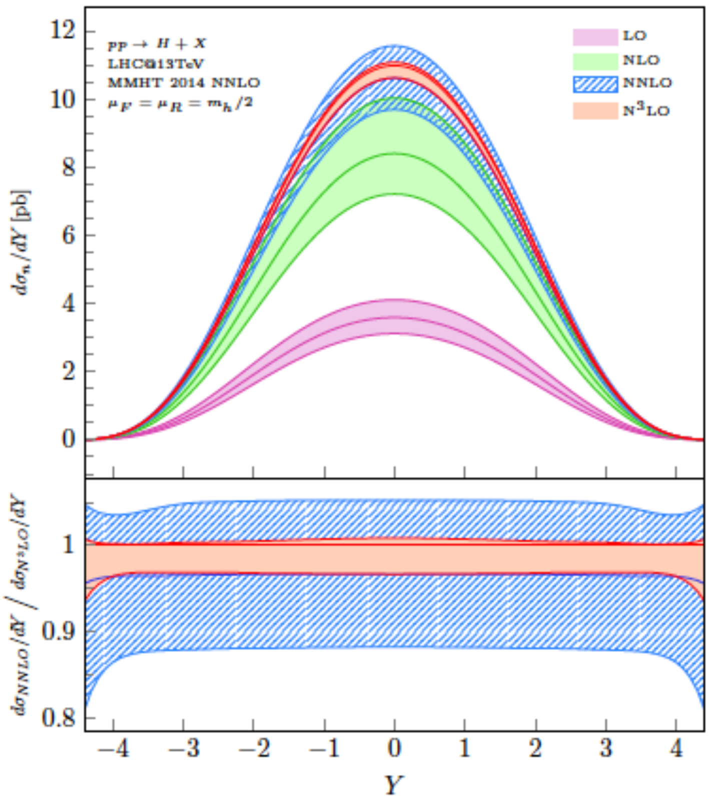
$$\sigma(gg \to H) = \alpha_s^2 \Big(\sigma_{LO} + \alpha_s \delta\sigma_{NLO} + \alpha_s^2 \delta\sigma_{NNLO} + \alpha_s^3 \delta\sigma_{NNNLO} + \dots \Big)$$

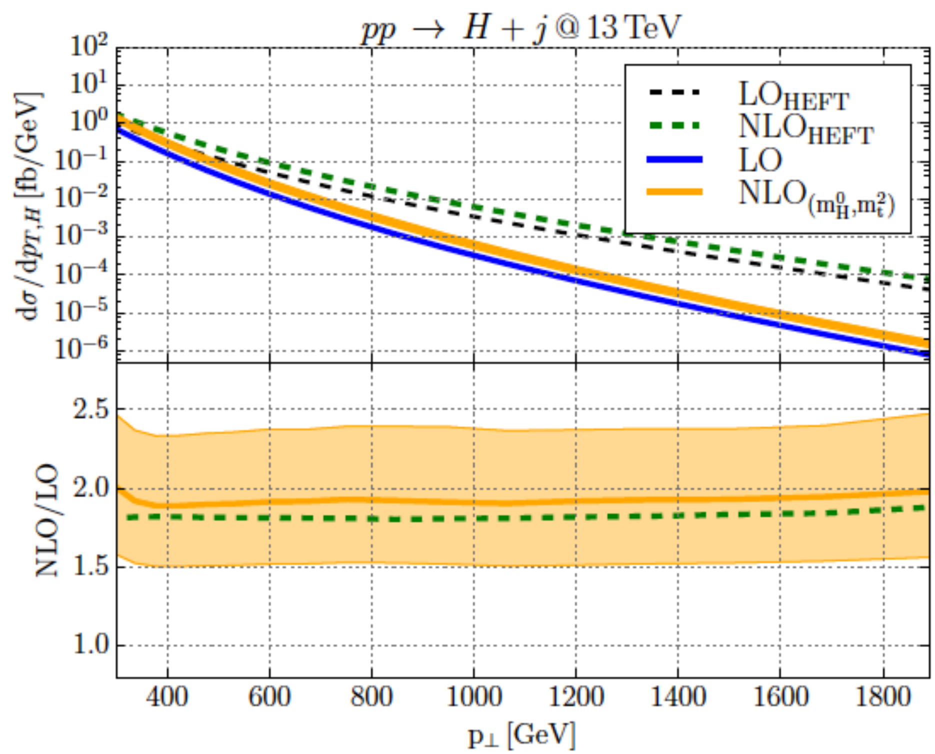
arXiv1807.11501; arXiv1810.09462

[Anastasiou, et al, arXiv:1503.06056]

Higher order effects





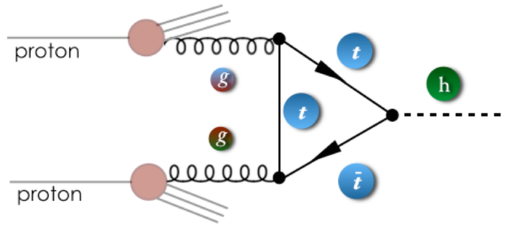


arXiv1807.11501; arXiv1810.09462

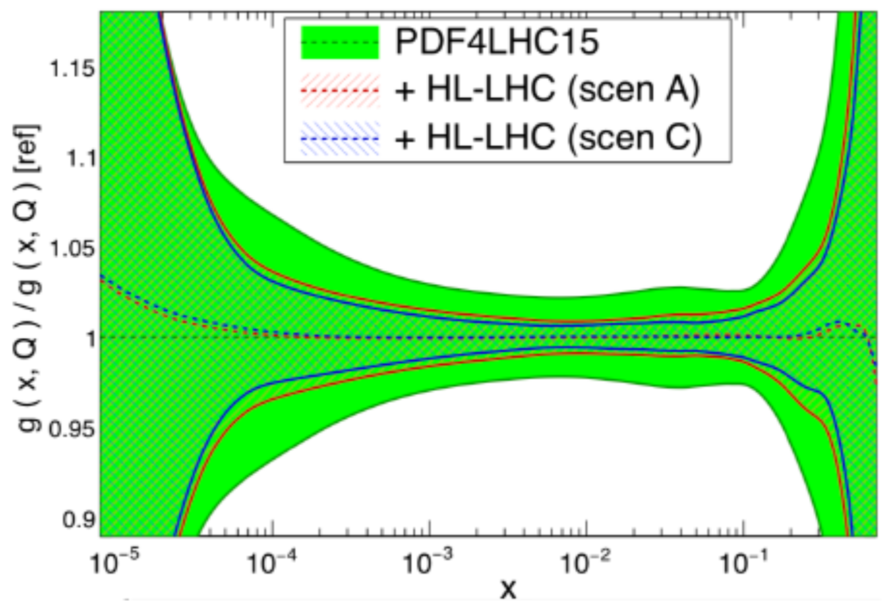
arXiv:1801.08226

Gluon fusion is largest Higgs rate PDF@HL-LHC

$$\sigma(p_1, p_2; M_H) = \sum_{a,b} \int_0^1 dx_1 dx_2\, f_{h_1,a}(x_1, \mu_F^2)\, f_{h_2,b}(x_2, \mu_F^2) \times \hat{\sigma}_{ab}(x_1 p_1, x_2 p_2, \alpha_S(\mu_R^2); \mu_F^2)$$

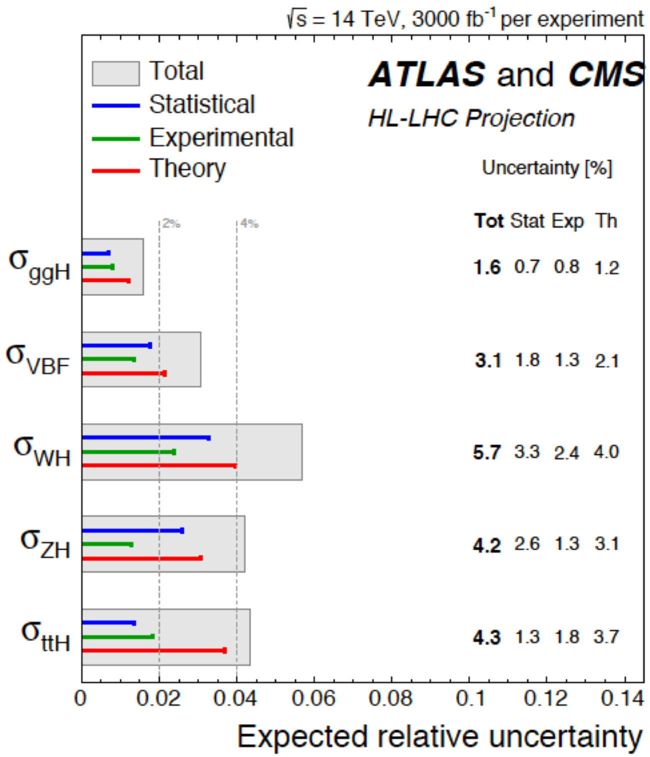


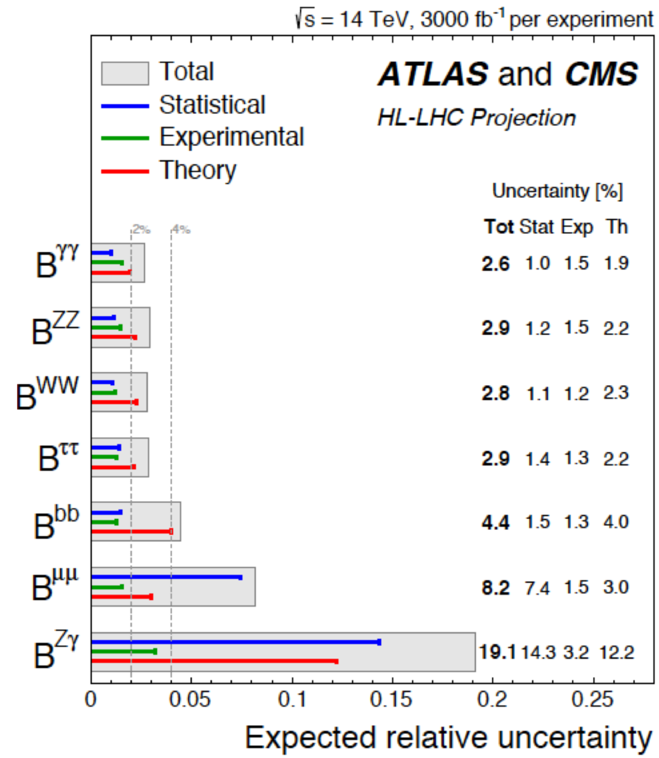
- Rates depend on probability of finding quarks and gluons in proton with a given energy.
- Before 2015, different PDF fits to data gave predictions which differed by ±~7%.
- New PDF fits including LHC measurements and more terms in the α_s expansion agree to ±2-3% for Higgs production.



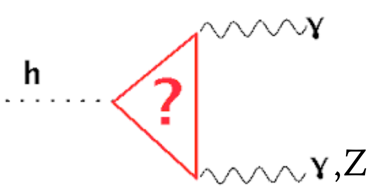
Eur.Phys.J.C 78 (2018) 11, 962

Higgs production and decay at HL-LHC





Lots of theoretical work needed!



BR H→μμ and **BR H→Zγ** statistically limited

Other branching ratios and cross sections dominated by **theoretical** uncertainties

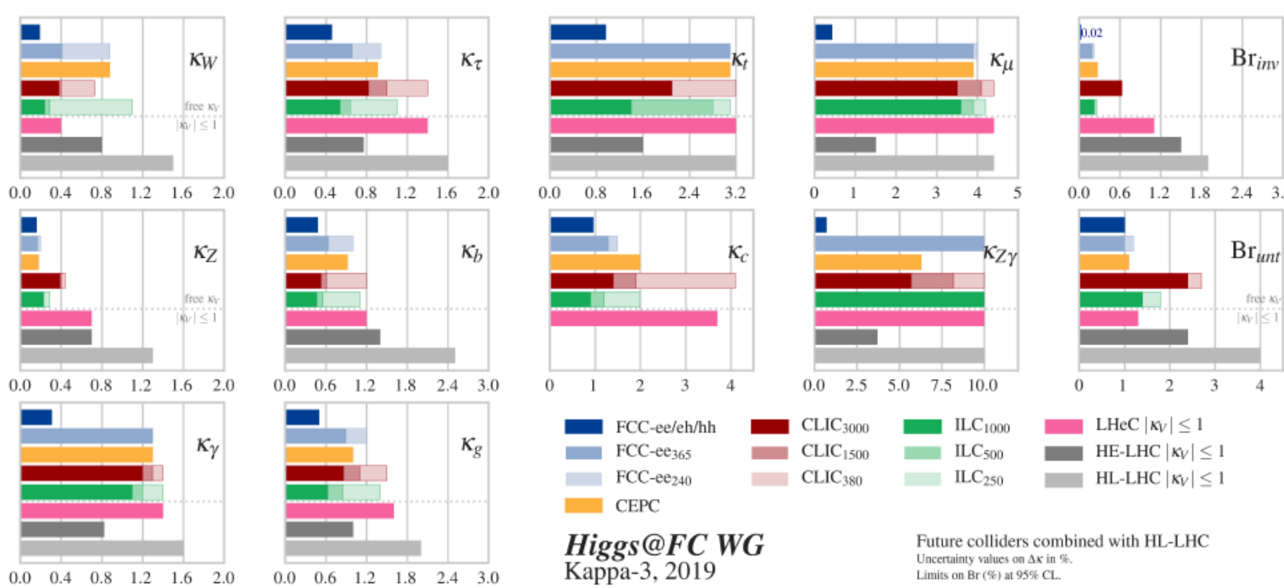
CERN-LPCC-2018-04

HL-LHC versus Future Colliders

پژوهشگاه دانش‌های بنیادی

k_i=(Higgs coupling to particle i)/(SM Higgs coupling to particle i)

kappa-0	HL-LHC	LHeC	HE-LHC		ILC			CLIC			CEPC	FCC-ee		FCC-ee/eh/hh
			S2	S2′	250	500	1000	380	15000	3000		240	365	
κ_W [%]	1.7	0.75	1.4	0.98	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14
κ_Z [%]	1.5	1.2	1.3	0.9	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12
κ_g [%]	2.3	3.6	1.9	1.2	2.3	0.97	0.66	2.5	1.3	0.9	1.5	1.7	1.0	0.49
κ_γ [%]	1.9	7.6	1.6	1.2	6.7	3.4	1.9	98⋆	5.0	2.2	3.7	4.7	3.9	0.29
$\kappa_{Z\gamma}$ [%]	10.	–	5.7	3.8	99⋆	86⋆	85⋆	120⋆	15	6.9	8.2	81⋆	75⋆	0.69
κ_c [%]	–	4.1	–	–	2.5	1.3	0.9	4.3	1.8	1.4	2.2	1.8	1.3	0.95
κ_t [%]	3.3	–	2.8	1.7	–	6.9	1.6	–	–	2.7	–	–	–	1.0
κ_b [%]	3.6	2.1	3.2	2.3	1.8	0.58	0.48	1.9	0.46	0.37	1.2	1.3	0.67	0.43
κ_μ [%]	4.6	–	2.5	1.7	15	9.4	6.2	320⋆	13	5.8	8.9	10	8.9	0.41
κ_τ [%]	1.9	3.3	1.5	1.1	1.9	0.70	0.57	3.0	1.3	0.88	1.3	1.4	0.73	0.44

