Electroweak symmetry breaking

Search for the missing piece of the Standard Model III

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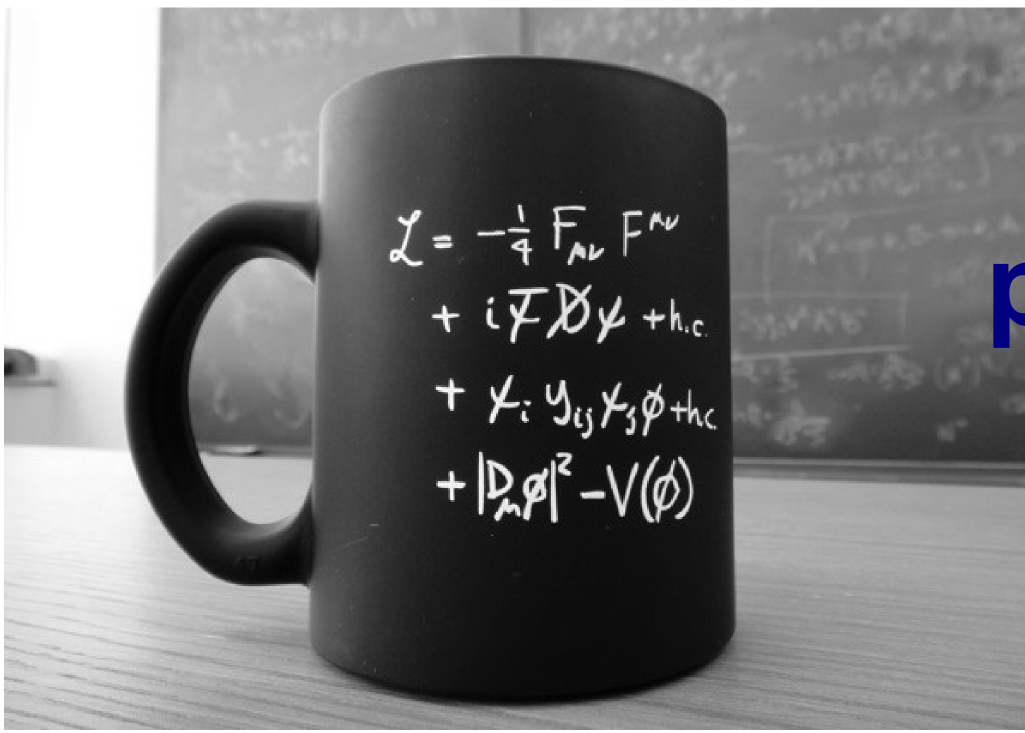
Plan for today

Summary of previous lectures

VV scattering

Searching for deviations in VV scattering



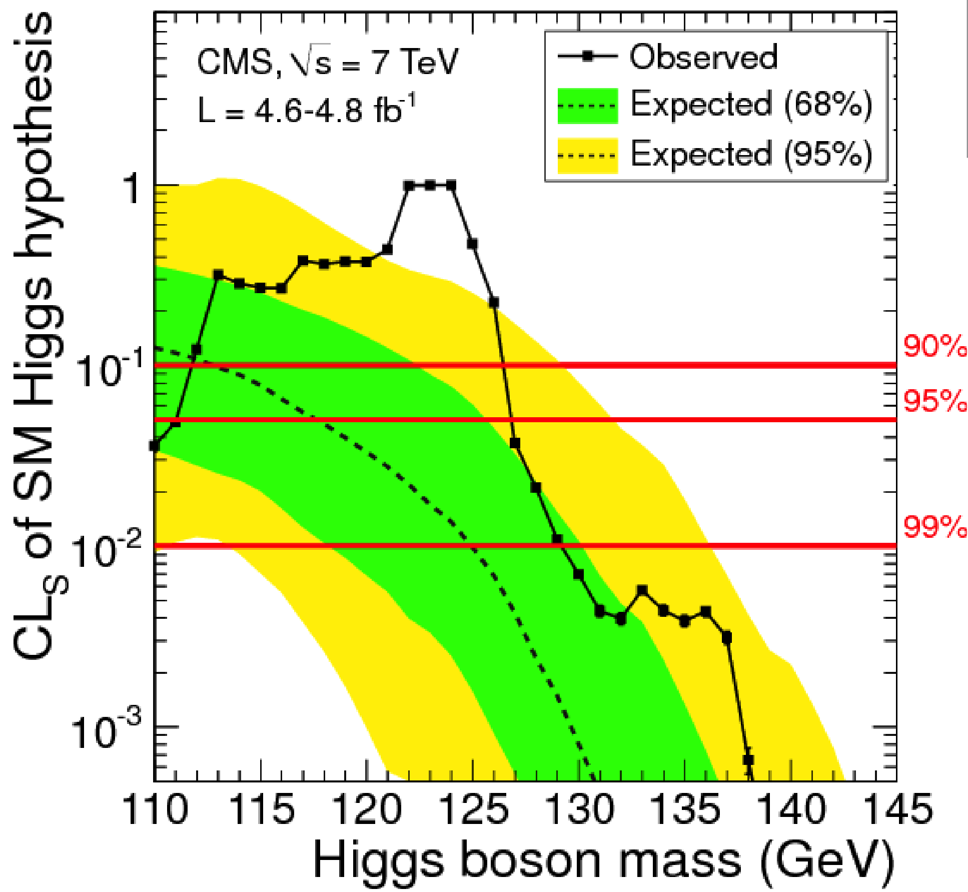
Summary of the previous lectures

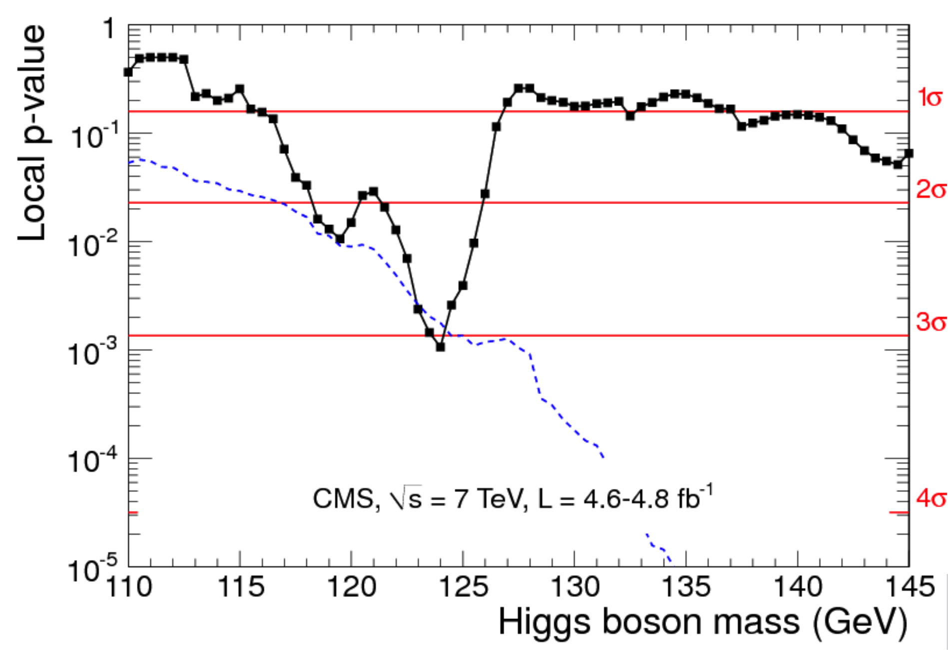
Close to conclusion?

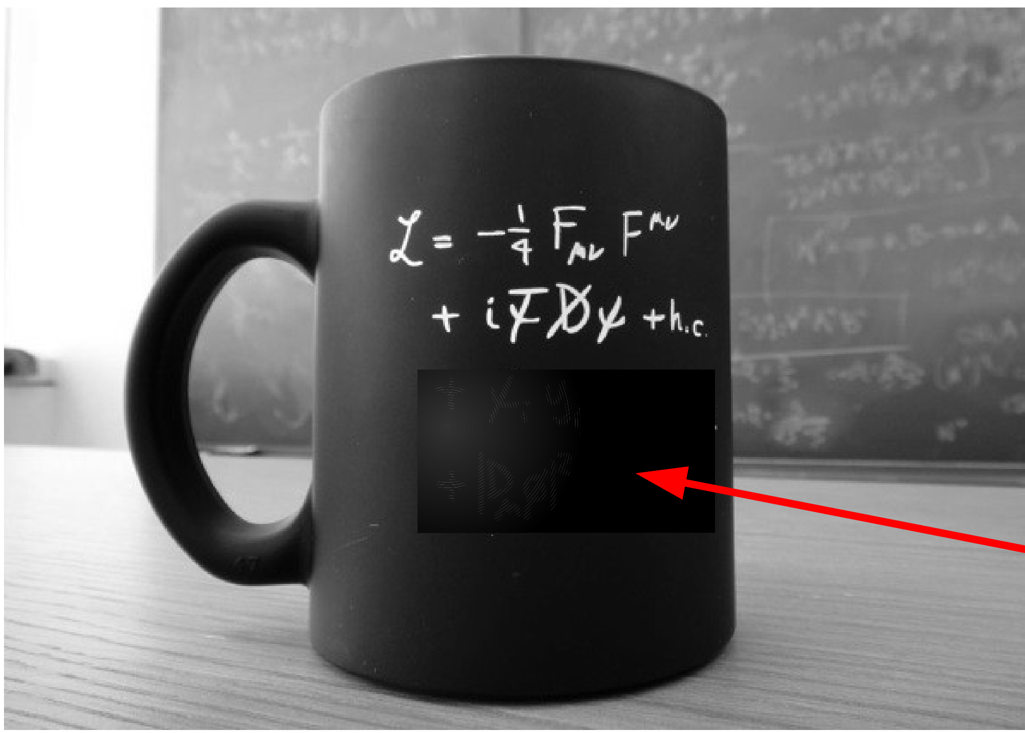
- With 2011 data we have excluded most of the Higgs mass range
- Except where it is most favored to be found: m_H<127GeV/c^2
- No combined limit between ATLAS and CMS until individual discovery or exclusion
- Observe an excess in the full mass range which as been searched:

  ATLAS 10% probability (in 110-146 GeV)

  CMS 2.1σ local significance (in 110-145 GeV)





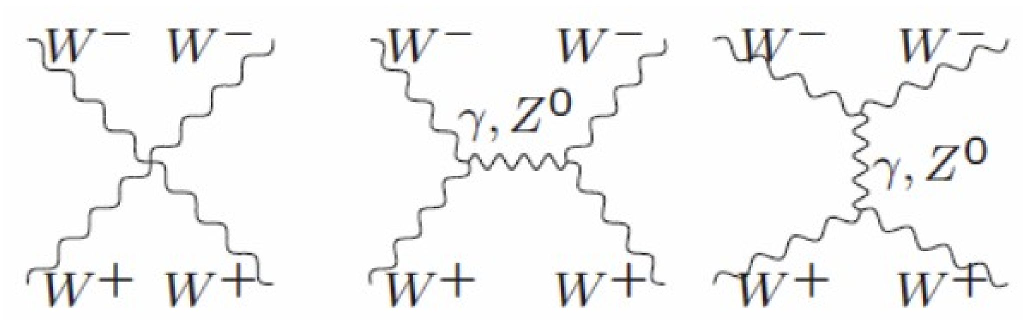


VV scattering

let's take one step back

What's special about vector boson scattering

- It's the **key process to understand the EWK symmetry breaking mechanism**

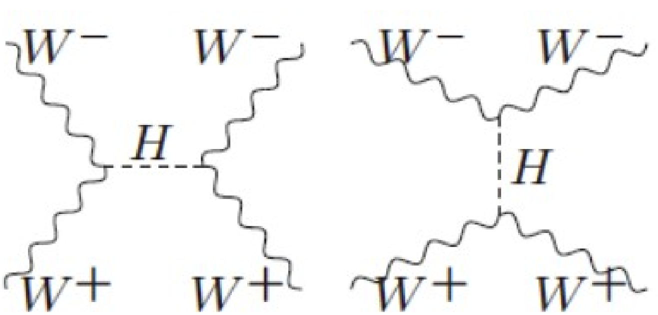


$$M_{gauge} = -\frac{g^2}{4M_W^2}(4 - \frac{3}{\rho})u + \ldots$$

with, $u = -\frac{s}{2}(1 + \cos\theta)$

$\rho = (M_W^2/M_Z^2)\cos^2\theta_W$

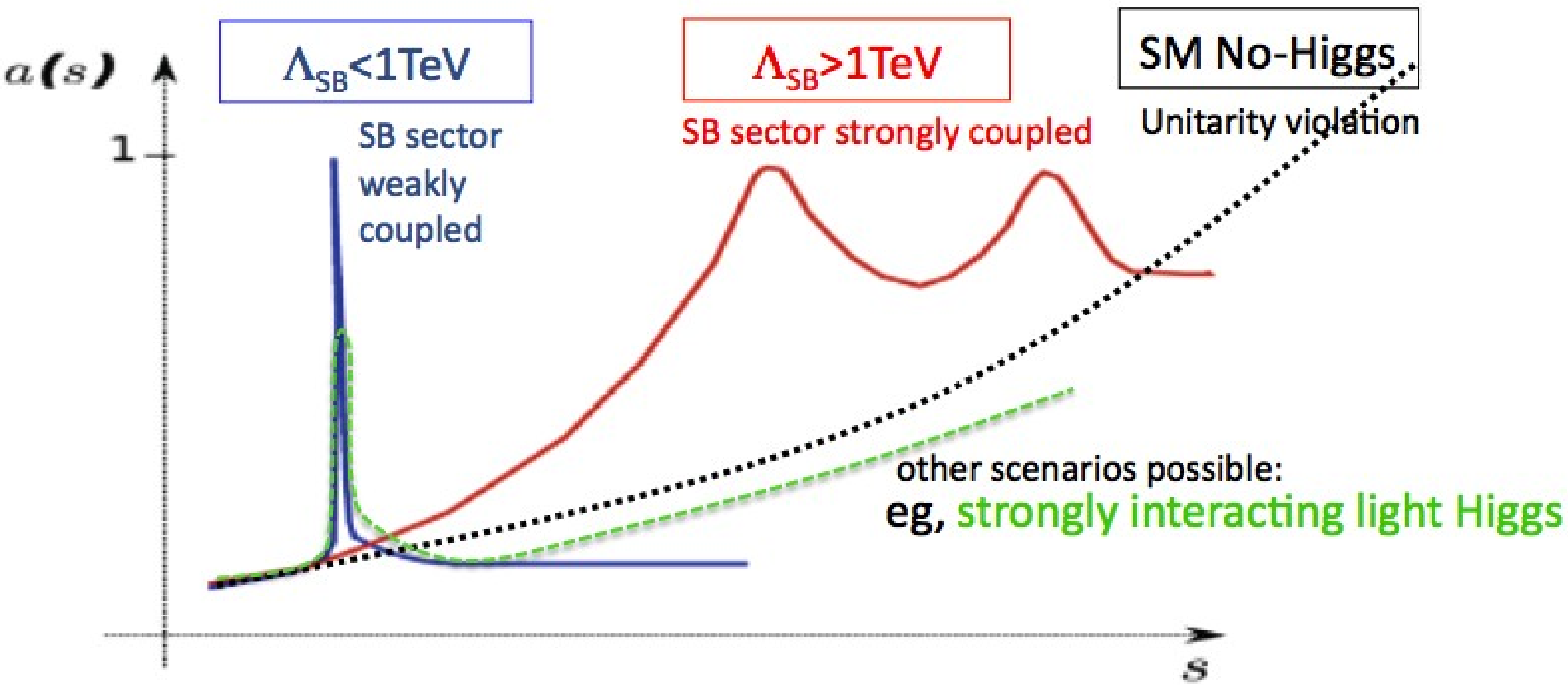
- **Unitarity is restored by introducing a new scalar field:**