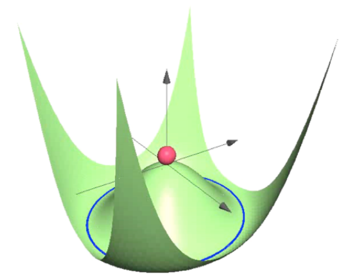


arXiv:1905.03764

Higgs self coupling, Top Mass at HL-LHC

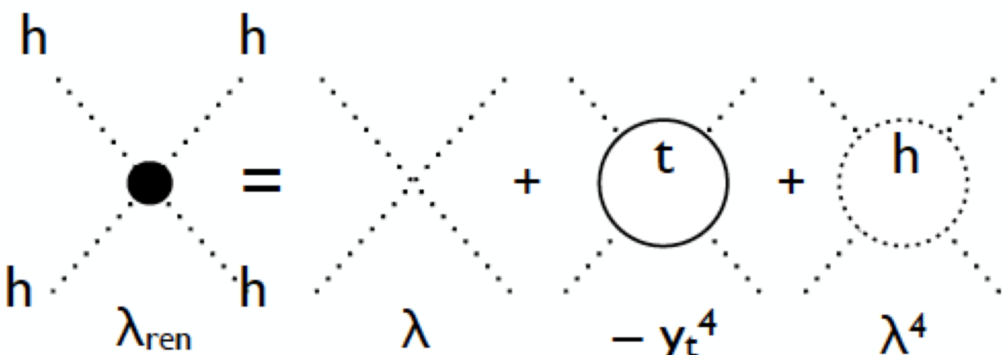
$$V_{SM}(H) = -\mu^2 |H|^2 + \lambda |H|^4$$

$\lambda_{SM} = 0.13$

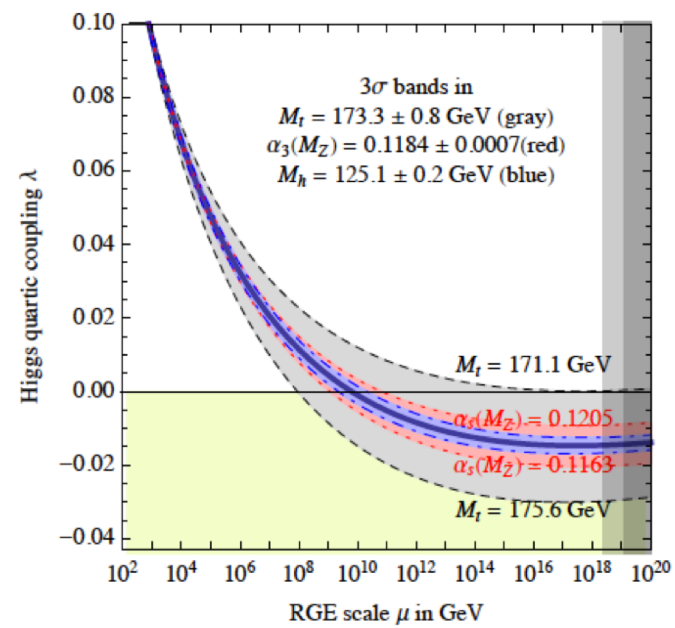


Giudice et al

Quantum fluctuations of Higgs, top, …



$$\Rightarrow \frac{d\lambda}{d\log\mu} \propto \lambda^4 - y_t^4 \quad \propto a\, m_H^4 - b\, m_t^4$$



If $\lambda < 0$, the potential is unbounded from below and has no state of minimum energy.

CMS-PAS-FTR-16-006

HL-LHC: $\delta m_{top} \sim 0.2$ GeV

Indirect probes for Higgs self couplings

❖ Unitarity, HH→HH, Re (a_0)<1/2: $|k_\lambda| < 6.5$

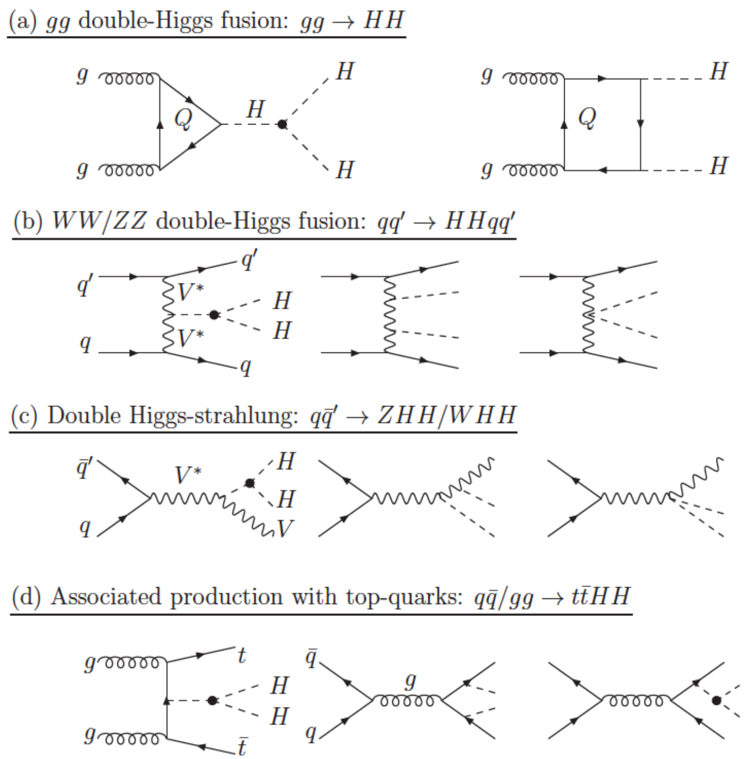
$k_\lambda = \lambda / \lambda_{SM}$

❖ Stability of Higgs potential, Is Higgs potential bounded from below?
If we there is no NP, bounding the Higgs potential from below requires:
$|k_\lambda| < 3$.

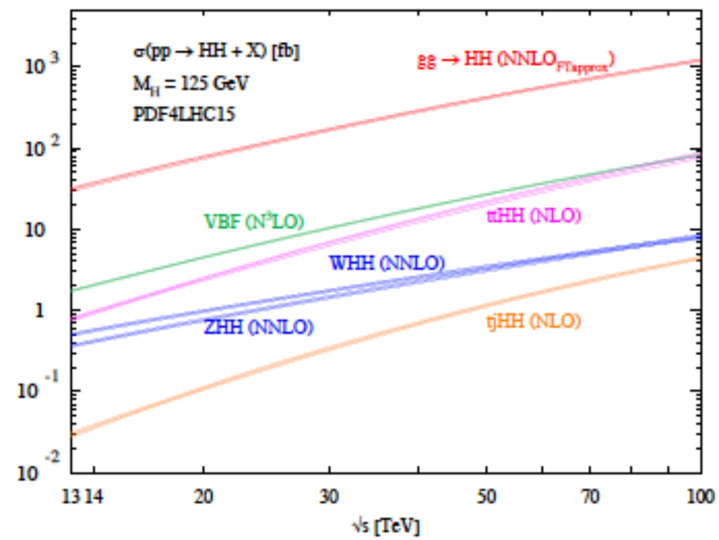
❖ Higgs Decay to ZZ and WW:

$+ \ldots$ $\qquad \lambda/\lambda_{SM} > -14.3$

HH production at the LHC



$\sigma(gg \to HH) \approx 0.1\% \times \sigma(gg \to H)$



$\sqrt{s}$ [TeV]	$\sigma^{\mathrm{NLO}}_{gg\to HH}$ [fb]	$\sigma^{\mathrm{NLO}}_{qq'\to HHqq'}$ [fb]	$\sigma^{\mathrm{NNLO}}_{q\bar{q}'\to WHH}$ [fb]	$\sigma^{\mathrm{NNLO}}_{q\bar{q}\to ZHH}$ [fb]	$\sigma^{\mathrm{LO}}_{q\bar{q}/gg\to t\bar{t}HH}$ [fb]
8	8.16	0.49	0.21	0.14	0.21
14	33.89	2.01	0.57	0.42	1.02
33	207.29	12.05	1.99	1.68	7.91
100	1417.83	79.55	8.00	8.27	77.82

arXiv:1212.5581

HH production at LHC

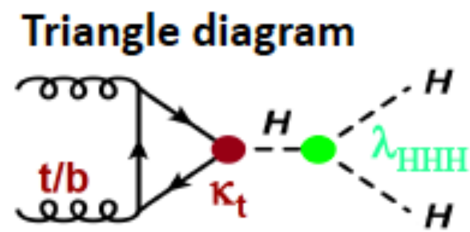
- For large s, dependence on $\boldsymbol{\lambda}$ suppressed
- More sensitivity to negative $\boldsymbol{\lambda}$
- Exact cancellation at threshold
- b quark contribution ~2%

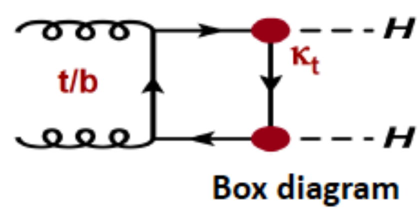
$$\frac{d\sigma(gg \to HH)}{dt} = \frac{\alpha_s^2}{32768\pi^3 v^4}\left(|\, F_0\,|^2 + |\, F_2\,|^2\right)$$

$m_t^2 >> s, p_T^2$

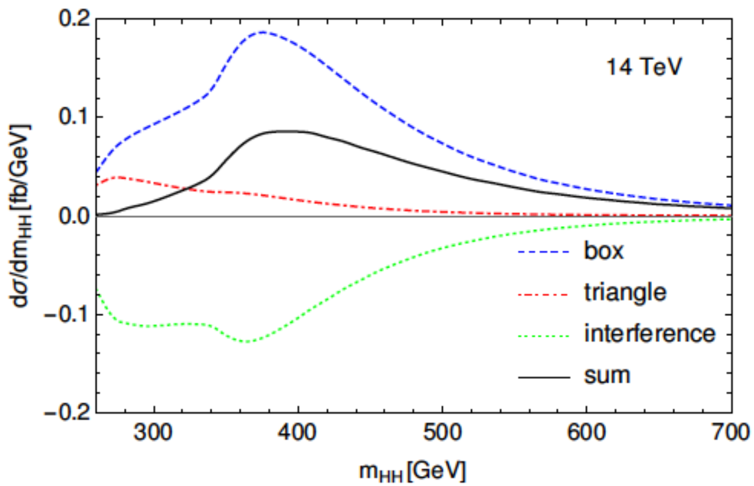
$$F_0 \to -\frac{4}{3} + \frac{4M_H^2}{s - M_H^2}\kappa_\lambda$$

$$F_2 \to 0$$



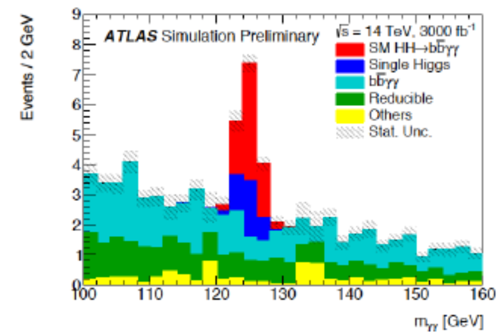


- Gluon fusion contributions
- **At high energy dominated by box**
- Note cancellation at threshold

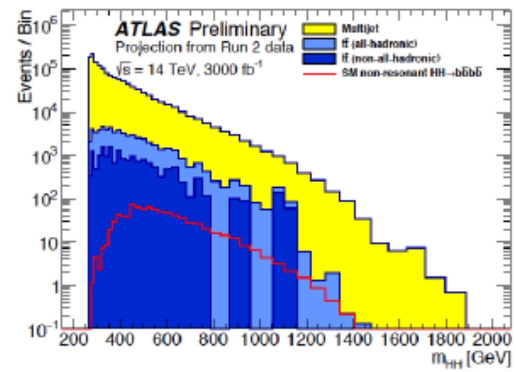


HH search at the HL-LHC

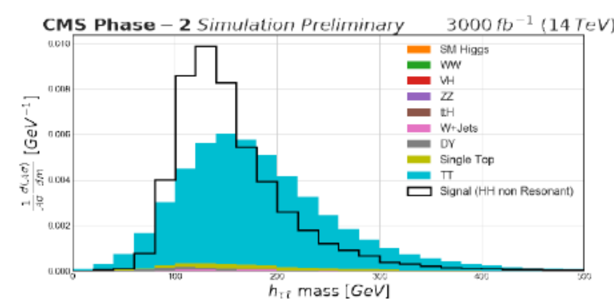
- **HH→bbγγ:**
  - Small BR: 291 events with 3ab $^{-1}$
  - Low bkg
  - Photon resolution critical



- **HH→bbττ:**
  - Sizeable BR: ~8k events with 3ab $^{-1}$
  - Relatively low background
  - Incomplete reconstruction of the event due to the presence of neutrinos
    → Challenging separation from tt and Drell-Yan bkg



- **HH→4b:**
  - Large BR: ~37k events with 3ab^{-1}
  - Large QCD bkg
  - Large dependence on background modelling uncertainty



arXiv:1902.00134

Results of HH study

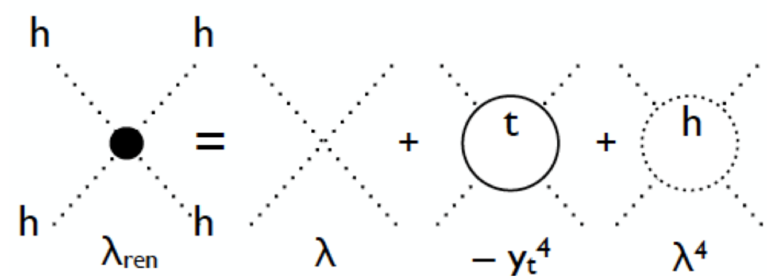
Expected **significance** of HH production with(without) systematics at HL-LHC

- **4σ (4.5σ) expected with ATLAS+CMS !**

	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined		Combined	
	4.5		4.0	

Measurement of $k_\lambda = \lambda / \lambda_{SM}$

$0.52 < k_\lambda < 1.5$



+ ?

Need a future collider!

IPM
پژوهشگاه دانش‌های بنیادی

SM Physics

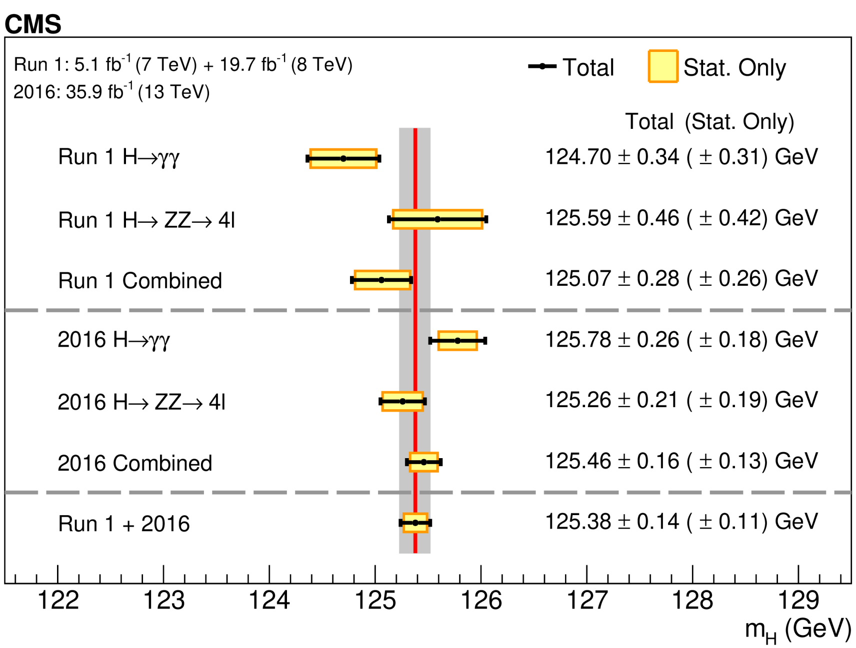
Precision W-boson mass

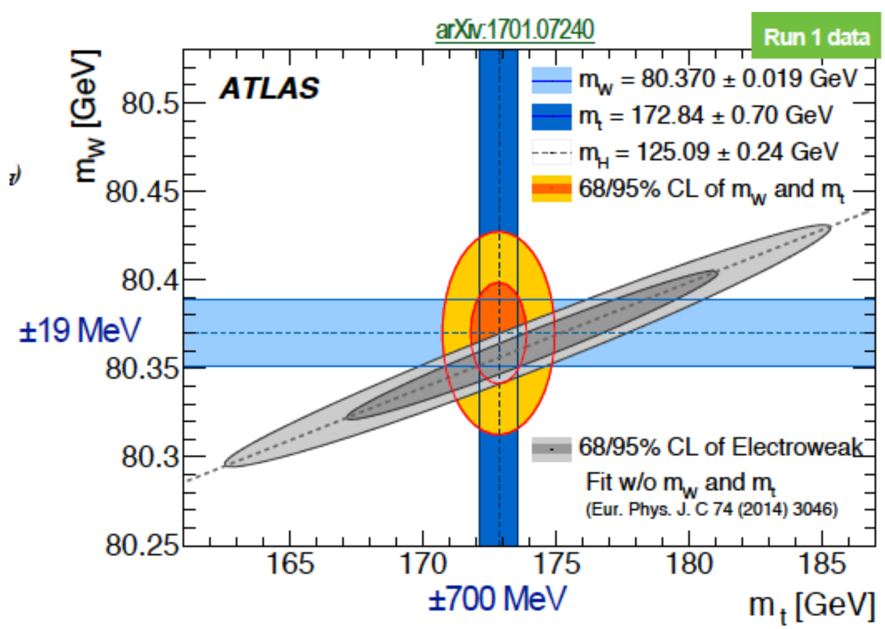
Quantum fluctuations of Higgs, heavy W, Z, & top

m_{top}, m_W and m_H are connected via loop effects → constrain and test SM

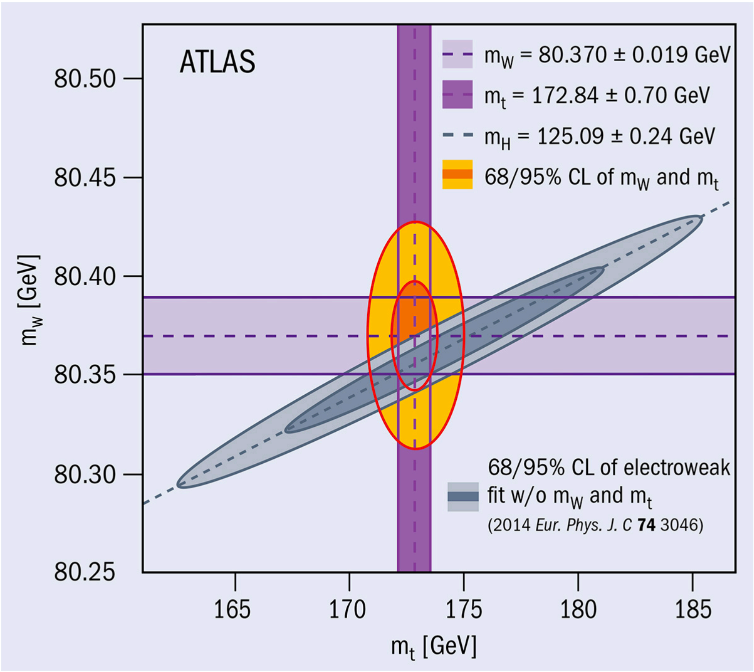
$\Delta r_t \sim m_t^2$ $\Delta r_{Higgs} \sim \ln(m_H^2)$

$$M_W \sim \frac{gv}{2} + \frac{M_t^2}{v}(\ldots) + (\ldots.) \log\left(\frac{M_H^2}{M_W^2}\right) + \ldots.$$





Precision W-boson mass



The measured Higgs boson mass is well consistent with the EW prediction tests (indirect).

+ ?

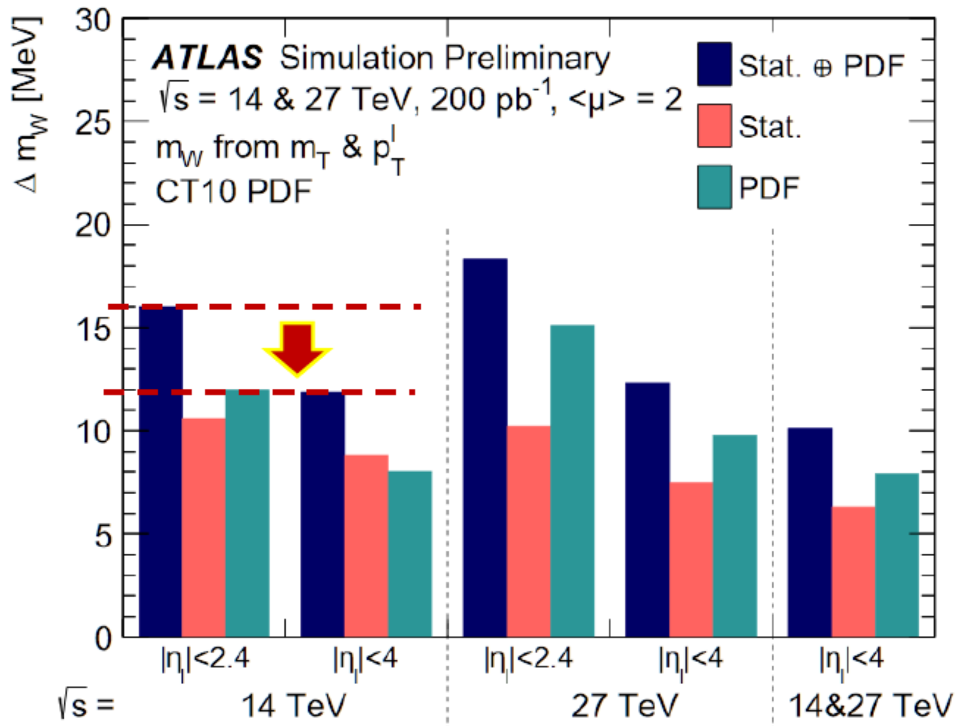
$\Delta r_t \sim m_t^2$ $\quad$ $\Delta r_{Higgs} \sim \ln(m_H^2)$

M_H=125 GeV seems almost maliciously designed to prolong the agony of BSM theorists….

Precision W-boson mass @ HL-LHC

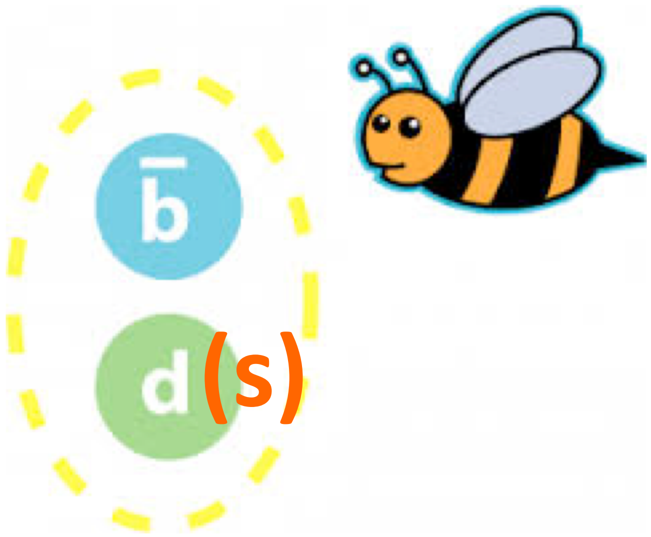
Low-PU run (μ~2) at HL-LHC:

- 200 pb^{-1}, $|\eta| < 2.4$: 2×10^6 evts. 16 MeV
- 200 pb^{-1}, $|\eta| < 4$; 12 MeV
- 1 fb^{-1}, $|\eta| < 4$; 9 MeV
- + ultimate PDF; 5 MeV



ATL-PHYS-PUB-2018-026

B_s-Meson

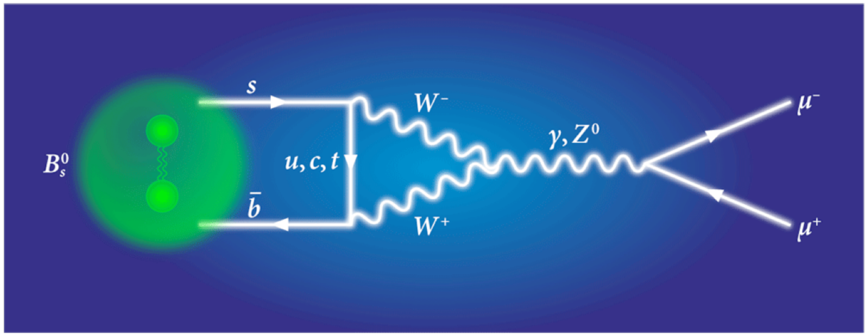


$B_s^0 \to \mu^+\mu^-$

m_B = 5366.3±0.6 MeV

- Rare SM process sensitive to New Physics

SM: $B(B^0_s \to \mu^+\mu^-) = (3.57 \pm 0.17) \times 10^{-9}$



Suppressed by $(m_\mu/m_B)^2$

- Recent CMS: $B(B^0_s \to \mu^+\mu^-) = (3.57^{+0.72}_{-0.63}) \times 10^{-9}$ --> **$\delta B \sim 23\%$**