$$M_{Higgs} = \frac{g^2}{4M_W^2}u + \ldots$$

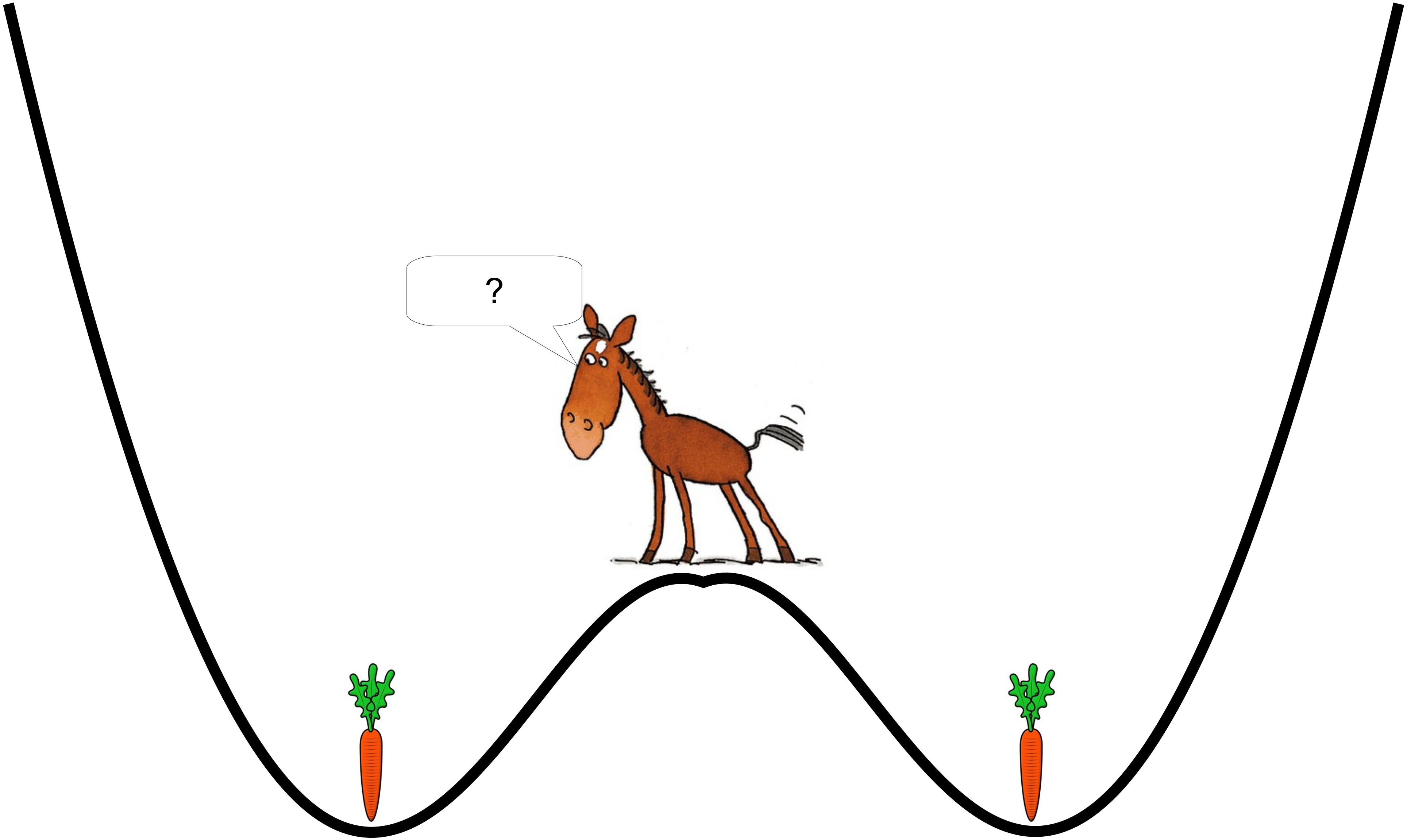
What's special about vector boson scattering - 2

- **If the SM Higgs is there**
  - the VV spectrum will be resonant
  - probe effectively the full mass range
- **If no Higgs is found**:
  - will interact strongly at $\Lambda \approx 1$ TeV
  - observe deviation from SM prediction



Whether the Higgs exists or not, VV scattering deserves dedicated study

Introducing the Higgs mechanism



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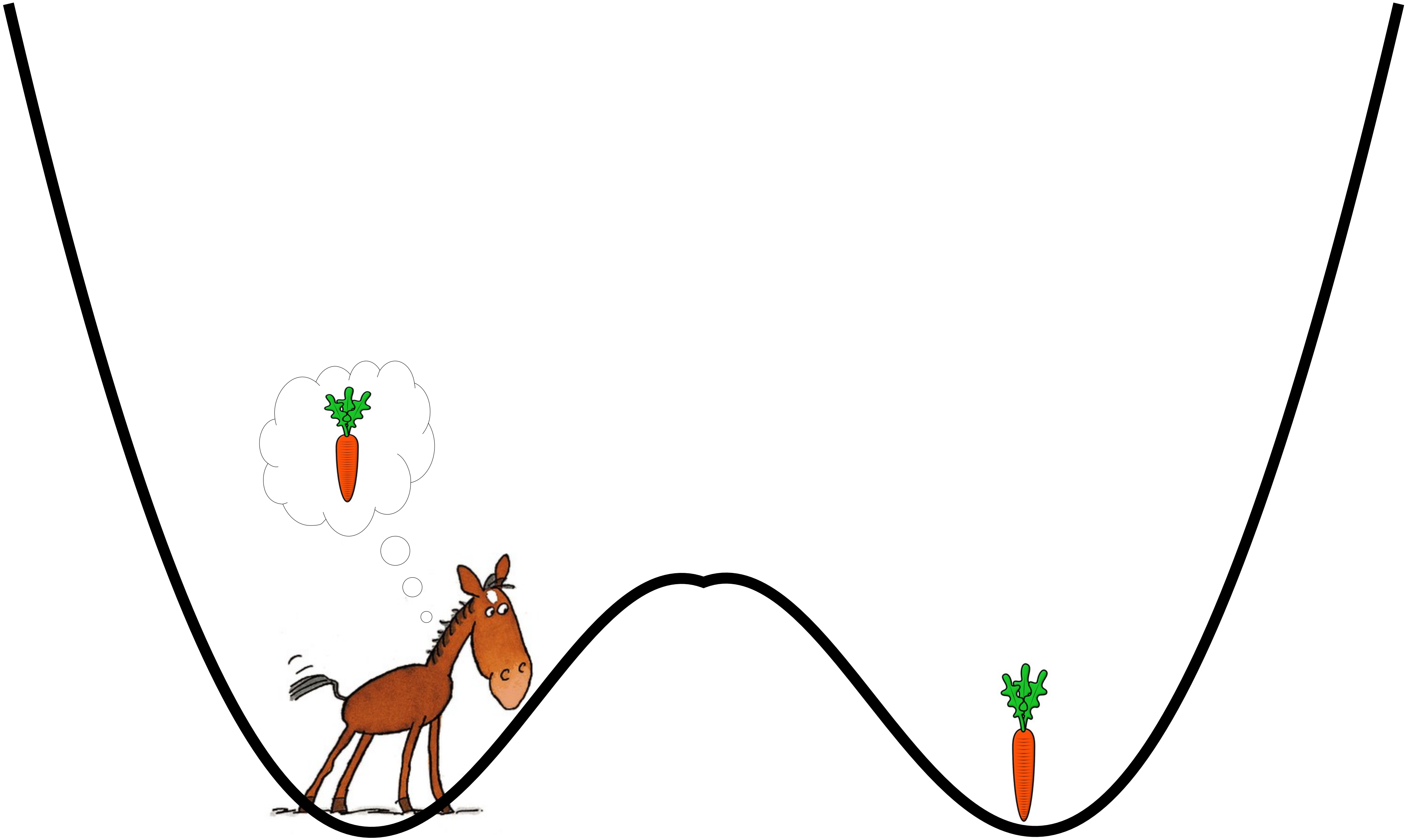