- From the combination of ATLAS, CMS, LHCb, the $B^0_s \to \mu^+\mu^-$ branching fraction is obtained to be

$$(2.69^{+0.37}_{-0.35}) \times 10^{-9}$$

$\delta B \sim 14\%$

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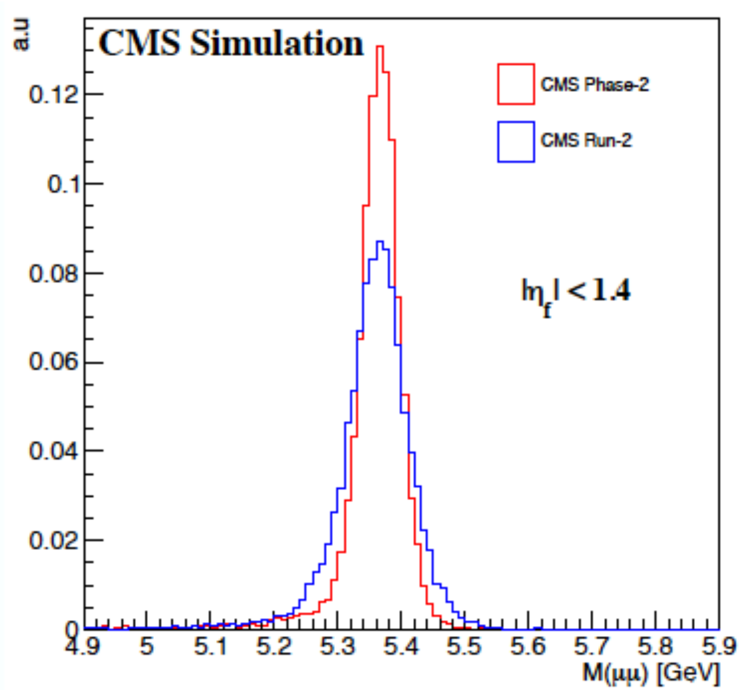
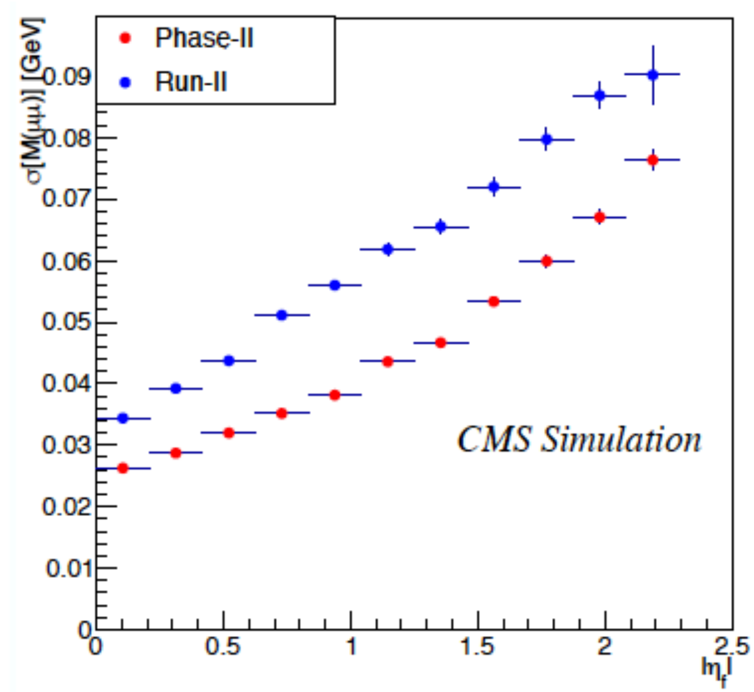
$B_s^0 \rightarrow \mu^+\mu^-$ Reconstruction





- Using the B_s signal, it is shown that there is 40-50% improvement on the mass resolutions.

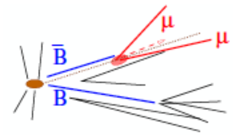
- Improved mass resolutions are crucial for the analysis in order to discriminate the signal from background events.

FTR-18-013

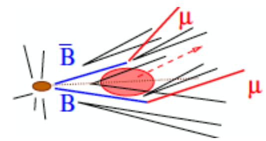
$B_s^0 \to \mu^+\mu^-$

Signal $B_s^0 \to \mu^+\mu^-$

- two muons from one decay vertex



Background



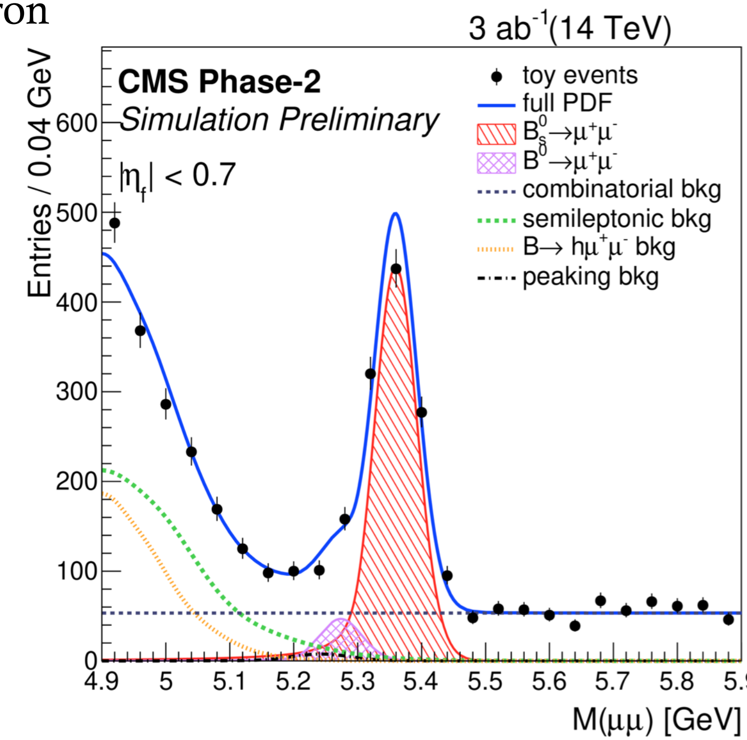
- combinatorial (from sidebands)
  - two semileptonic (B) decays (gluon splitting)
  - one semileptonic (B) decay and one misidentified hadron

- rare single B decays (from MC simulation)

-non-peaking: e.g. $B^0_s \to K^-\mu^+ \nu$, $\Lambda_b \to p+\mu^+ \nu$

-peaking, e.g. $B^0_s \to K^+K^-$, shifted into B^0 mass region

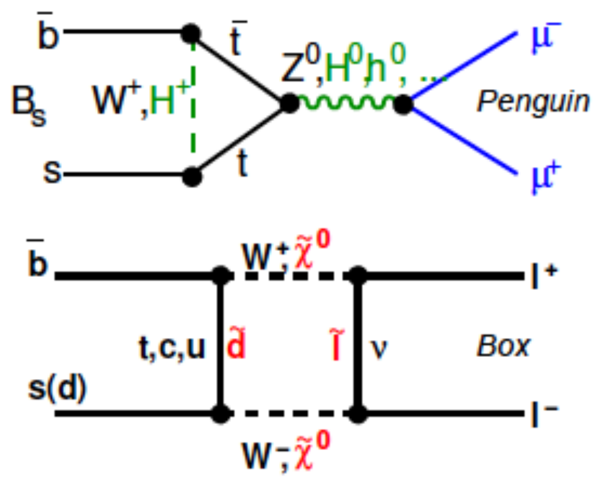
HL-LHC **$\delta B(B^0_s \to \mu^+\mu^-) \sim 7\%$**



FTR-18-013

$B_s^0 \rightarrow \mu^+\mu^-$
Beyond SM Sensitivity

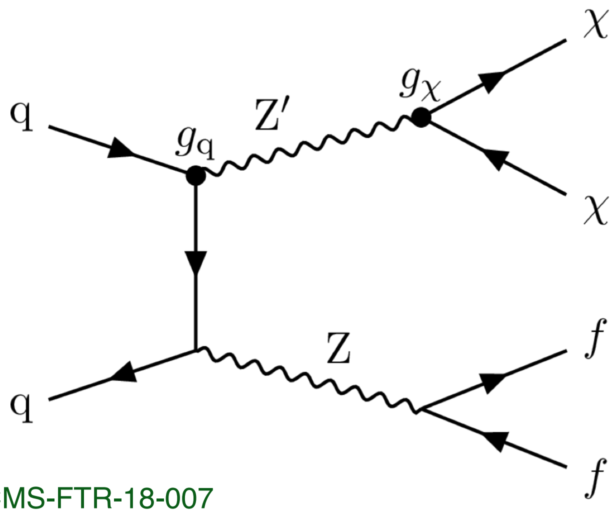
- Branching ration can be increased by several order of magnitudes
- MSSM Branching fraction is proportional to $(\tan\beta)^6$