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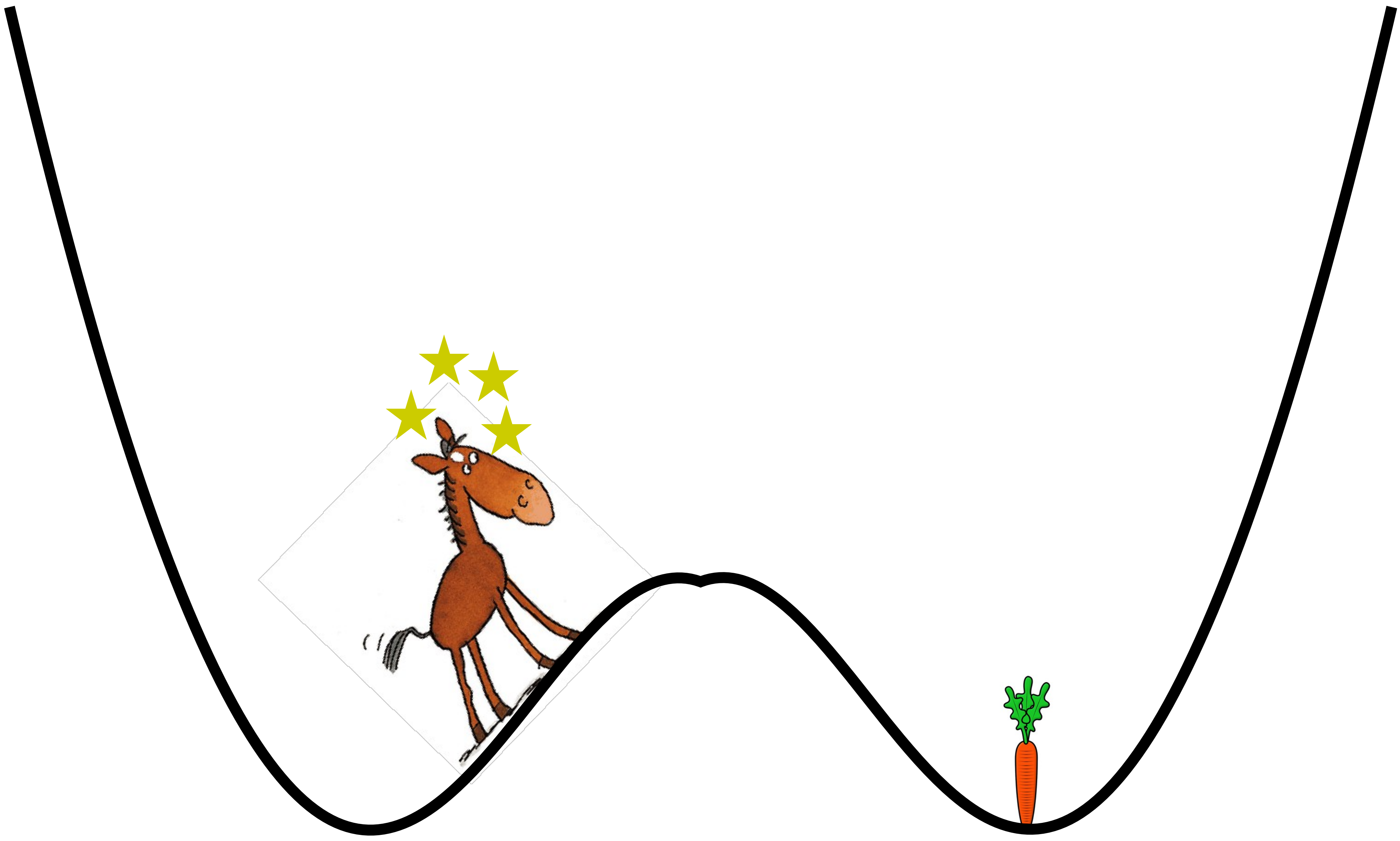
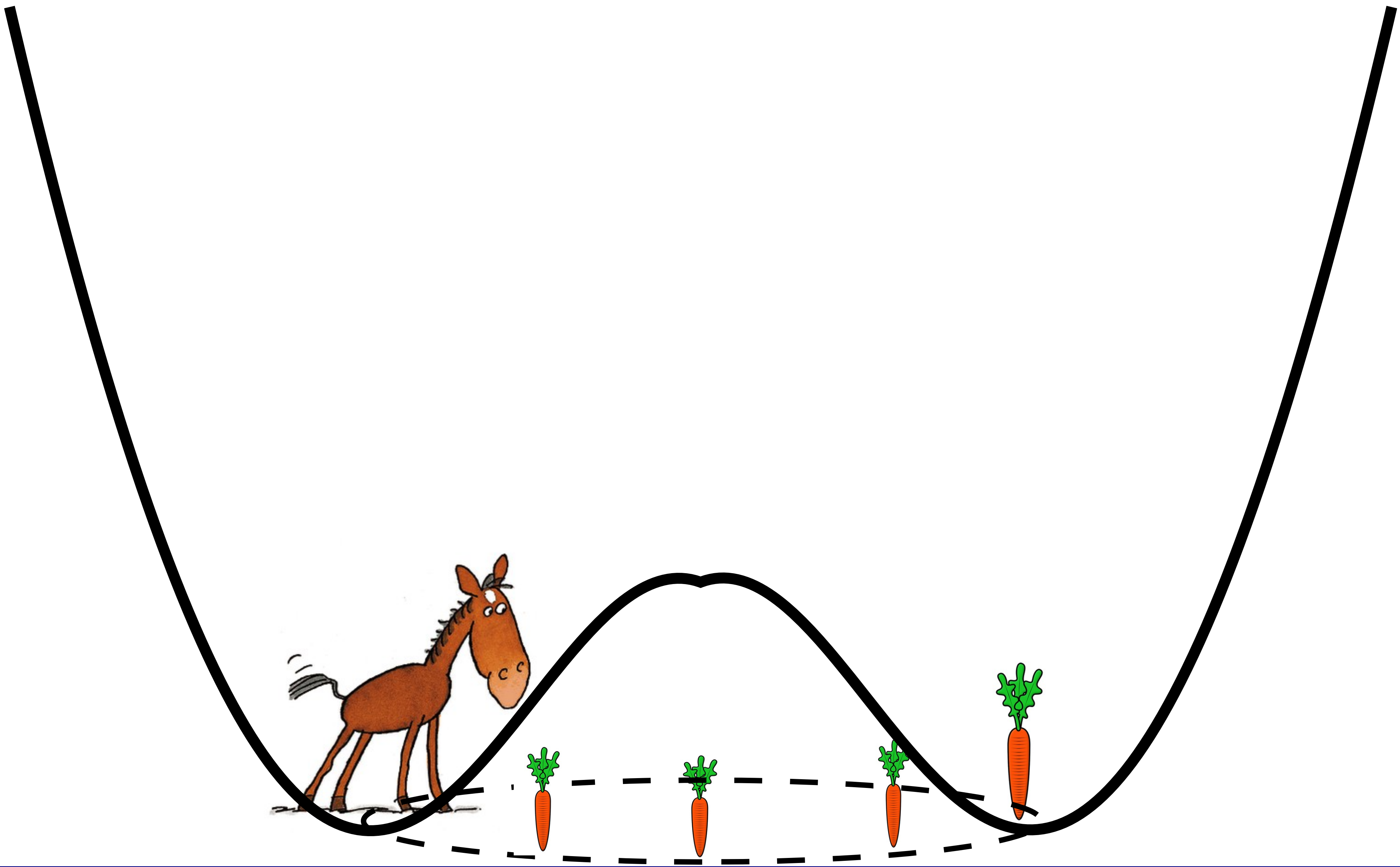
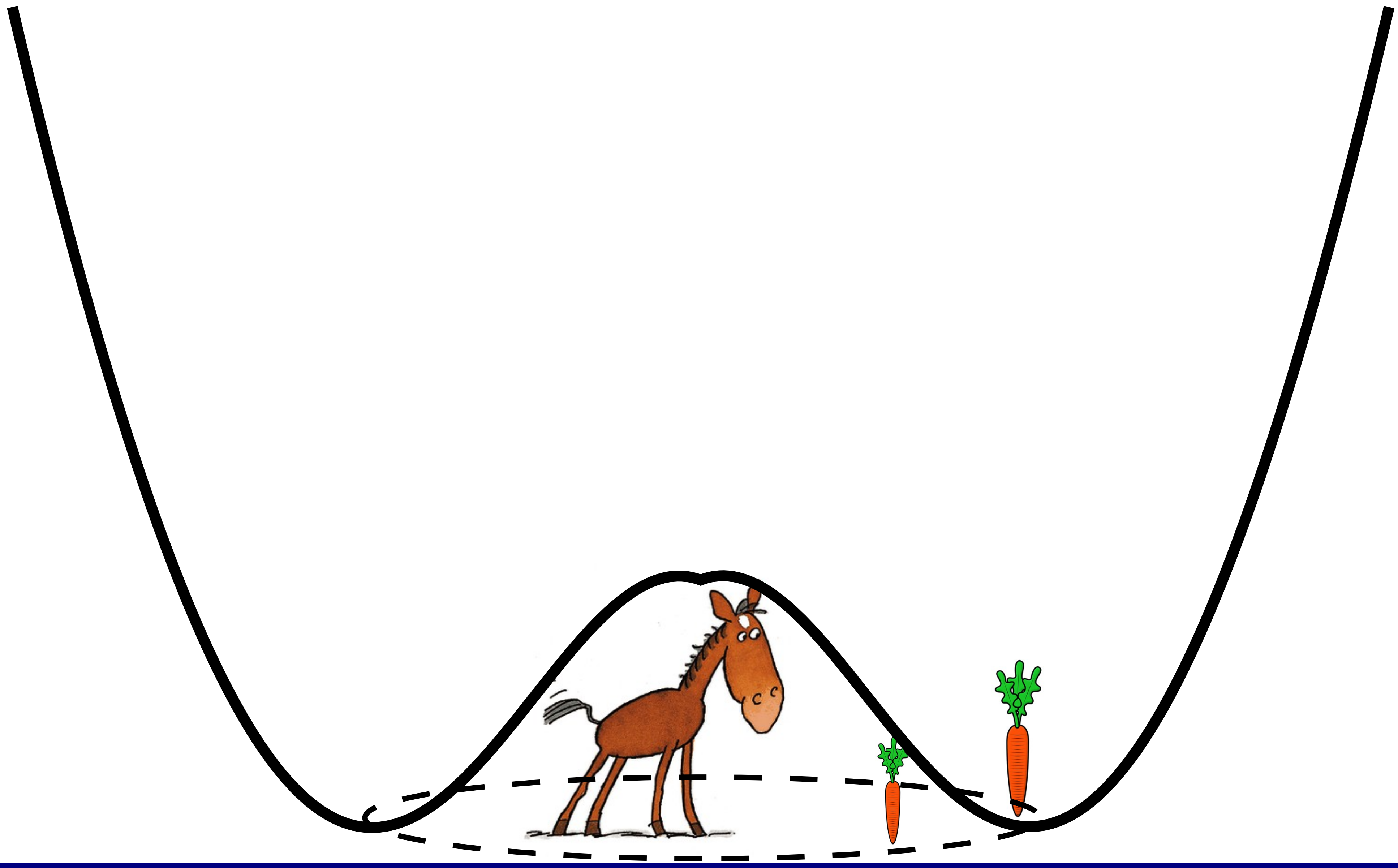


Introducing the Higgs mechanism



Introducing the Higgs mechanism



Goldstone bosons

- **Picture an infinite straight rope** (it has translation invariance)
  - break its translational invariance in directions perpendicular to it

$$\frac{1}{c^2}\frac{\partial^2\phi}{\partial t^2} = \frac{\partial^2\phi}{\partial x^2} \qquad \rightarrow w^2 = c^2\, k^2$$

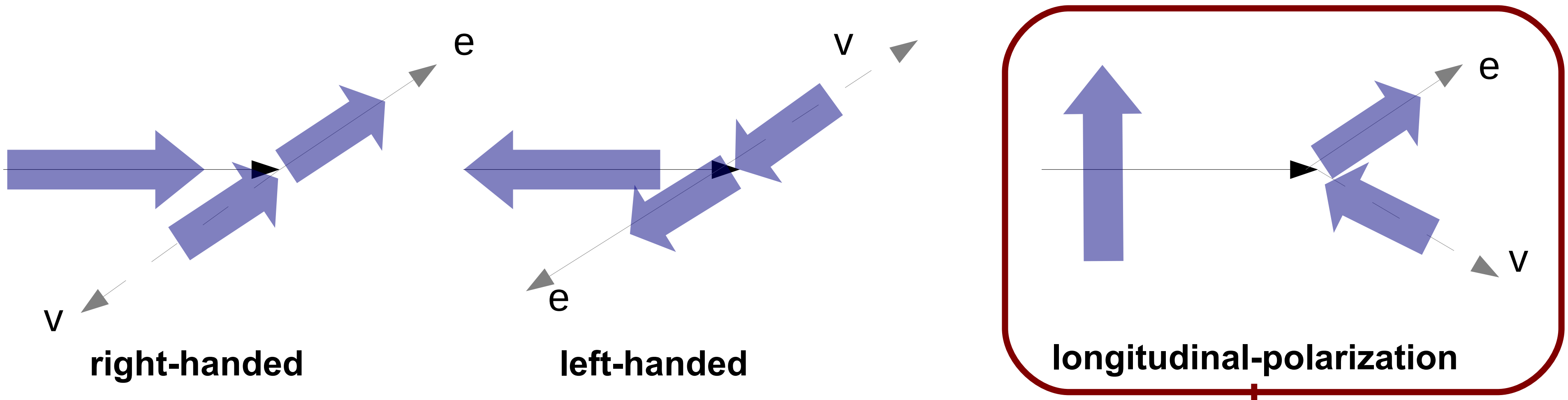
  - the transverse waves are the Goldstone modes
  - Waves can propagate with arbitrary frequency

    → after quantization will generate massless particles

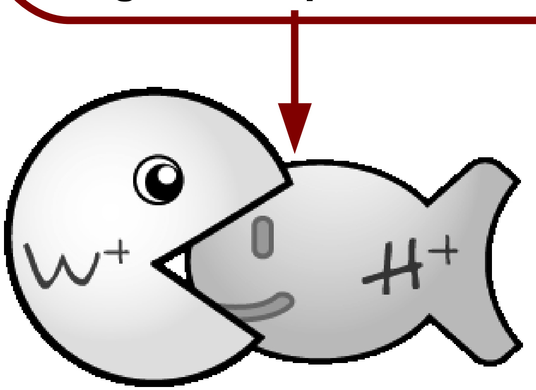
- **EWK ground state / the vacuum is said to be "spontaneously broken"**
  - A spontaneously broken symmetry always produces a massless scalar particle.
  - If the symmetry is approximate, the particle won't be massless, but can be very light.

Vector bosons at high energy

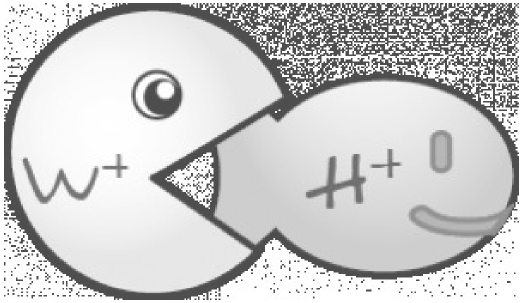
- **In the limit $m_W/s^{1/2} \rightarrow 0$ and $m_Z/s1^{/2} \rightarrow 0$**
  - the mass can be neglected, vector bosons acquire large boost
  - W/Z become effectively goldstone bosons because longitudinal polarization dominates
- Pictorially:



- **The longitudinal component corresponds in practice to a "swallowed" goldstone bosons ►**



Vector bosons at high energy



- At high $s^{1/2}$ the longitudinal component becomes dominant
- Vector bosons are in practice goldstone bosons
  - The fields can be generically written as: $U = exp\left(i\frac{\omega^\alpha \tau^\alpha}{u_v}\right)$
  - Behavior is purely chiral
  - The Lagrangian of interactions is given by:

W field — Vacuum expectation value — Pauli matrices

$$\mathcal{L}_{EWChL} = \mathcal{L}^{(2)} + \mathcal{L}^{(4)} + \ldots = \frac{u^2}{4} Tr\{D_\mu U D^\mu U^\dagger\} + \alpha_4 \left(Tr\{D_\mu U D^\mu U^\dagger\}\right)^2 + \alpha_5 \left(Tr\{D_\mu U D^\nu U^\dagger\}\right)^2$$

Kinematic term

Terms that do not introduce anomalous triple gauge couplings

- Different choices of α_4 and α_5 correspond to different models of the strongly interacting electroweak breaking sector

Electroweak Chiral Formalism

- In this approximation the global symmetry is now $SU(2)_{L+R}$

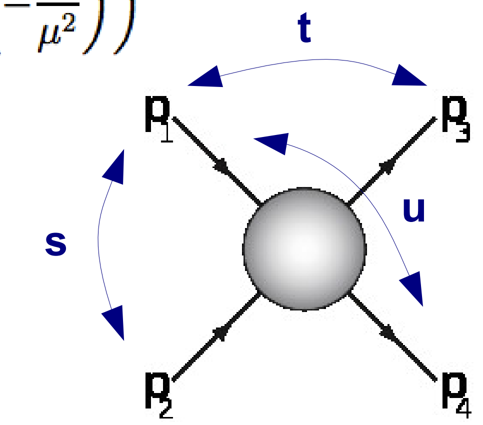
- The scattering amplitude is generically written as:

$$\mathcal{M}(V_L^a V_L^b \to V_L^c V_L^d) \equiv A(s,t,u)\delta^{ab}\delta^{cd} + A(t,s,u)\delta^{ac}\delta^{bd} + A(u,t,s)\delta^{ad}\delta^{bc}$$

with the amplitude given generically by:

$$\begin{aligned} A(s,t,u) &= \frac{s}{u^2} + \frac{1}{4\pi u^4}\left(2\alpha_4(\mu)s^2 + \alpha_5(\mu)(t^2+u^2)\right) + \\ &+ \frac{1}{16\pi^2 u^4}\left(-\frac{t}{6}(s+2t)\log\left(-\frac{t}{\mu^2}\right)\right) - \\ &- \frac{1}{16\pi^2 u^4}\left(\frac{u}{6}(s+2u)\log\left(-\frac{u}{\mu^2}\right) - \frac{s^2}{2}\log\left(-\frac{s}{\mu^2}\right)\right) \end{aligned}$$

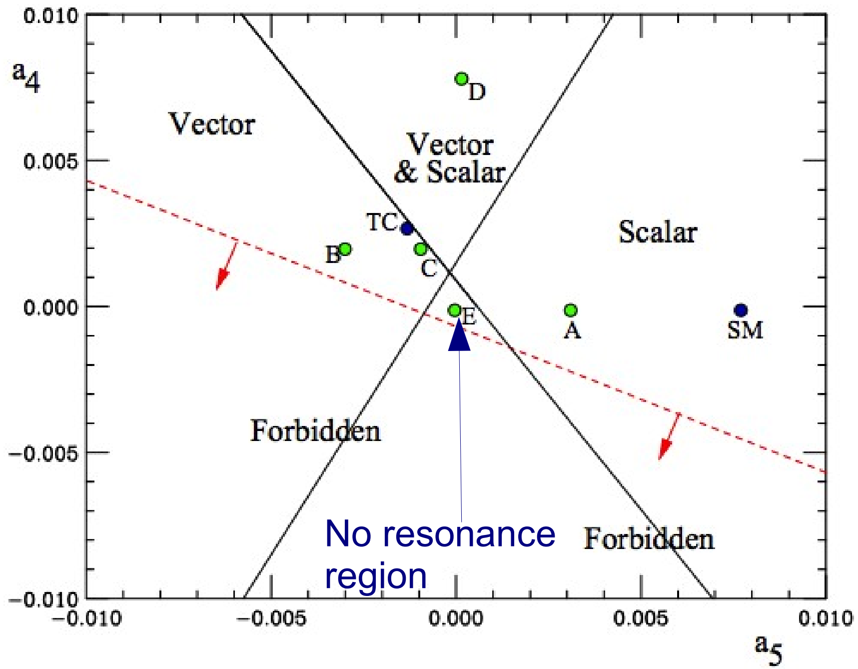
- Note: s,t,u are the classic Mandelstam variables ►
  - for WW scattering $s+t+u=4M_W^2$



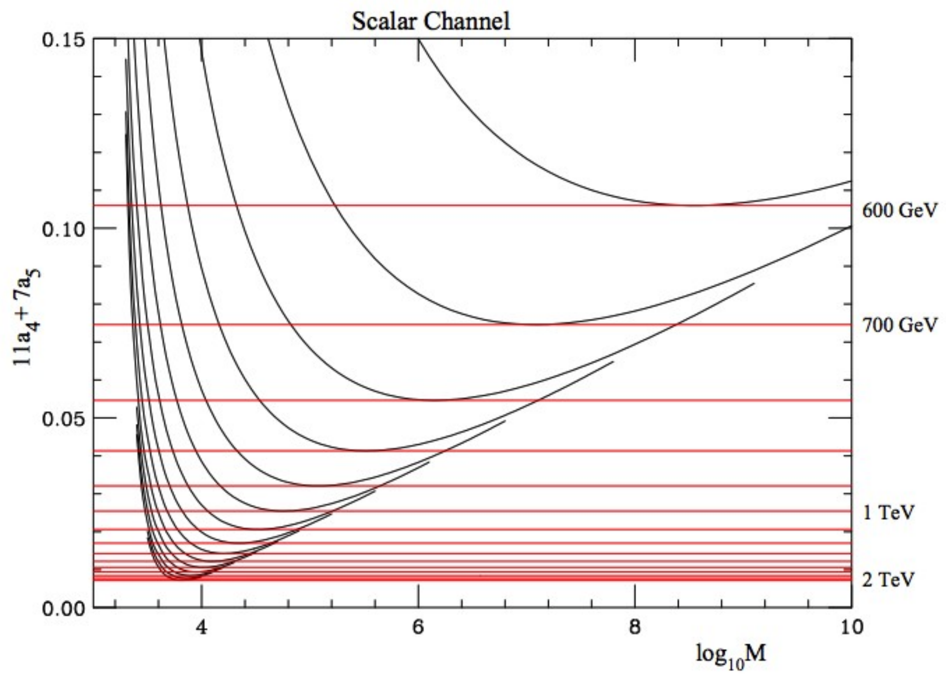
WW scattering in EWKchL formalism

- **The amplitude is now given by:** $\mathcal{M}(W_L^{\pm}W_L^{\pm} \to W_L^{\pm}W_L^{\pm}) = A(t,s,u) + A(u,t,s)$
- A unitarization procedure has to be performed otherwise it will diverge
- Two approaches followed (see details in Butterworth et al aXiv:hep-ph/0201098)

Pade protocol: Im A = $|A|^2$ is implied by elastic untiarisation for s>0.



N/D protocol: besides ensuring partial wave unitarity and matching 1-loop EWKchL computation. Constraints are imposed in the Numerator/Denominator of the partial waves



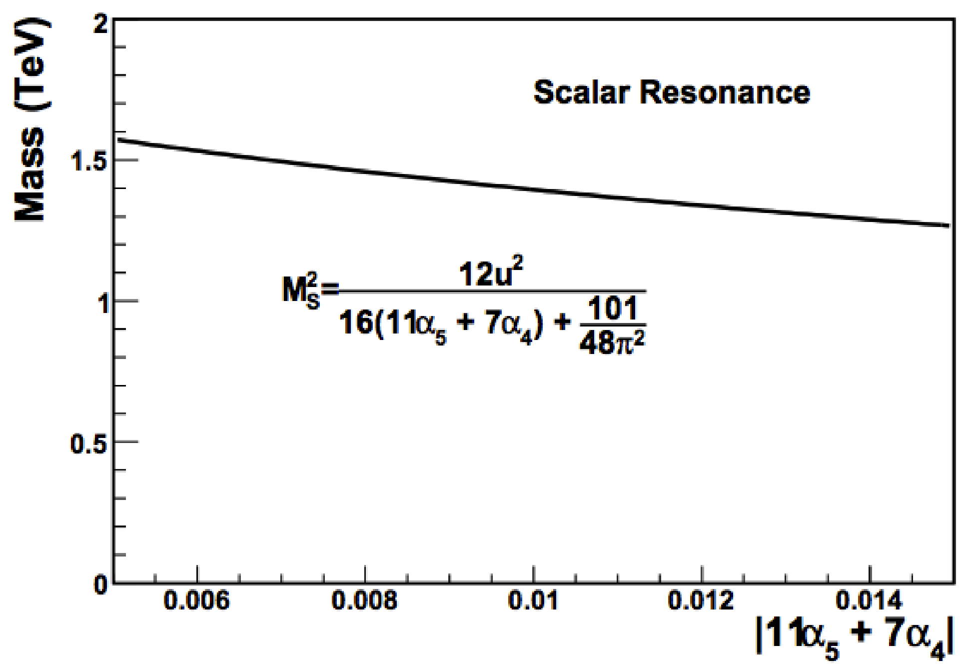
Partial waves may lead to resonances (scalar, vectorial, tensorial)→ play similar role to Higgs

Examples in the Padé protocol

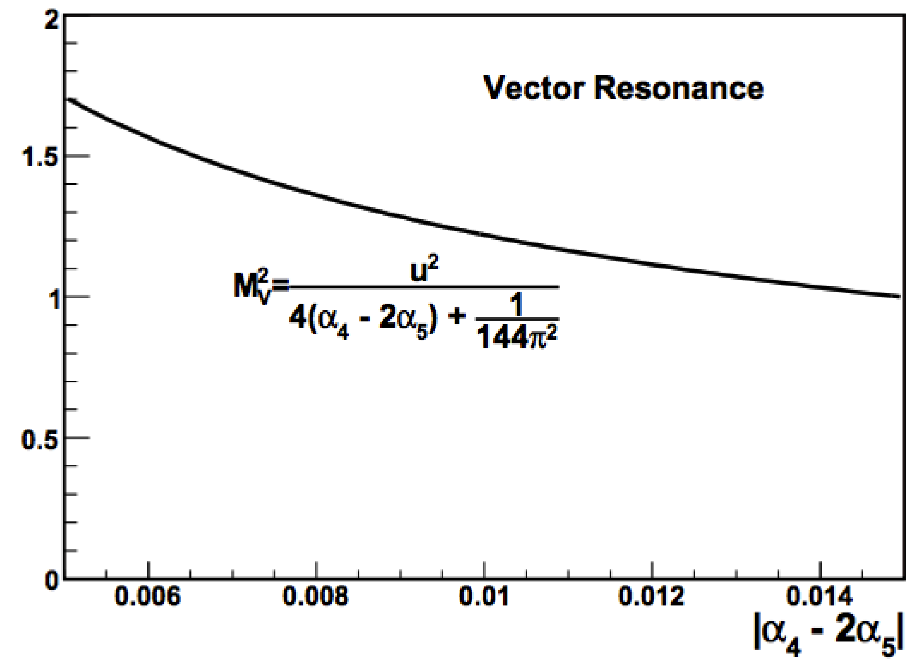
- Parameterize the scalar and vectorial resonances in terms of simple combinations of α_5 and α_4 parameters.

- Examples for μ=1 TeV

$$M_S^2 = \frac{12u_v^2}{16[11\alpha_5(\mu) + 7\alpha_4(\mu)] + \frac{101-50\log(M_S^2/\mu^2)}{48\pi^2}}, \qquad \Gamma_S = \frac{M_S^3}{16\pi u_v^2}$$



$$M_V^2 = \frac{u_v^2}{4[\alpha_4(\mu) - 2\alpha_5(\mu)] + \frac{1}{144\pi^2}}, \qquad \Gamma_V = \frac{M_V^3}{96\pi u_v^2}$$



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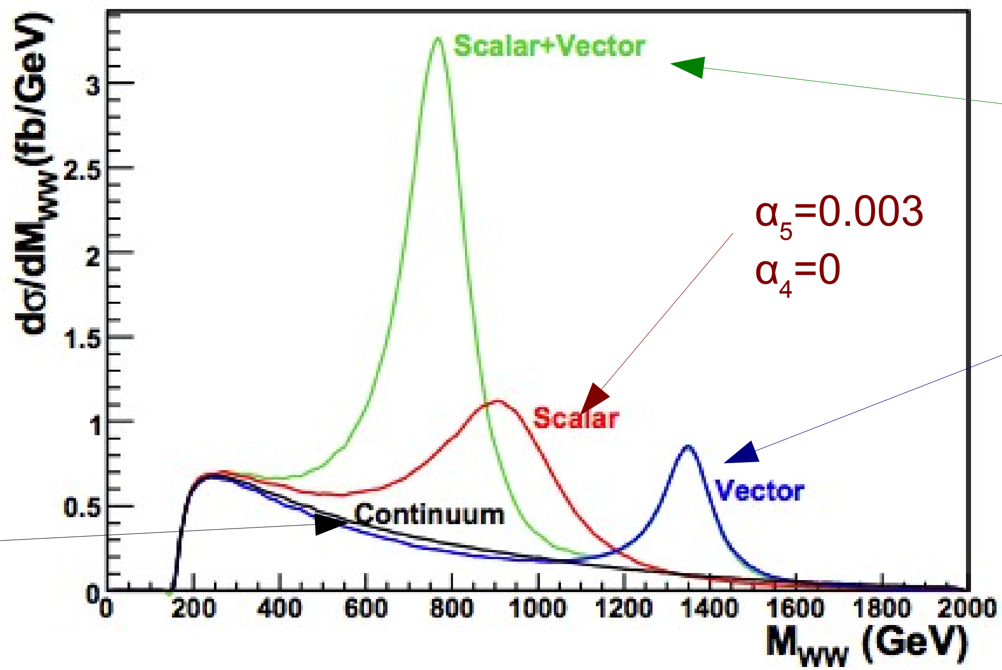


$\alpha_5=0$
$\alpha_4=0.008$

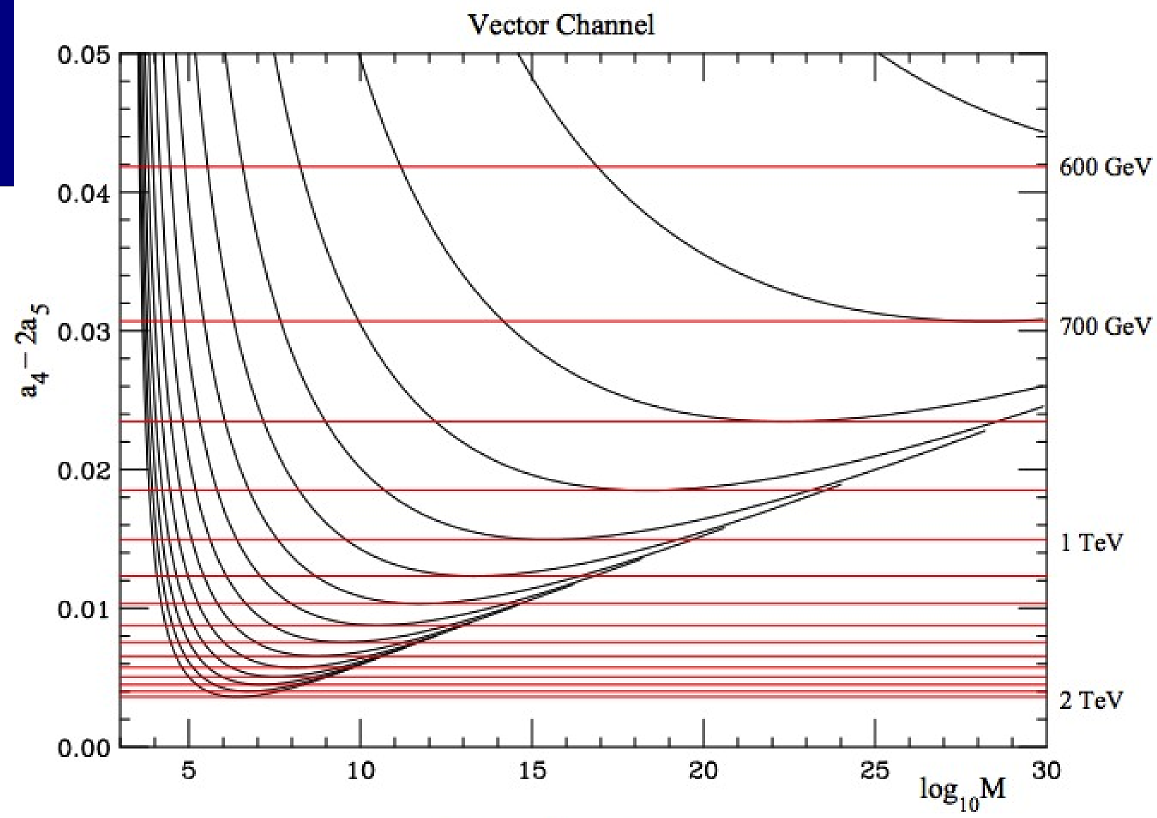
$\alpha_5=0.003$
$\alpha_4=0$

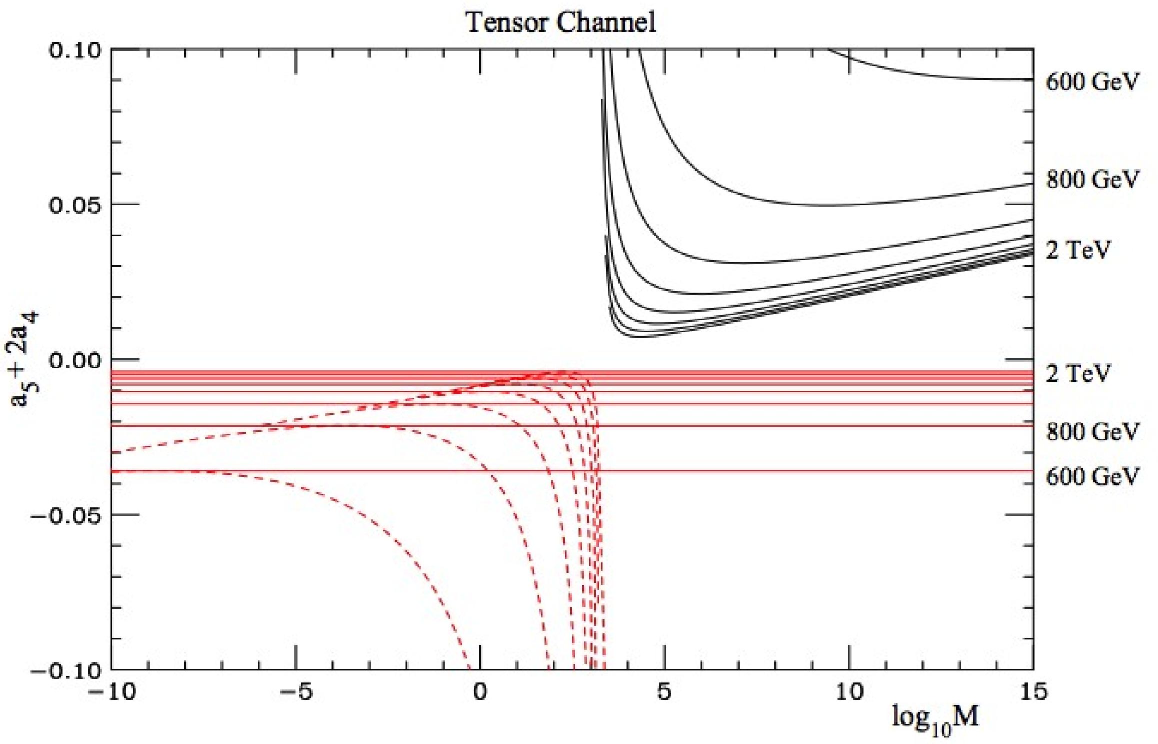
$\alpha_5=-0.003$
$\alpha_4=0.002$

$\alpha_5=0$
$\alpha_4=0$

Examples for N/D

- The mass of the resonance in the N/D protocol depends as well on α_4, α_5 and in the μ=M (cut-off parameter)
- Contours for physical solutions are given for different resonanc (predictions for scalars are in slide 12)