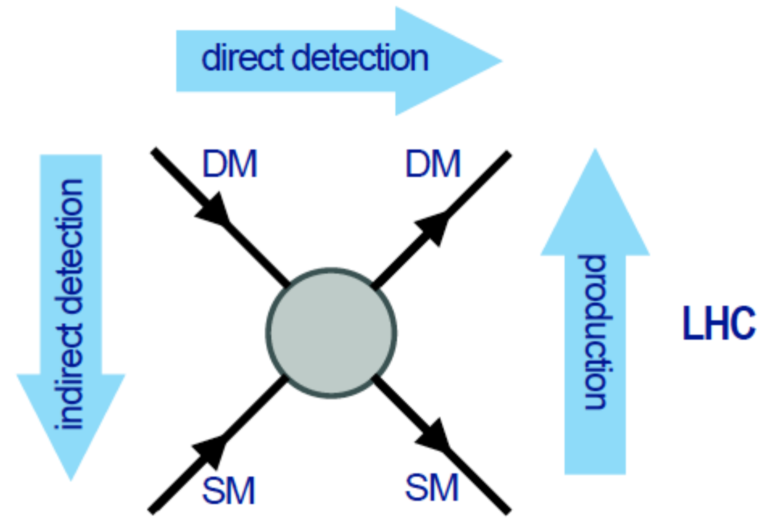
More info: arXiv:1212.4887

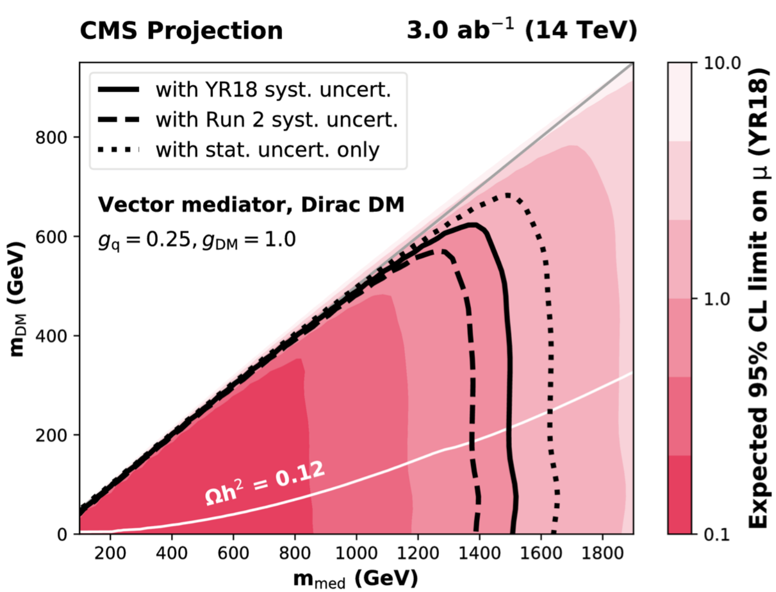
BSM Searches

Mono-Z



CMS-FTR-18-007

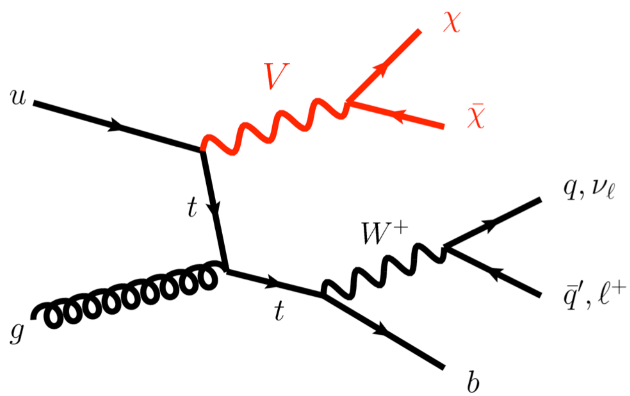


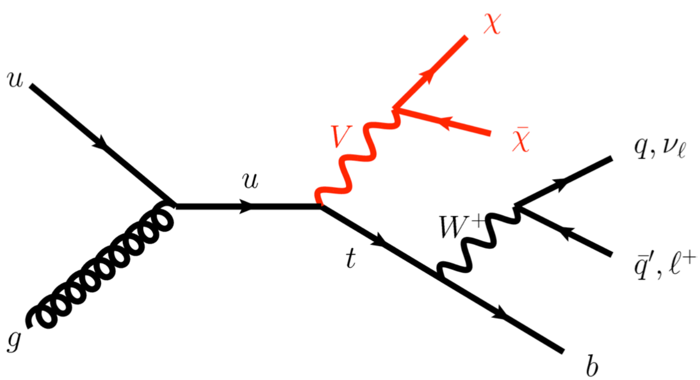


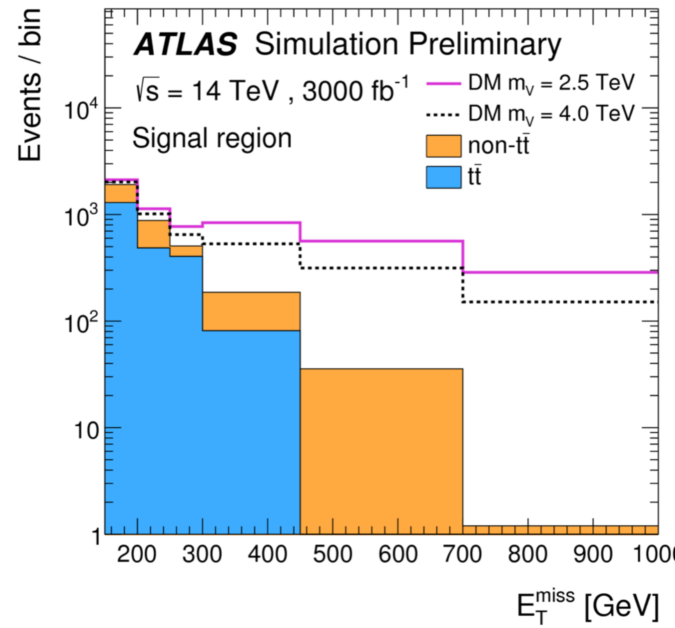
Quantity	Requirement
Number of charged leptons	= 2, with opposite charge, same flavour
Muon p_T	$> 20\,\mathrm{GeV}$
Leading (trailing) Electron p_T	$> 25(20)\,\mathrm{GeV}$
Jet multiplicity	≤ 1 jet with $p_T > 30\,\mathrm{GeV}$
b Jet multiplicity	No b jet $p_T > 20\,\mathrm{GeV}$
Hadronic τ multiplicity	No τ with $p_T > 18\,\mathrm{GeV}$
Dilepton mass	$\lvert M(\ell\ell) - m_Z \rvert < 15\,\mathrm{GeV}$
Dilepton p_T	$> 60\,\mathrm{GeV}$
Dilepton ΔR	< 1.8
p_T^{miss}	$> 200\,\mathrm{GeV}$
$\Delta\phi(\vec{p}_T^{\,\ell\ell}, \vec{p}_T^{\,miss})$	> 2.6
$\lvert p_T^{miss} - p_T^{\ell\ell} \rvert / p_T^{\ell\ell}$	< 0.4
$\Delta\phi(\vec{p}_T^{\,j}, \vec{p}_T^{\,miss})$	> 0.5 rad

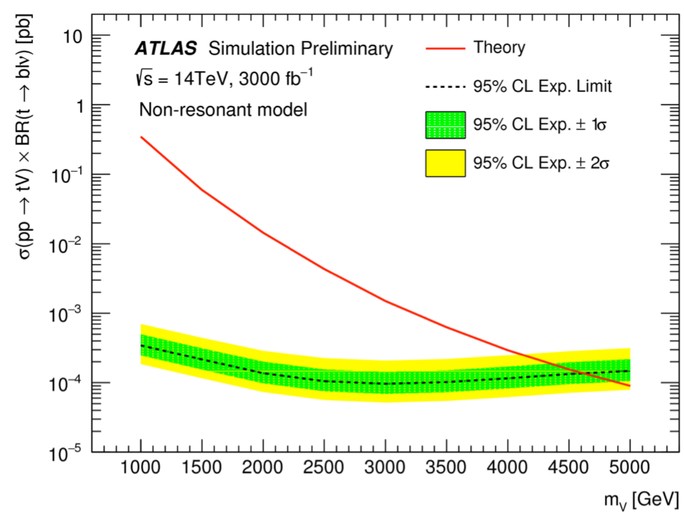
Mono-top

FCNC tqV portal to DM









Limit on m_V ~ 4.5 TeV (for m_{DM} = 1 GeV)

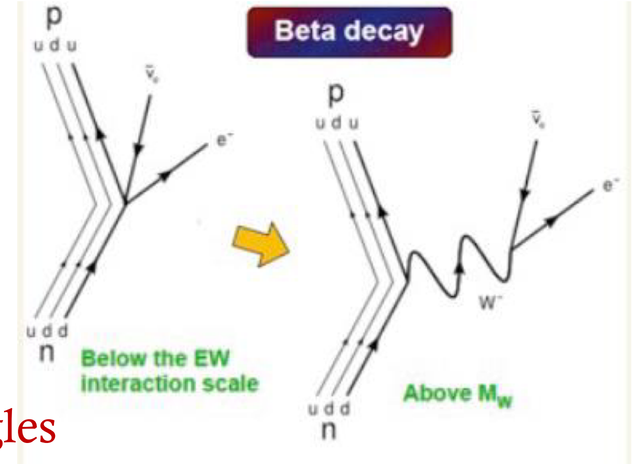
ATL-PHYS-PUB-2018-024

Search for Excited Leptons

Quarks and leptons are probed to be elementary up to scales of 10^{-15} m or TeV.

Maybe substructure? Constituents = "preons". New strong gauge (metacolor) interaction of scale Lambda **Λ** is introduced.

Concept similar to Fermi's theory of beta decay.
Pati & Salam, PRD 10 (1974).



May address open questions:

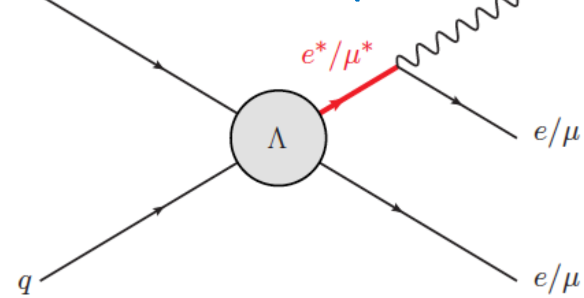
- Replication of SM families
- Their complex pattern of masses and mixing angles
- Large number of fundamental particles

[1] J. C. Pati, A. Salam, and J. A. Strathdee, "Are quarks composite?", Phys. Lett. B 59 (1975) 265
[2] H. Terazawa, M. Yasue`, K. Akama, and M. Hayshi, "Observable effects of the possible substructure of leptons and quarks", Phys. Lett. B 112 (1982) 387
[3] E. Eichten, K. D. Lane, and M. E. Peskin, "New Tests for Quark and Lepton Substructure", Phys. Rev. Lett. 50 (1983) 811
[4] U. Baur, M. Spira, and P. M. Zerwas, "Excited quark and lepton production at hadron colliders", Phys. Rev. D 42 (1990) 815

Search for Excited Leptons

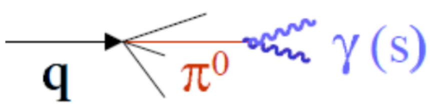
$$\mathcal{L}_{CI} \propto \frac{1}{\Lambda^2} j^{\mu} j_{\mu}$$

$\mathbf{\Lambda} = M_{e^*/\mu^*}$



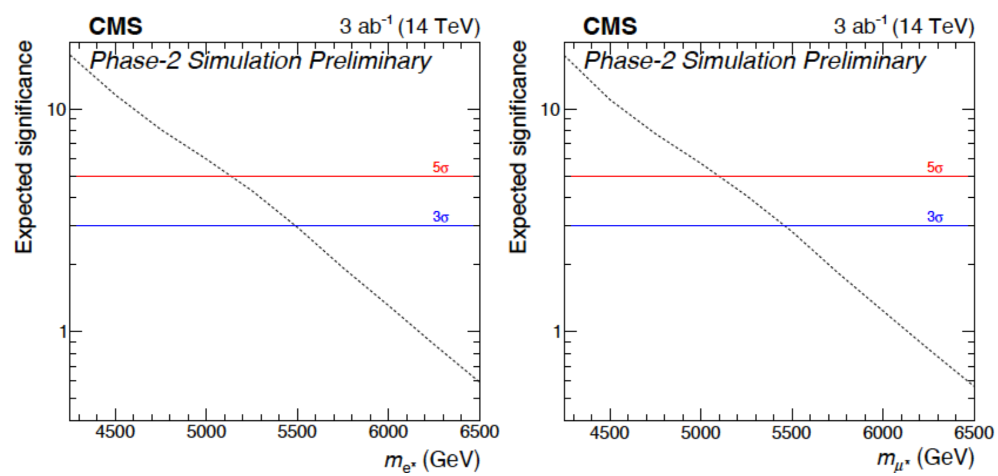
Backgrounds:

- Prompt photon background such as Z$\boldsymbol{\gamma}$, top pair+ $\boldsymbol{\gamma}$, WW+ $\boldsymbol{\gamma}$ … are estimated by MC
- Jet background: driven from data using a fake rate method



	Electron channel		Muon channel	
	Signal	Bkg	Signal	Bkg
Integrated luminosity	1.0%	1.0%	1.0%	1.0%
Lepton efficiency	0.5%	0.5%	0.5%	0.5%
Photon efficiency	2.0%	2.0%	2.0%	2.0%
PDF & scales	1.0%	5.0%	1.0%	5.0%
Summary of all backgrounds	-	25.0%	-	25.0%

1$\boldsymbol{\sigma}$ reach up to ~ M_{e^*/μ^*} = 6.2 TeV



CMS PAS FTR-18-029

Summary

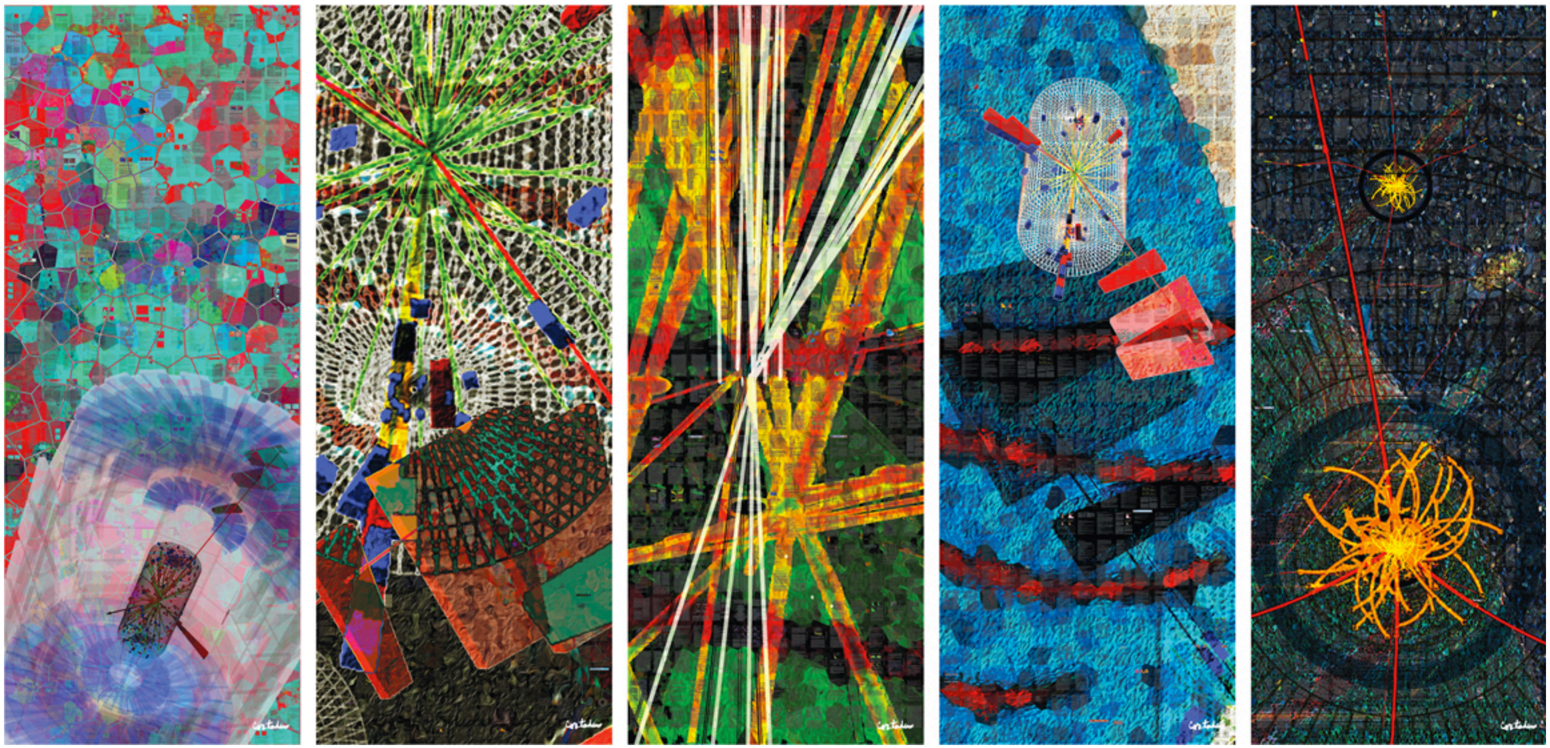
- HL-LHC:
  . excellent detectors,
  . advanced analyses,
  . progressed theoretical predictions

- Standard Model: High Precision Measurements

- Higgs: Many properties measurements will be improved

- BSM searches: Discover new physics or probe a large region of models parameter space

Thanks



Artwork by Xavier Cortada (with the participation of physicist Pete Markowitz),
"In search of the Higgs boson"

References and more information

- CMS Public Results:
  https://cms.cern/news/physics-results

- ATLAS Public Results
https://twiki.cern.ch/twiki/bin/view/AtlasPublic

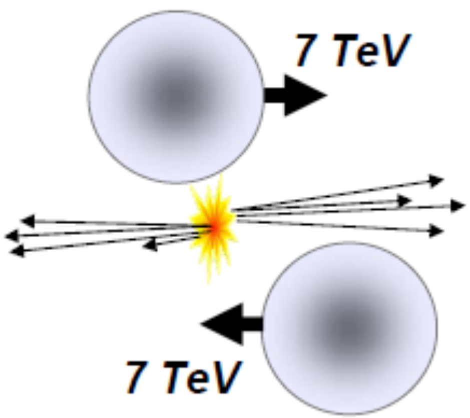
- I have benefited from some talks by CMS colleagues.