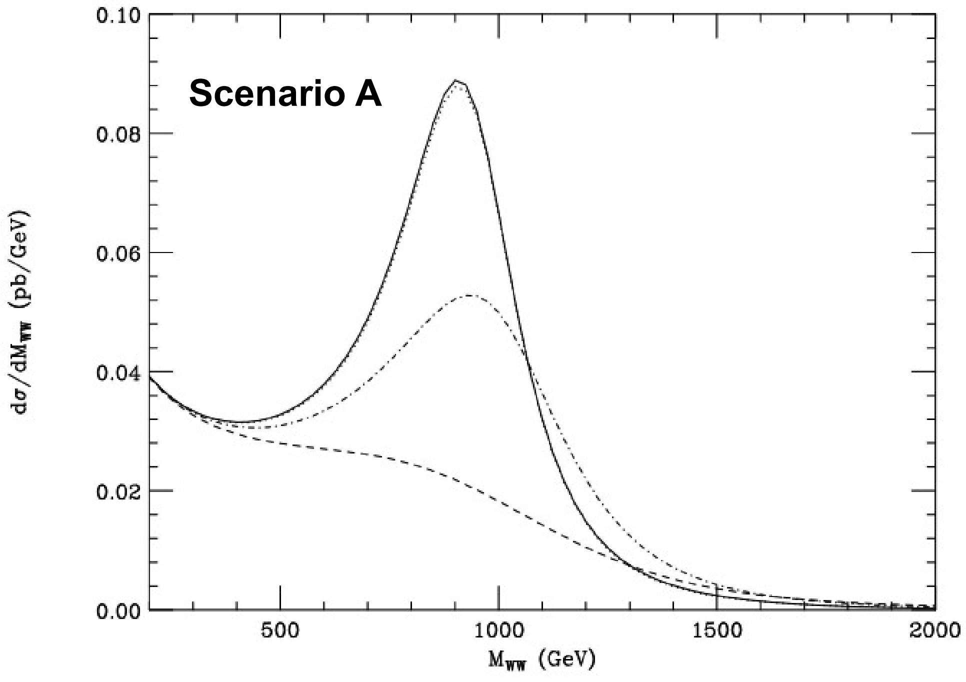


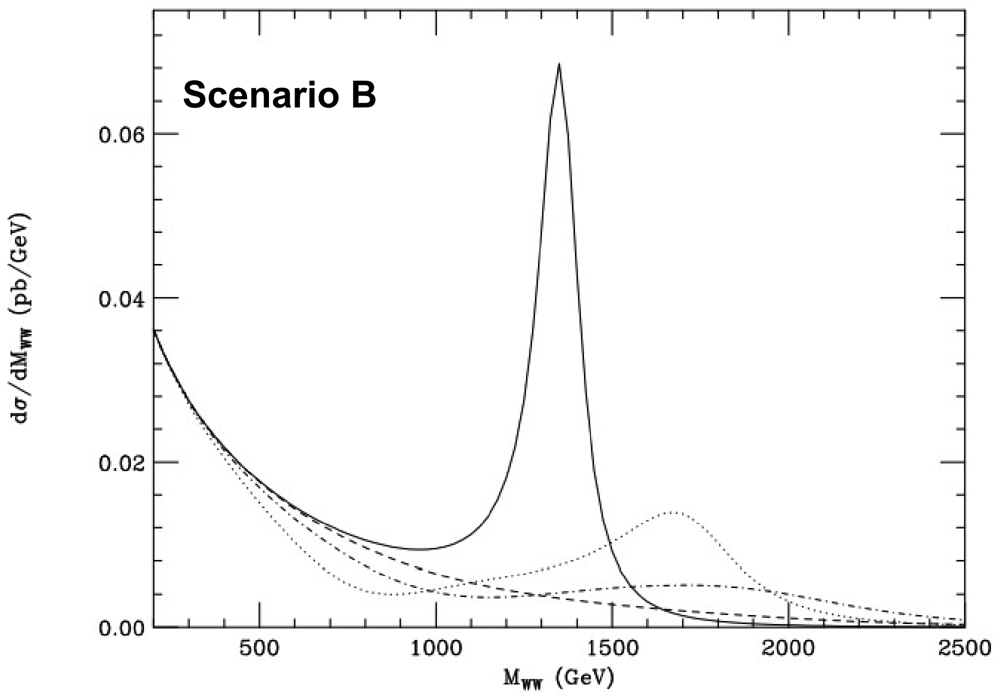
M_{WW} spectrum

- **Prediction can be compared for both models** in different scenarios and lead to broad/narrow resonance or a continuum spectrum

Scenario	a_4(1 TeV)	a_5(1 TeV)
A	0.0	0.003
B	0.002	-0.003
C	0.002	-0.001
D	0.008	0
E	0	0

Shown: Padé – solid N/D – dashed (shown for different μ)





M_{WW} spectrum – cont.

- **Prediction can be compared for both models** in different scenarios and lead to broad/narrow resonance or a continuum spectrum

Scenario	a_4(1 TeV)	a_5(1 TeV)
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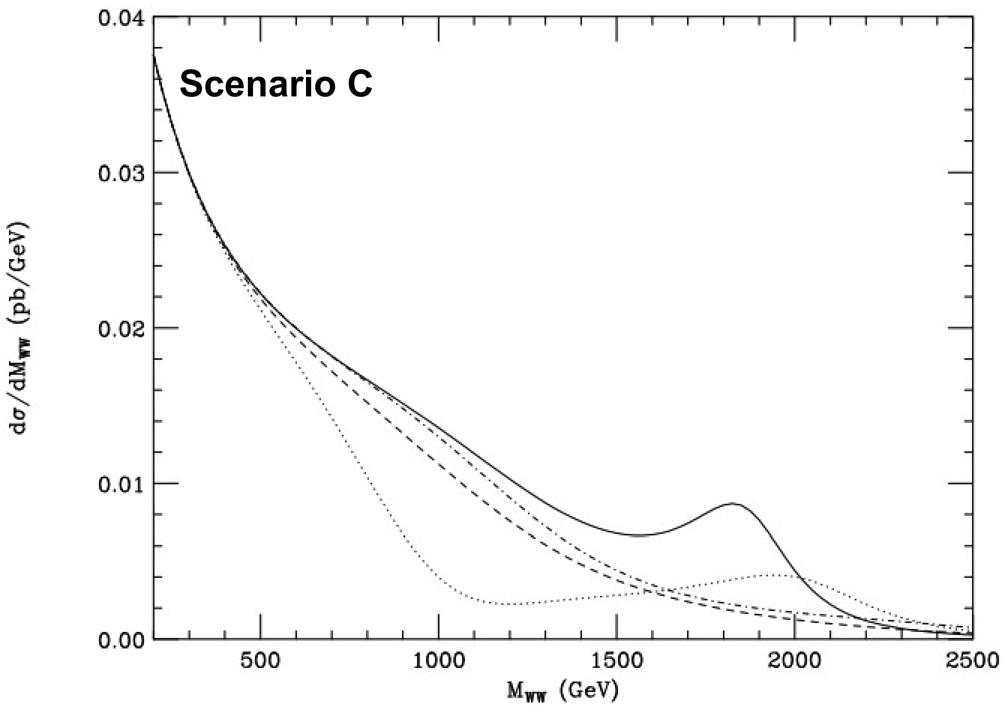

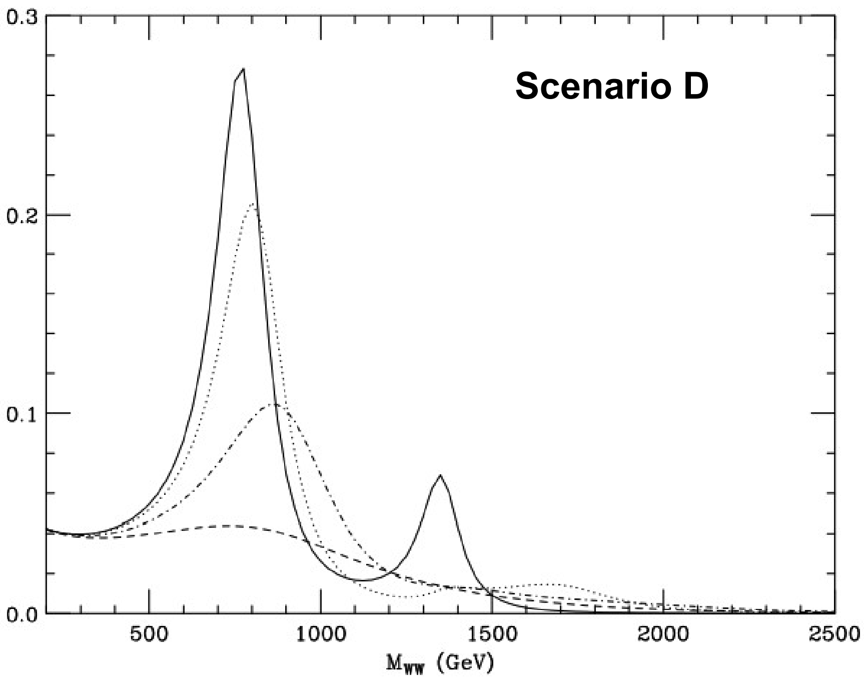

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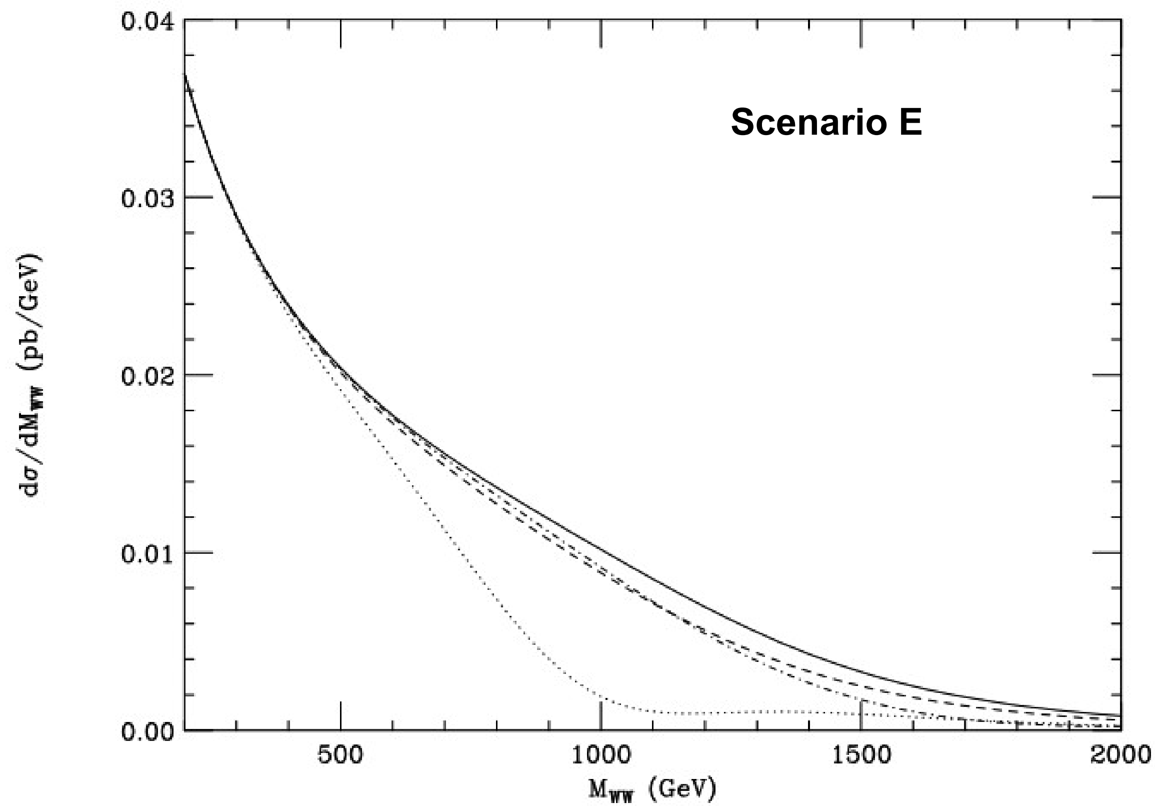
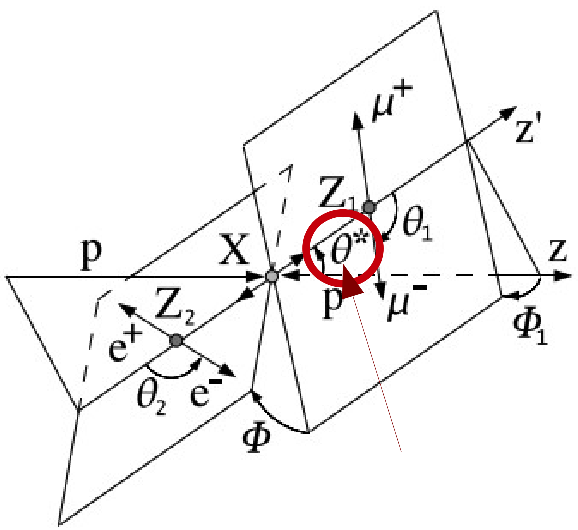
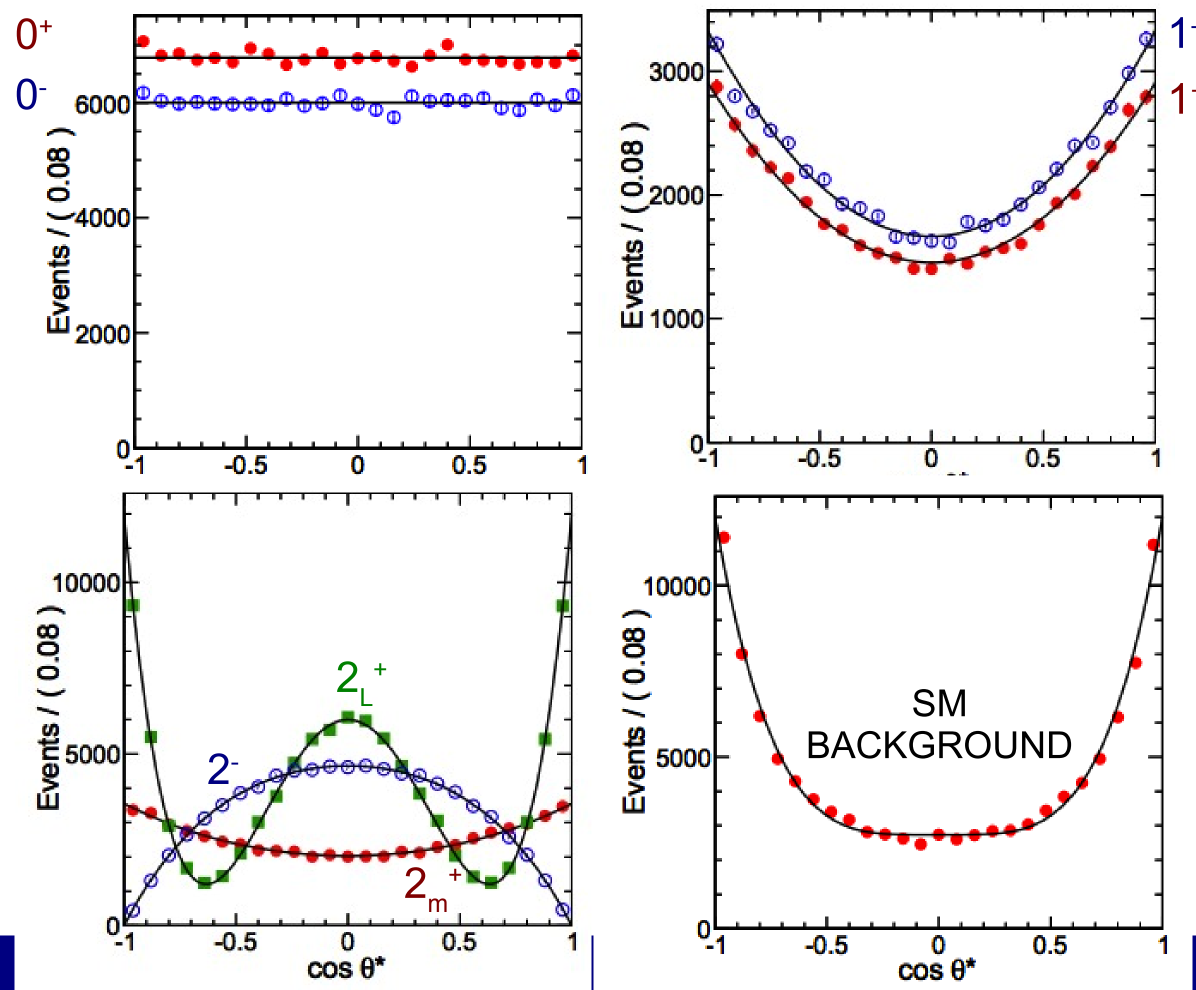