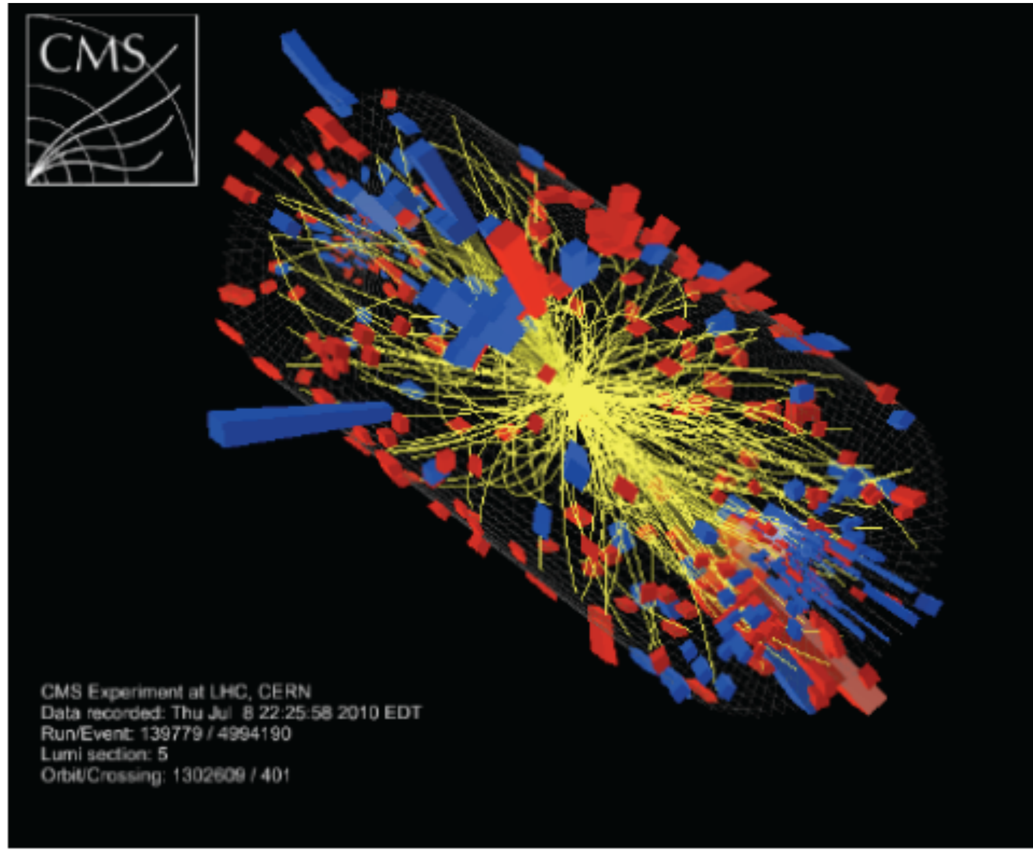
- A talk by A. Meyer.
- Talks by S. Dawson.
- A talk by J. Mnich.

Backup slides

Introduction: pp collisions

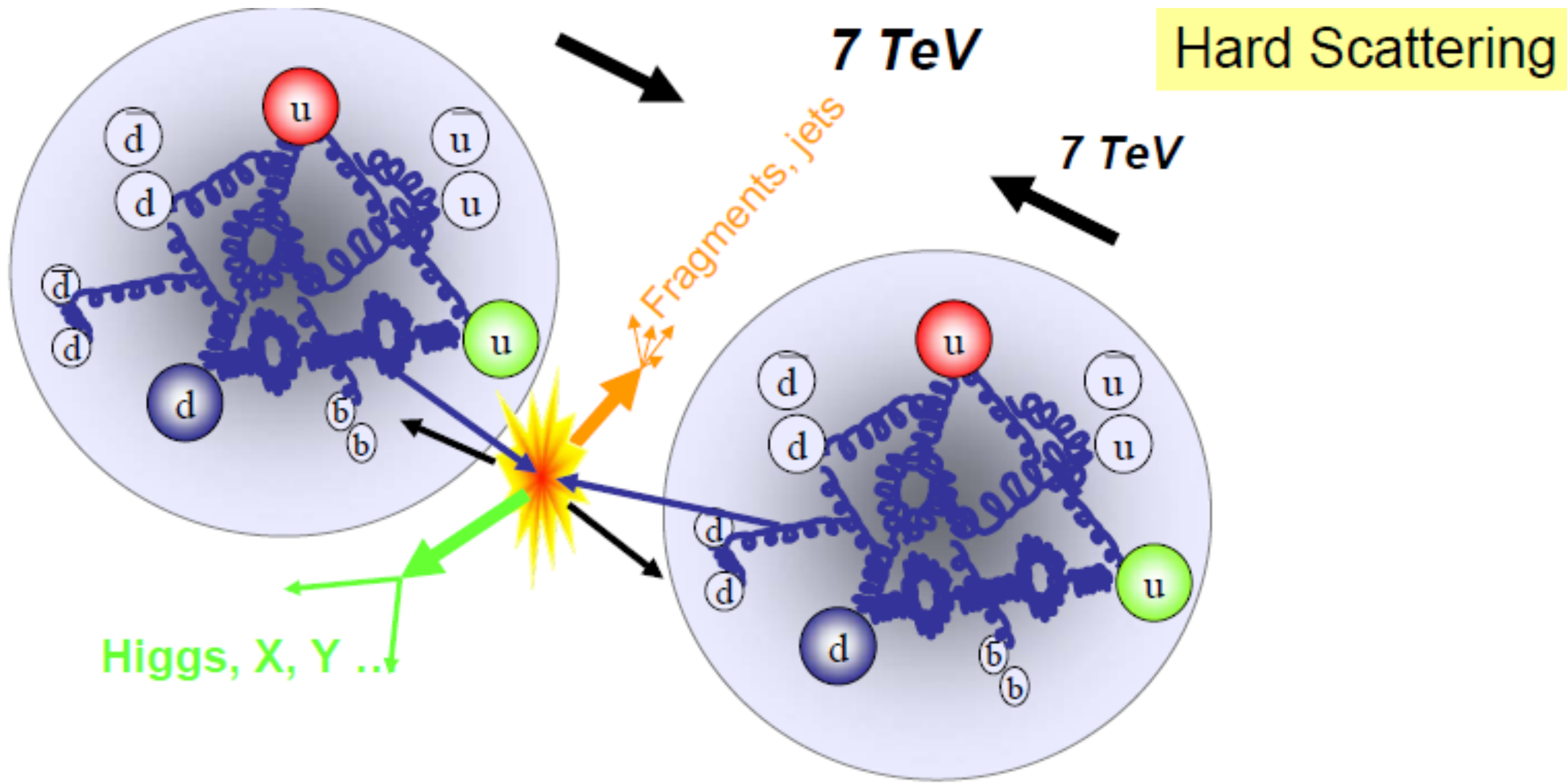
Soft Scattering





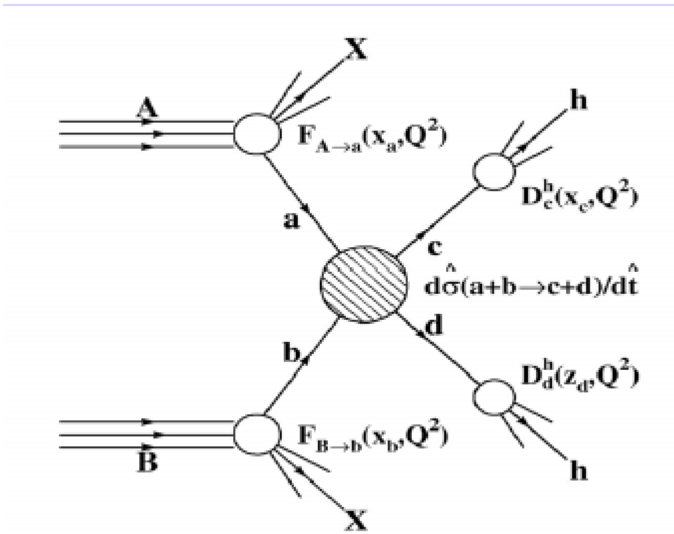
Peripheral collision events dominate
Most products along proton direction

Introduction: pp collisions

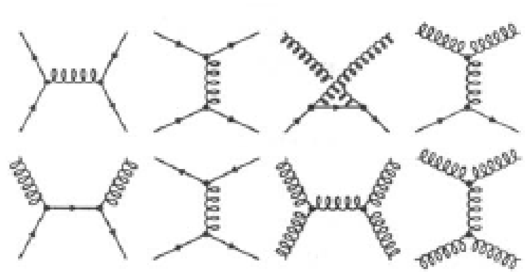


Gluon Fusion is dominant process
Does not need to be anti-proton
Hard scattering processes represent only a tiny fraction of the total inelastic pp cross section

Physics at Proton Colliders



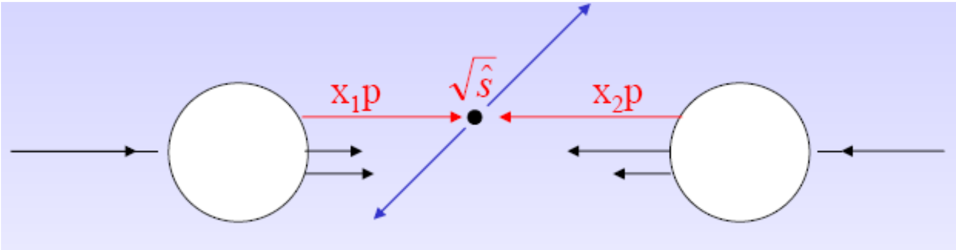
- Protons are composite, complex objects
  - partonic substructure
  - quarks and gluons
- Interesting hard scattering processes
  quark-(anti)quark
  quark-gluon
  qluon-gluon



However, hard scattering (high momentum transfer) processes are only a small fraction of the total cross section
- total inelastic cross section ≈ 70 mb (huge!)
- dominated by events with small momentum transfer

Proton-Proton Collisions

- **Proton beam can be seen as beam of quarks and gluons with a wide band of energies**
- **The proton constituents (partons) carry only a fraction $0 \leq x \leq 1$ of the proton momentum**



- **The effective centre-of-mass energy $\sqrt{\hat{s}}$ is smaller than $\sqrt{s}$ of the incoming protons**

$$\left.\begin{aligned} p_1 &= x_1\, p_A \\ p_2 &= x_2\, p_B \\ p_A = p_B &= 7\ \text{TeV} \end{aligned}\right\} \quad \sqrt{\hat{s}} = \sqrt{x_1\, x_2\, s} = x\,\sqrt{s} \quad (\text{if } x_1 = x_2 = x)$$

Note:
- **the component of the parton momentum parallel to the beam can vary from 0 to the proton momentum ($0 \leq x \leq 1$)**
- **the variation of the transverse component is much smaller (of order the proton mass)**

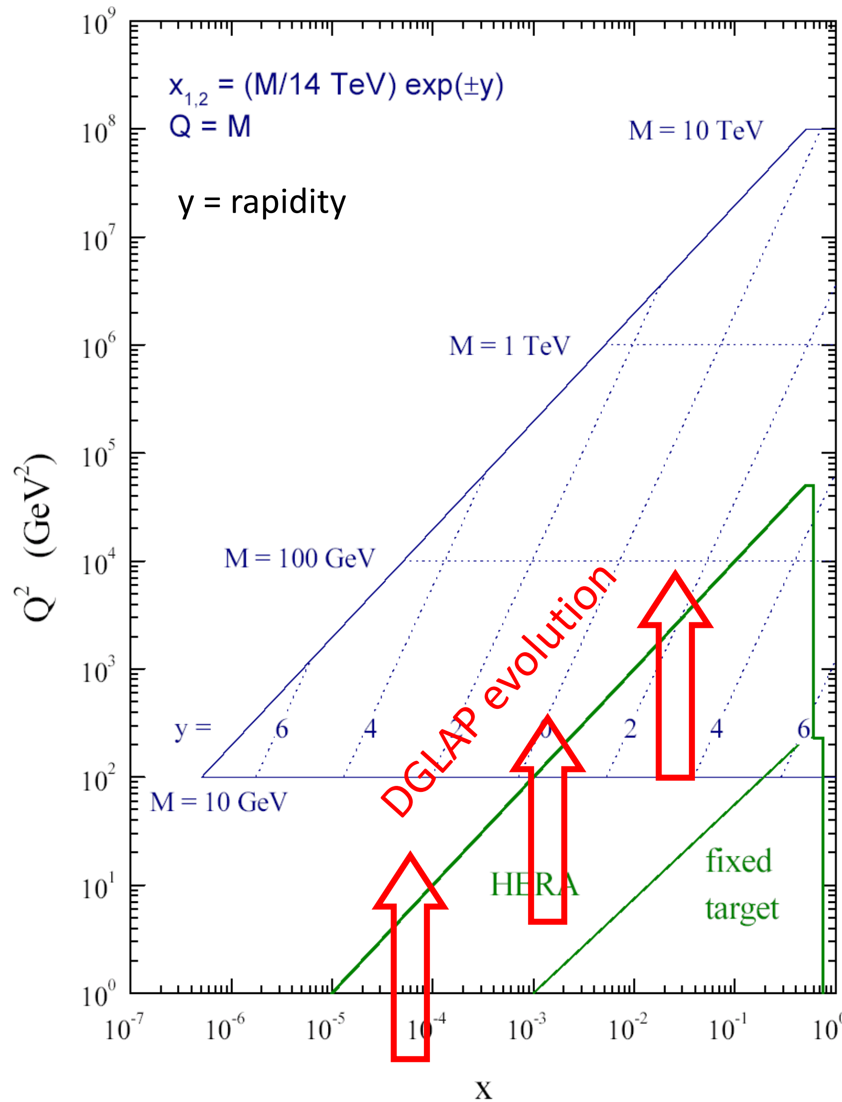
To produce a particle of mass		
mass	**LHC**	**Tevatron**
100 GeV	**$x \approx 0.007$**	**$x \approx 0.05$**
5 TeV	**$x \approx 0.36$**	**---**