Example: how to discriminate nature of resonance

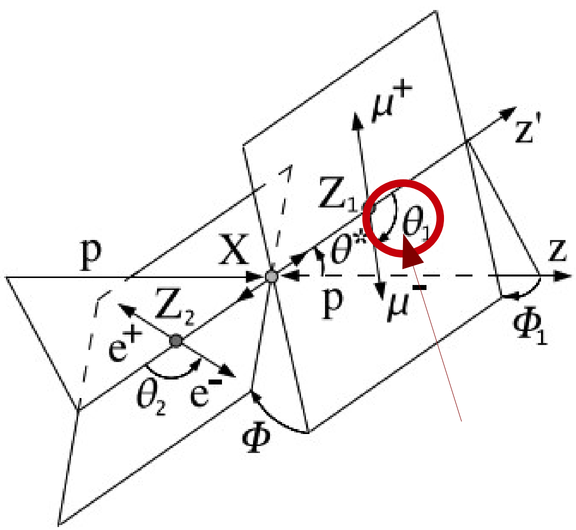
- As an example consider ZZ production after one of these generic resonances
- For θ^* (Z angle with respect to beam-line) in the ZZ rest-frame:
  - Distribution depends on spin and parity of the resonance

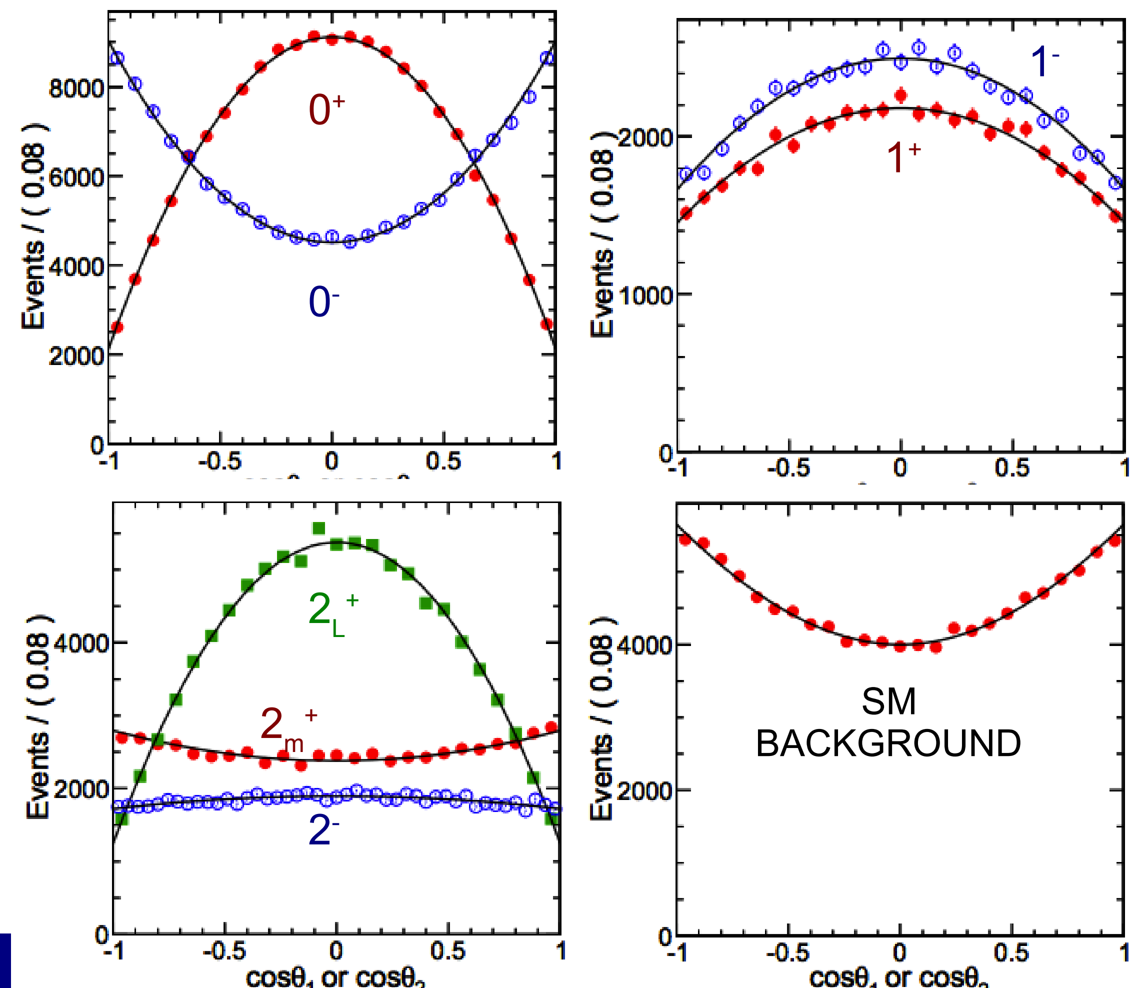




Example: how to discriminate nature of resonance

- As an example consider ZZ production after one of these generic resonances
- For θ_i (lepton angle with respect to Z direction) in the ZZ rest-frame:
  - Distribution depends on spin and parity of the resonance

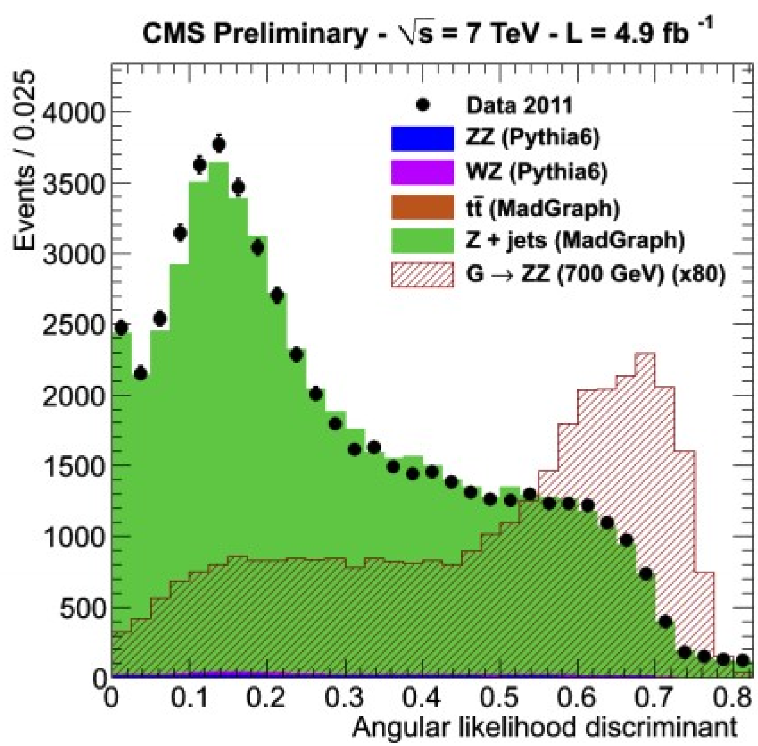




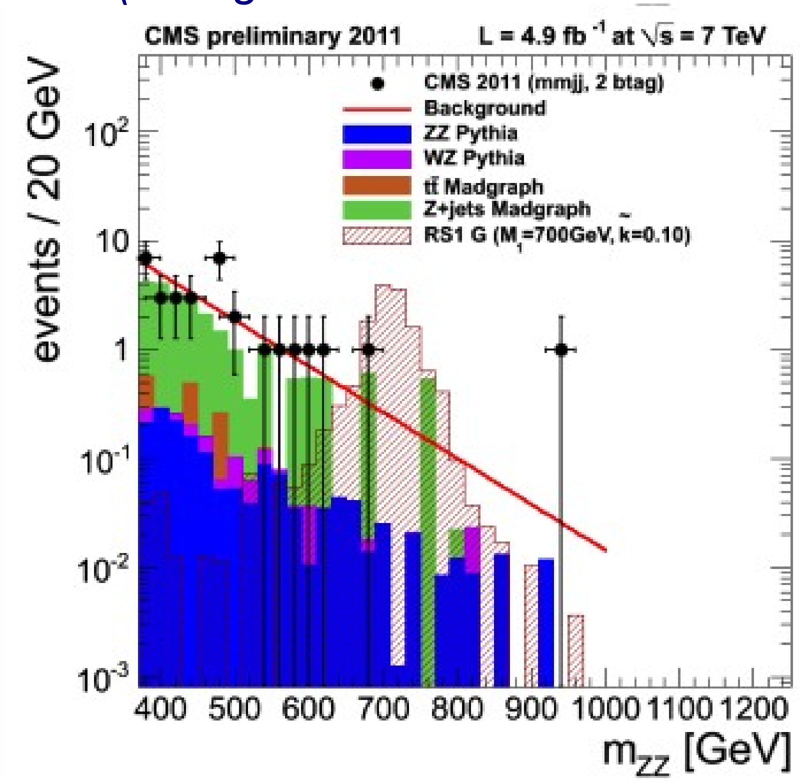
Example in practice: G → ZZ → 2l2q

- A graviton can be an example of a spin 2 particle
- Couplings to bosons suppressed in Randall-Sundrum original model but enhanced if SM fields propagate in the extra-dimension

Use likelihood ratio discriminator to select signal -like events

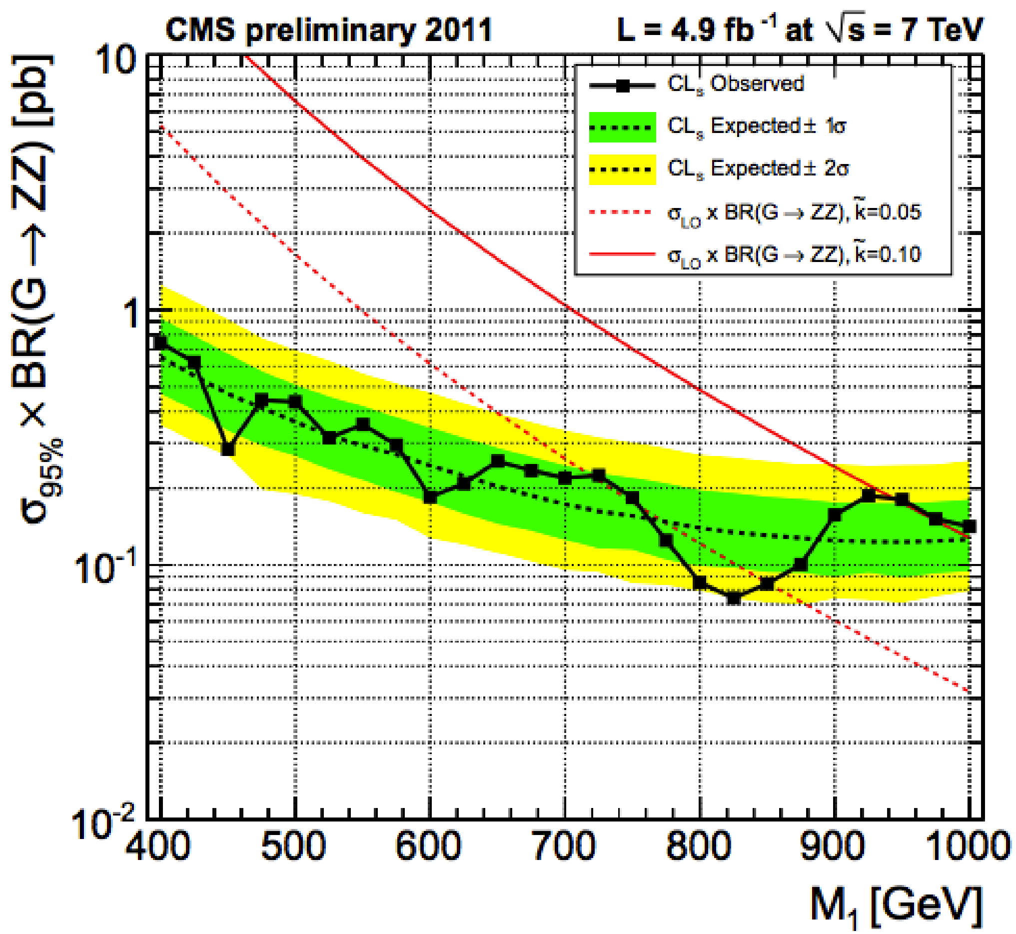


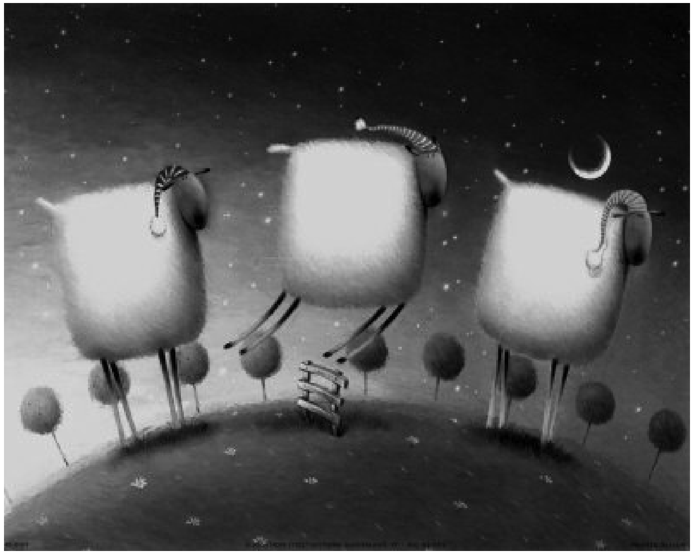
Search for resonance in the ZZ spectrum (background taken from sidebands)



Limits on G mass

- The model is specified by the curvature of the extra dimension – k
- Usually measured in units of Planck mass (2.435x10[18] GeV/c[2]): $\tilde{k} = \bar{k}/\bar{M}_{Pl}$
- Excluded up to 1 TeV (Note: RS1 searches excluded up to)



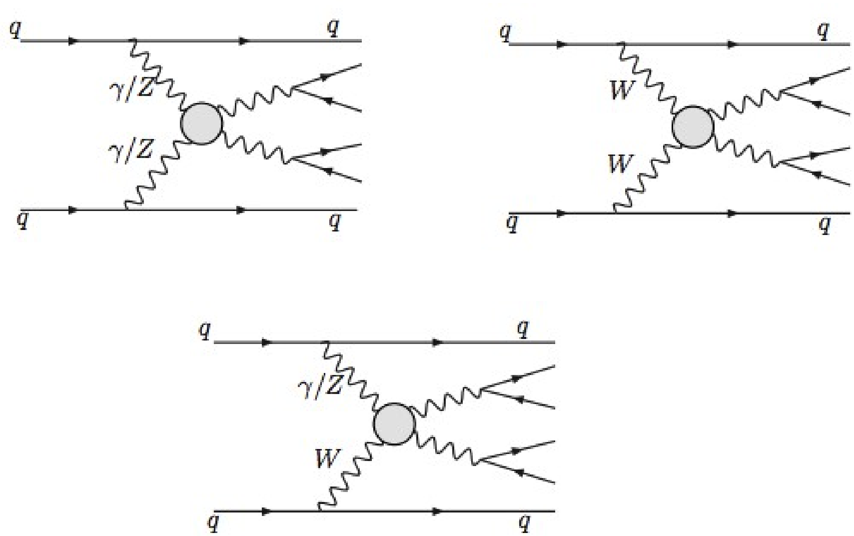


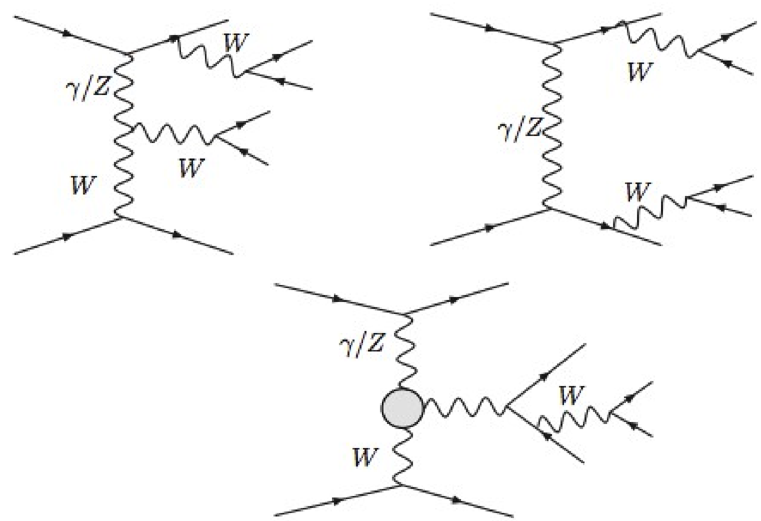
Searching for deviations in VV scattering

First step: scatter di-bosons

We don't have (yet) the technology to collide WW bosons. But we can collide protons

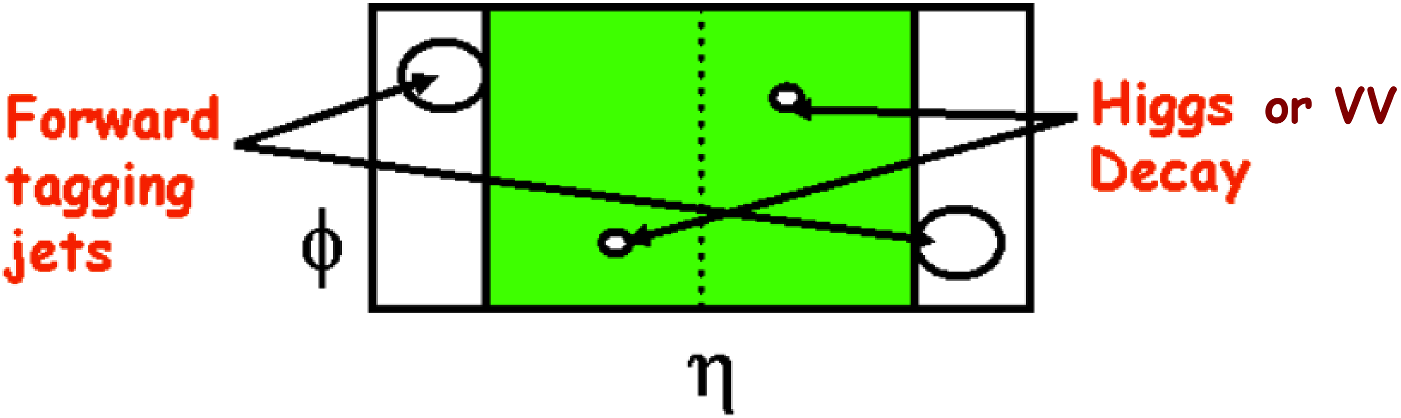
- **Pros**
  - $s^{1/2}$ is not fixed – depends on the partons colliding → can probe the full spectrum
  - VV fusion has distinctive signature
- **Cons**
  - It's a rare process: will take large luminosity acquired (typically >50fb^{-1} at 14 TeV)
  - Competes with non-VBF production





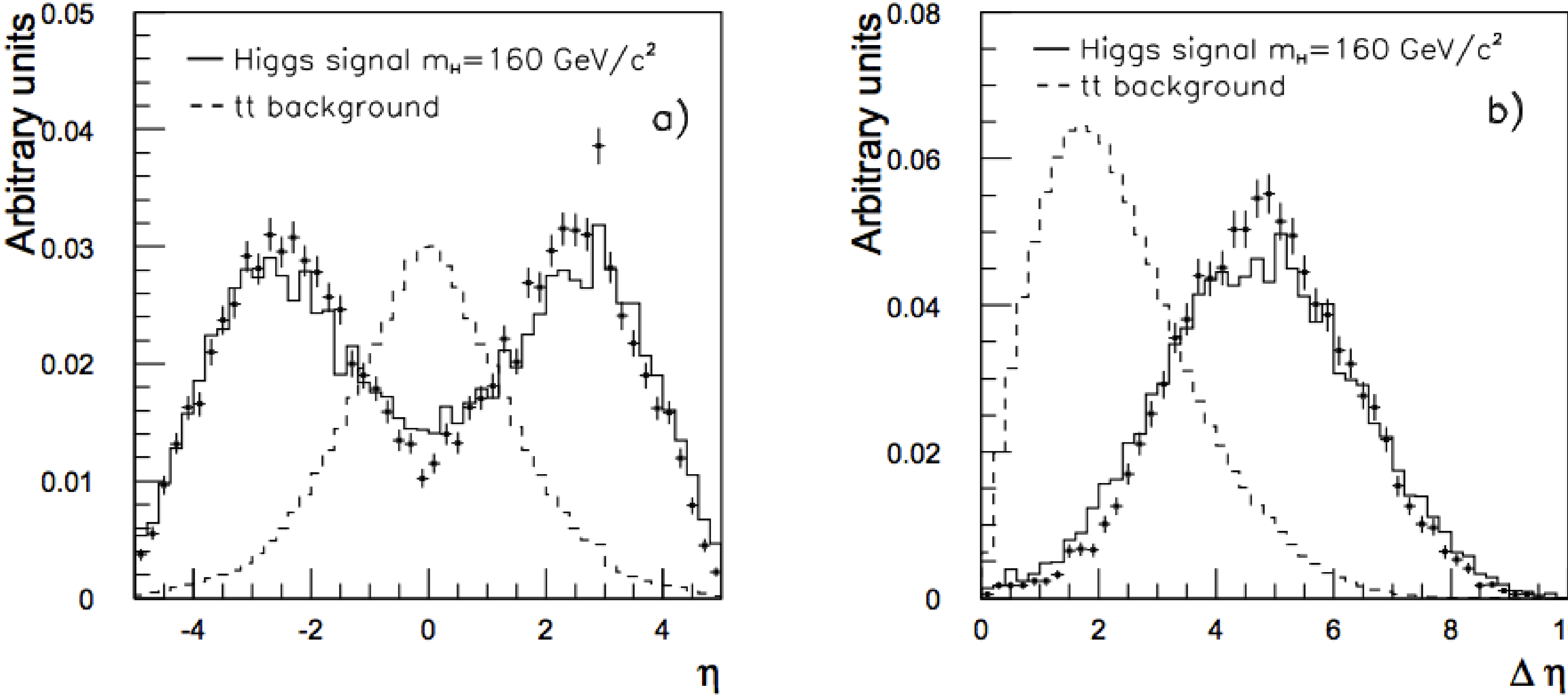
Signature for vector boson fusion

- We expect two high p_T jets with a large rapidity gap → large M_{jj}
- These are called the VBF - tag jets

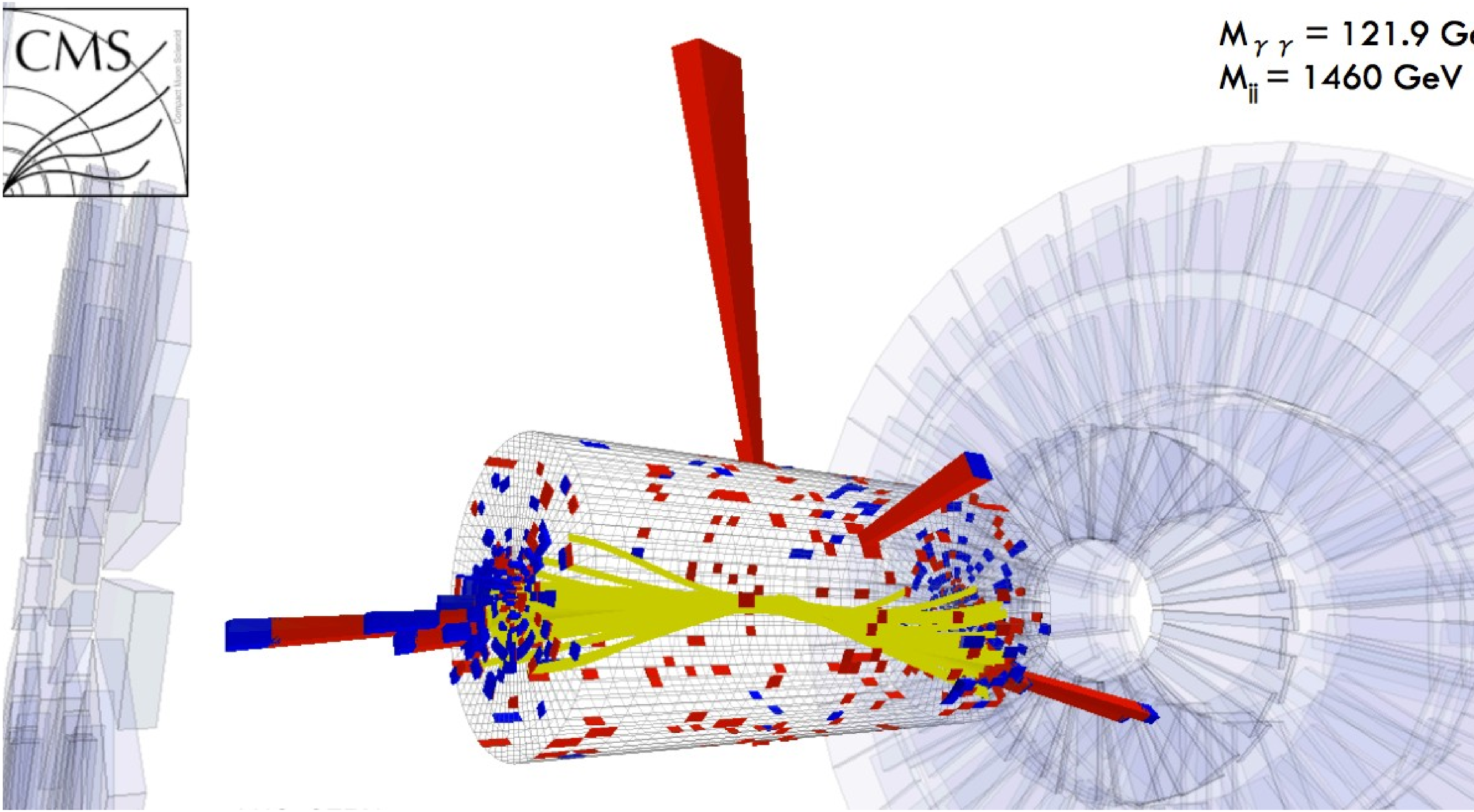


VBF tag jets

- Found mostly at large η : region instrumented only by calorimeters, poorer resolution, prone to pileup contamination
- Rapidity gap is totally distinct from QCD production