Parton Density Functions at the LHC

LHC is a proton-proton collider

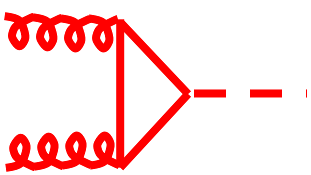
But fundamental processes are the scattering of

- **Quark – Antiquark**
- **Gluon – Gluon**
- **Quark – Gluon**



<u>Examples:</u>

$q\bar{q} \rightarrow W \rightarrow l\nu$



$gg \rightarrow H$

⇒ need precise PDF(x,Q²)
+ QCD corrections (scale)

Luminosity and event rate

Event rate = $\frac{dN}{dt} = \sigma \times \mathcal{L}$

Luminosity: $\mathcal{L} = \frac{n_1 n_2}{A} \times \frac{1}{f}$

Number of events over a period of time

$$N_{events} = \sigma \times \underbrace{\int \mathcal{L}\, dt}_{\text{Integrated luminosity}}$$

Integrated luminosity

$$N_{events} = \sigma \times \int \mathcal{L}\, dt \times \boldsymbol{\varepsilon}_A \times \boldsymbol{\varepsilon}_D$$

Detector Acceptance

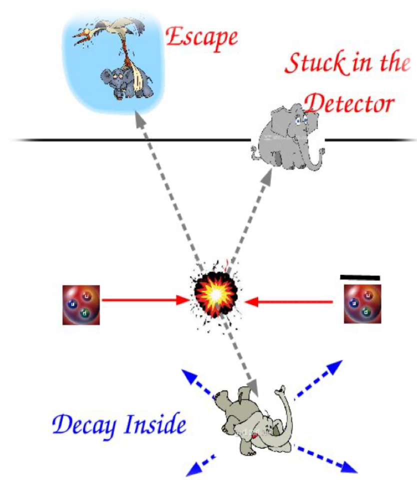
ID and Rec. Efficiency

In order to achieve the best sensitivity/discovery:

-Increase the integrated luminosity

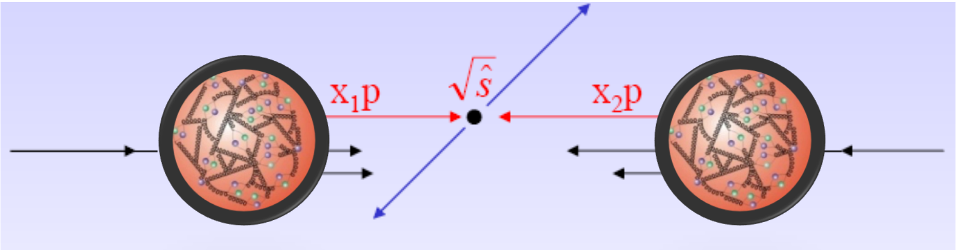
-Extend the detector coverage, i.e. higher $\boldsymbol{\varepsilon}_{\mathrm{A}}$ is welcome.

-Better detector performance, $\boldsymbol{\varepsilon}_{\mathrm{D}}$



Proton-Proton Collisions

- Proton beam can be seen as beam of quarks and gluons with a wide band of energies
- The proton constituents (partons) carry only a fraction $0 \leq x \leq 1$ of the proton momentum



- The effective centre-of-mass energy $\sqrt{\hat{s}}$ is smaller than $\sqrt{s}$ of the incoming protons

$$p_1 = x_1 p_A$$

$$p_2 = x_2 p_B$$

$$p_A = p_B = 7 \text{ TeV}$$

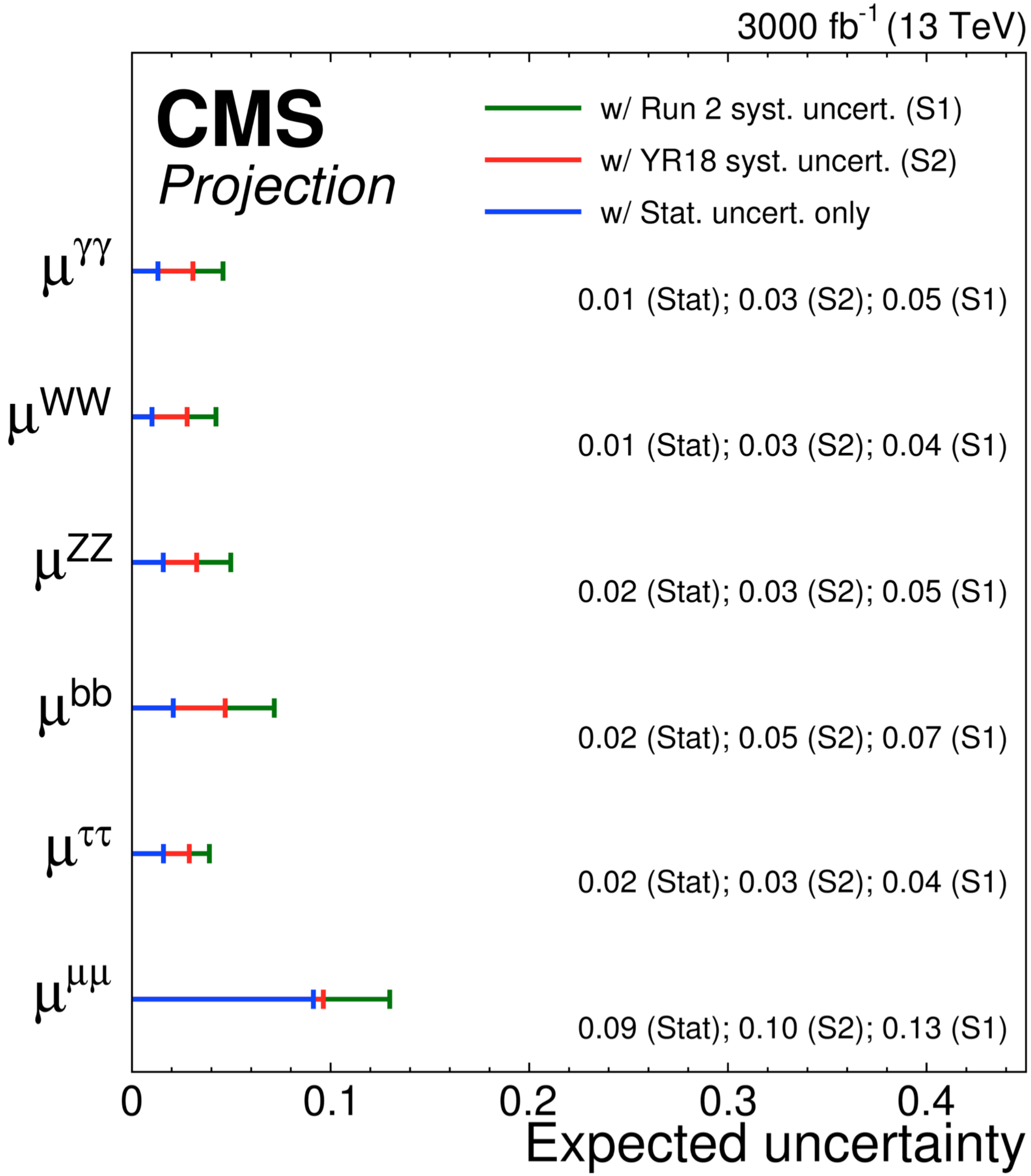
$$\sqrt{\hat{s}} = \sqrt{x_1 x_2 s} = x\sqrt{s}$$

$$(\text{if } x_1 = x_2 = x)$$

To produce a particle of mass		
mass	**LHC**	**Tevatron**
100 GeV	**$x \approx 0.007$**	**$x \approx 0.05$**
5 TeV	**$x \approx 0.36$**	**---**

Note:

- the component of the parton momentum parallel to the beam can vary from 0 to the proton momentum ($0 \leq x \leq 1$)
- the variation of the transverse component is much smaller (of order the proton mass)



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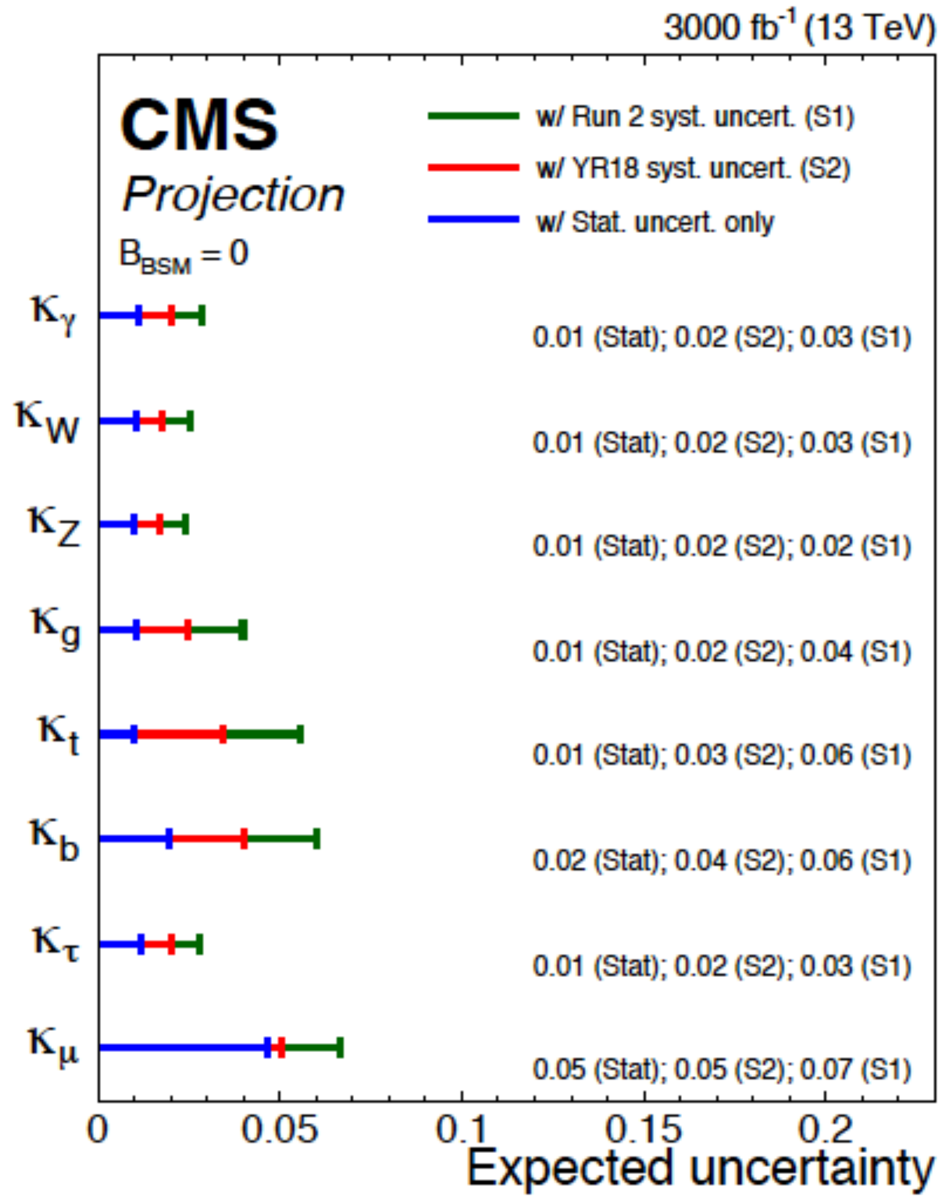
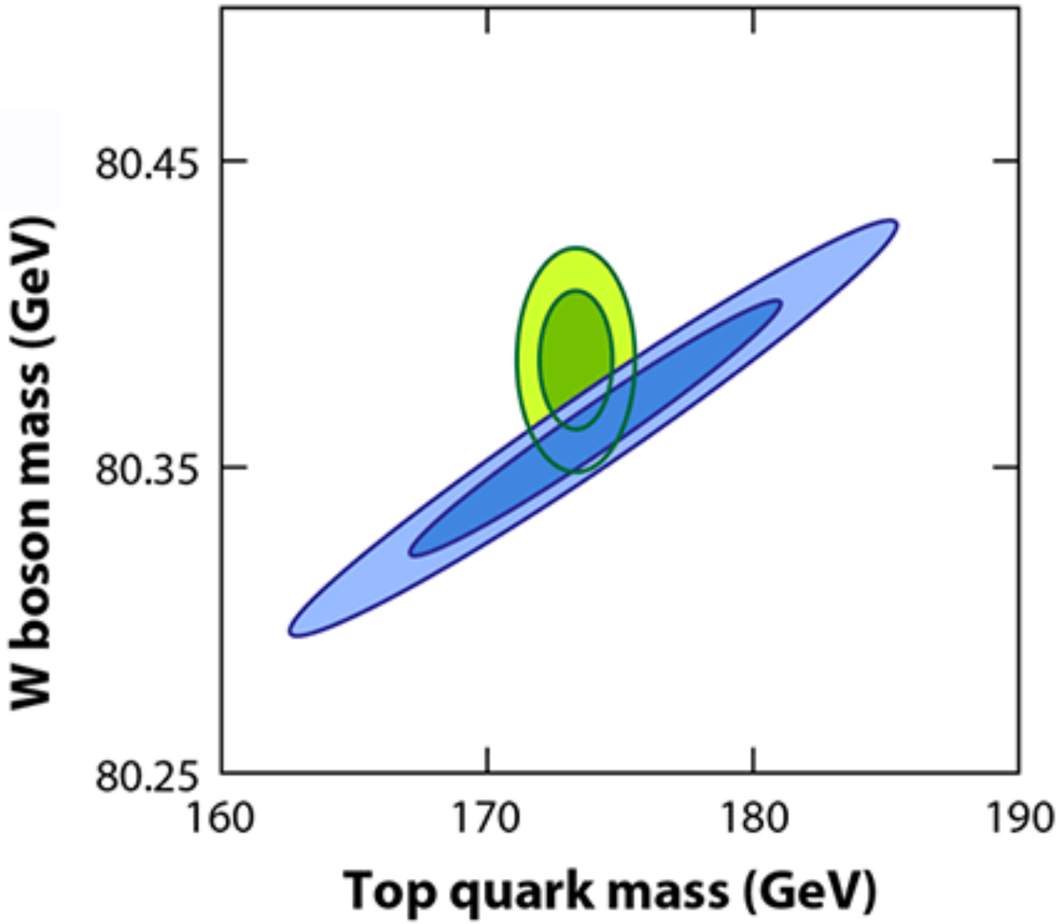


κ: 2-4%, κ_μ ~5%

CMS FTR-18-011



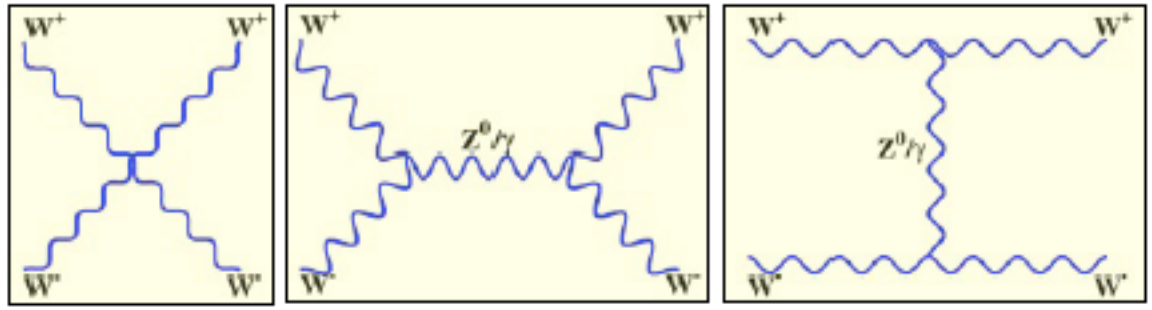
80.45
80.35
80.25
W boson mass (GeV)
160
170
180
190
Top quark mass (GeV)

WW Scattering and Unitarity Violation

پژوهشگاه دانش‌های بنیادی

$F_{\mu\nu}F^{\mu\nu}$-term contains self couplings between gauge bosons.

∴ WW ➔ WW possible; cross section:



massive gauge bosons: 2 transverse d.o.f. + 1 longitudinal d.o.f.
massless gauge bosons: 2 transverse d.o.f.

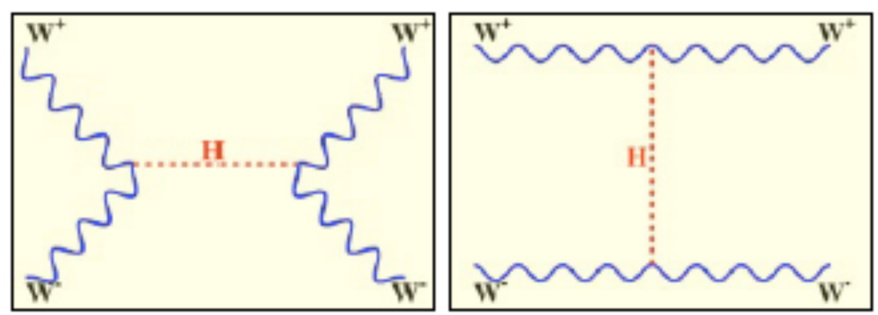
$$\sigma_{W_L W_L} \sim E_{cm}^2$$

$W_L W_L$ scattering probability becomes larger than unity for $E_{cm} > 1.2$ TeV ...
Violation of unitarity if force remains weak at this scale ...

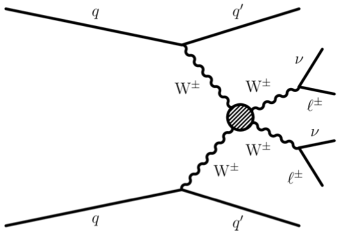
To restore unitary it needs some scalar boson "H" with

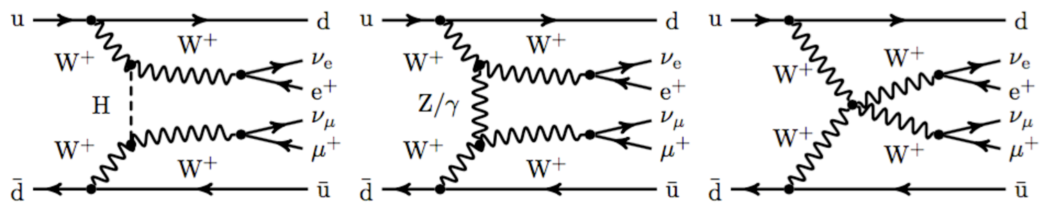
$$\left.\begin{array}{ll} g_{HWW} & \sim M_W \\ g_{Hff} & \sim m_f \\ M_H & < 1\ \text{TeV} \end{array}\right\} \quad \sigma \rightarrow \text{const}$$

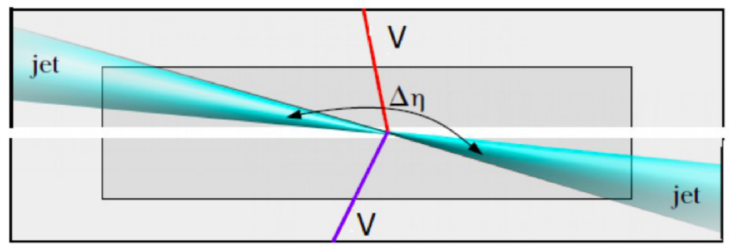
for large energies

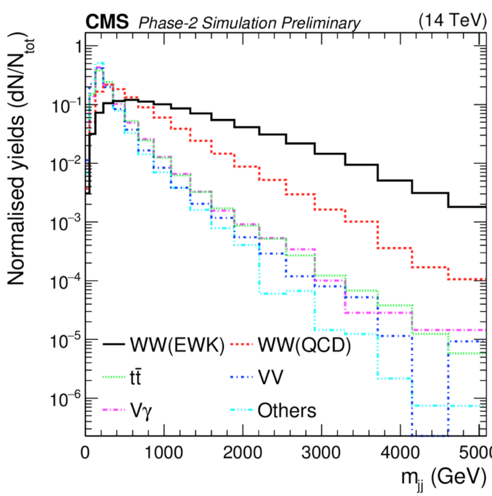


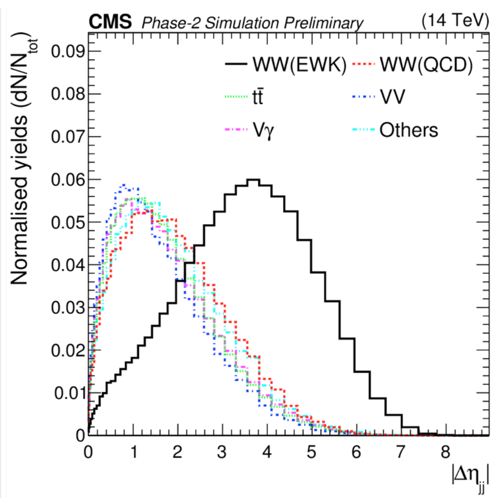
Vector boson scattering

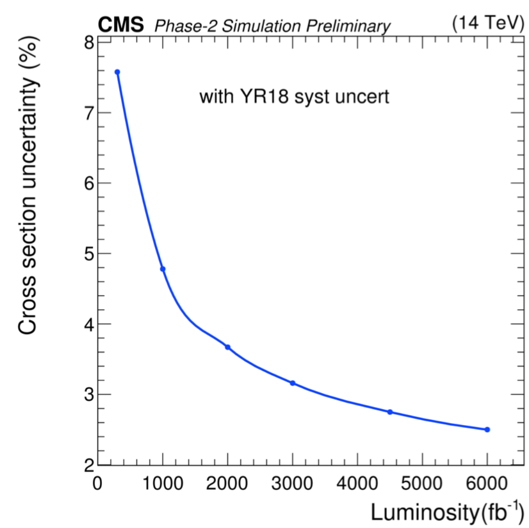












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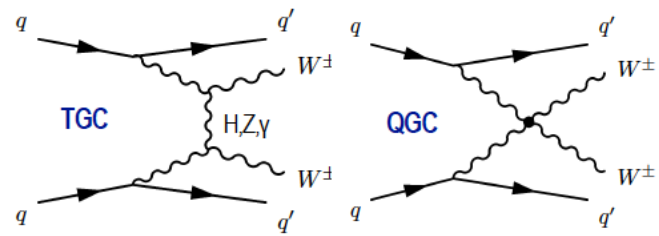
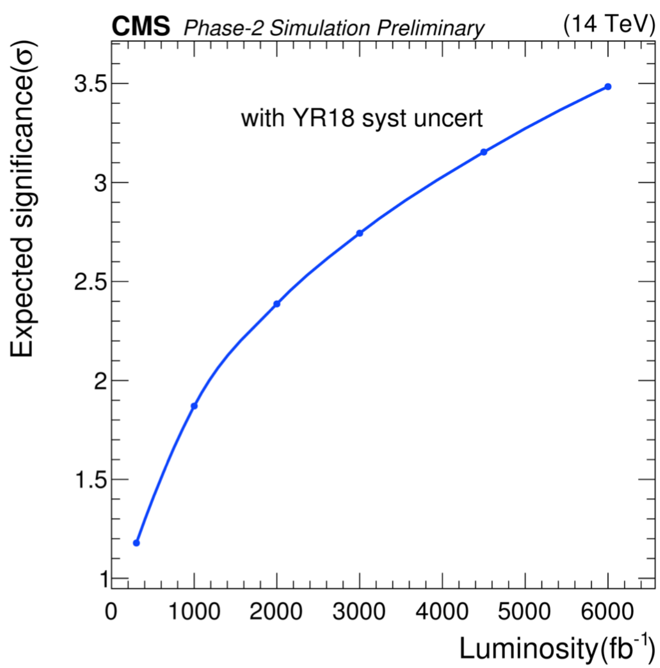
Longitudinal Vector Boson Scattering

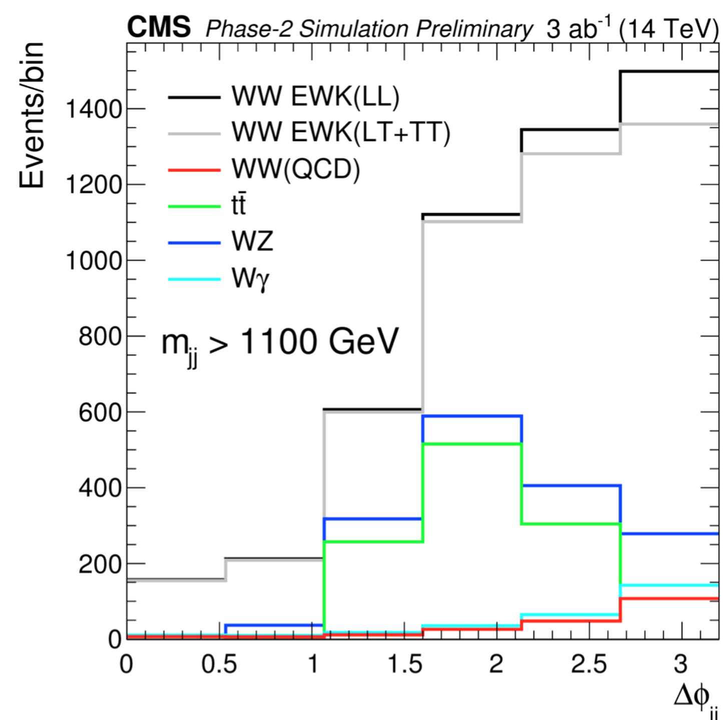
- Unitarization of $V_L V_L \rightarrow V_L V_L$ cross section at TeV scale:

  - Higgs boson and/or new physics to cancel divergence.

- Direct probe of EW-symmetry breaking mechanism
- At HL-LHC, forward detectors and acceptance will improve.







Need future collider!

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