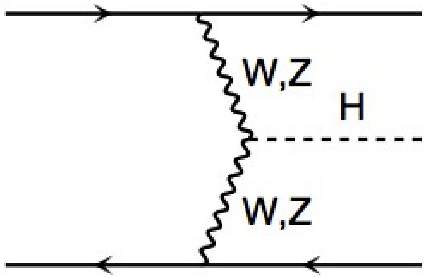


Example in real data: H → γγ



More on rapidity gap

- **In the t-channel $Q^2=(p_f-p_i)^2$ is always negative**



- Consequences on the vector boson propagator

$$\frac{-i}{k^2 - M^2}\left\{g^{\mu\nu} - \frac{k^\mu k^\nu}{M^2}\right\}$$

→ is highly suppressed, except if $Q^2 \sim 0$

- In this limit:

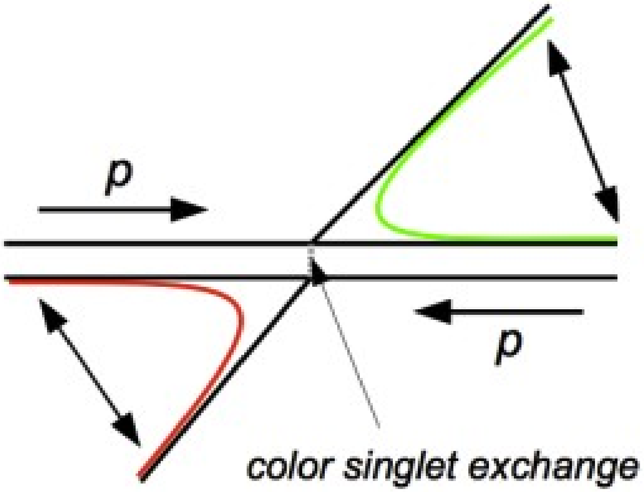
$$Q^2 = (p_f - p_i)^2 = E_q^2 \cdot (1-x) \cdot \theta$$

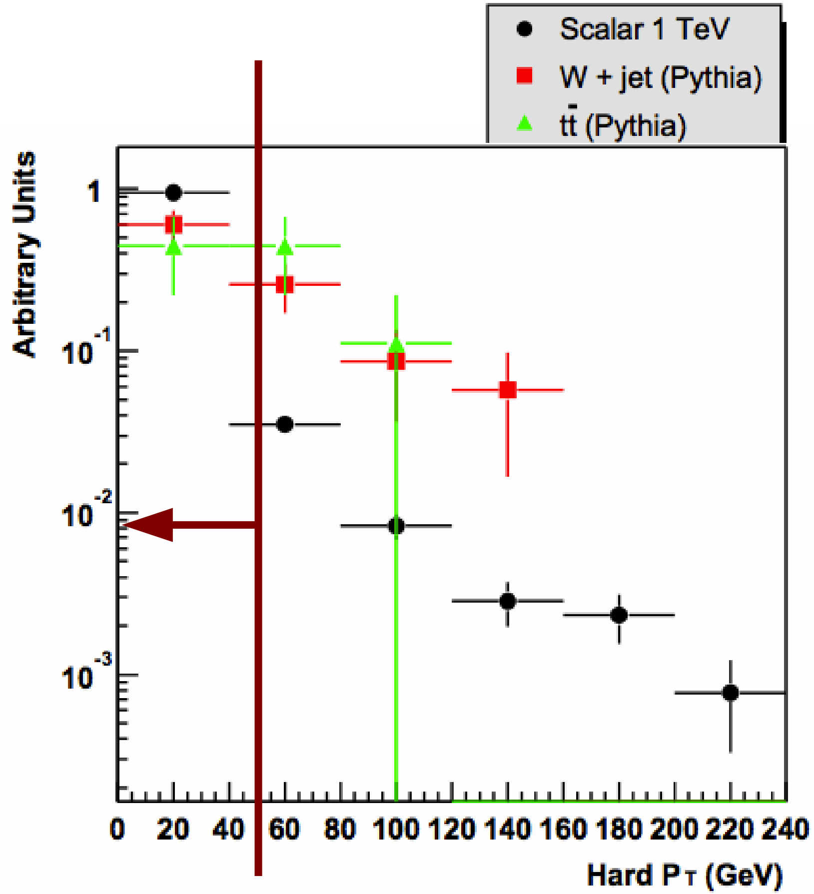
Energy of the quark — Fraction taken by the V boson — Scattering angle

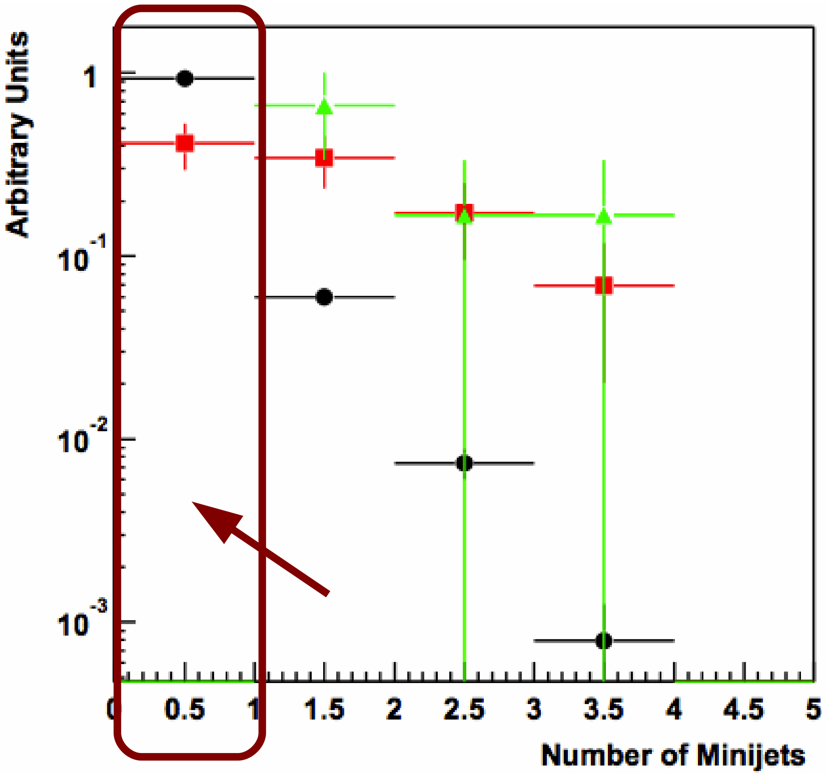
θ is necessarily small leading to large rapidities of the tag jets

More on rapidity gap

- Scattering of approx. collinear partons leads to **well balanced event**
- Due to EWK nature of the interaction **no hadronic activity** is **expected in the central region**







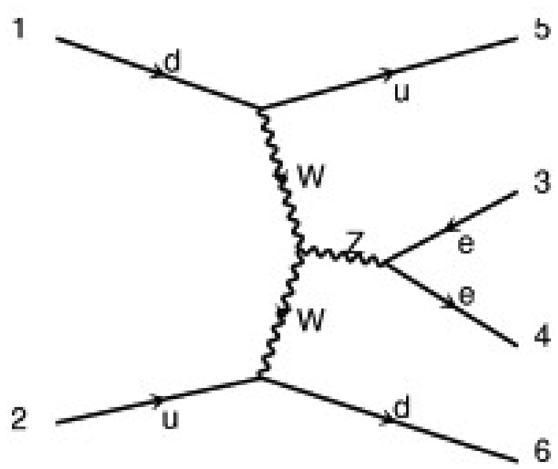
The Zeppenfeld variable

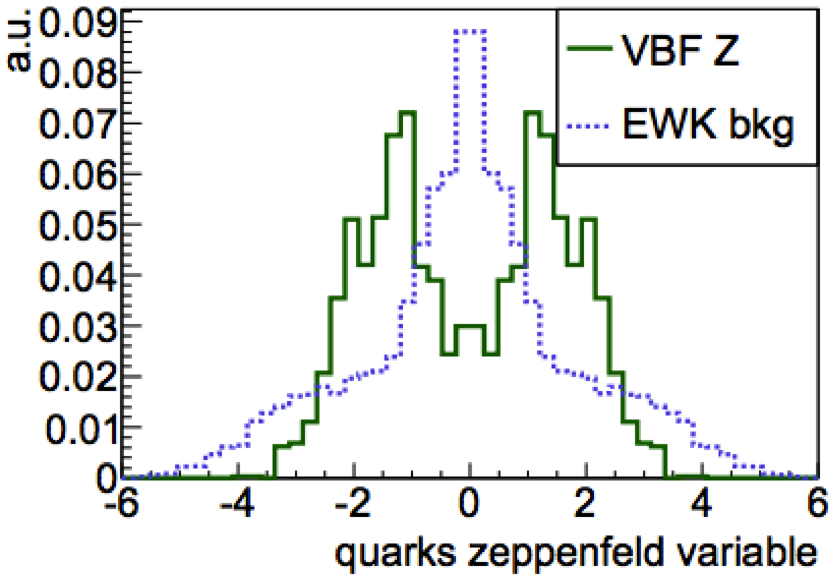
- Another distinctive variable is defined as:

$$z_i^* = \frac{z_i}{\Delta\eta} = \frac{\eta_i - \langle\eta\rangle}{\Delta\eta}$$

it translates and measures the rapidity relatively

to the reference defined by the two tag jets

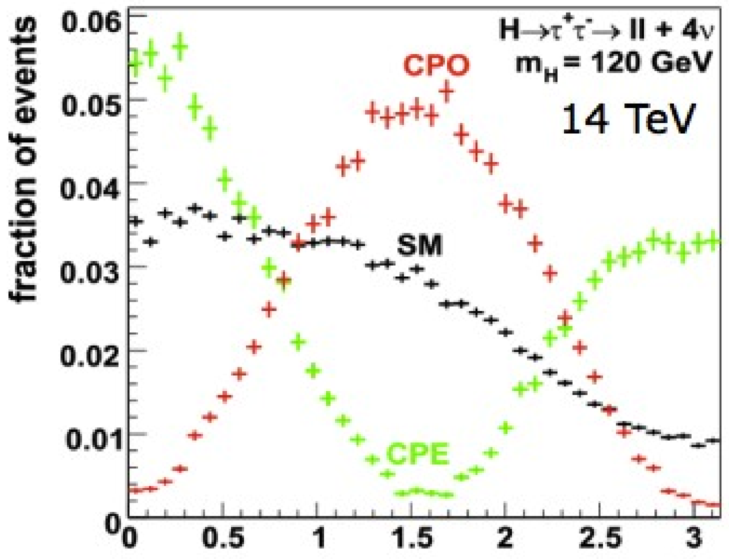




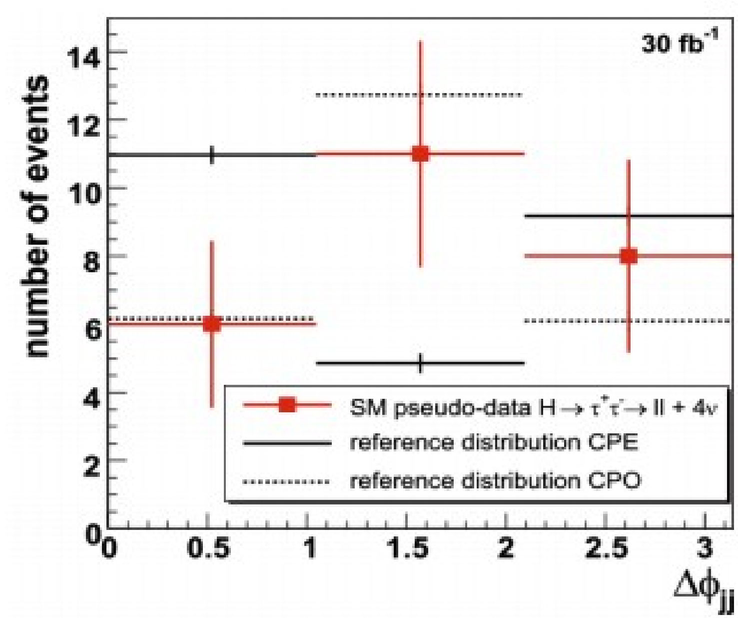
Resonance properties from VBF tags

- The azimuthal angle between the tag jets carries a distinctive hallmark
- Can be used to probe anomalous couplings

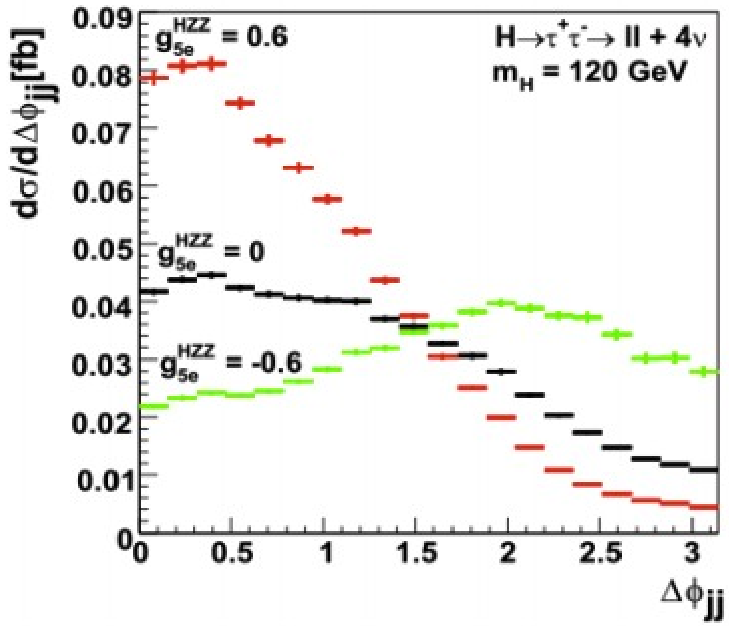
(Notice the integrated luminosity, and $_{Ecm}$ considered)

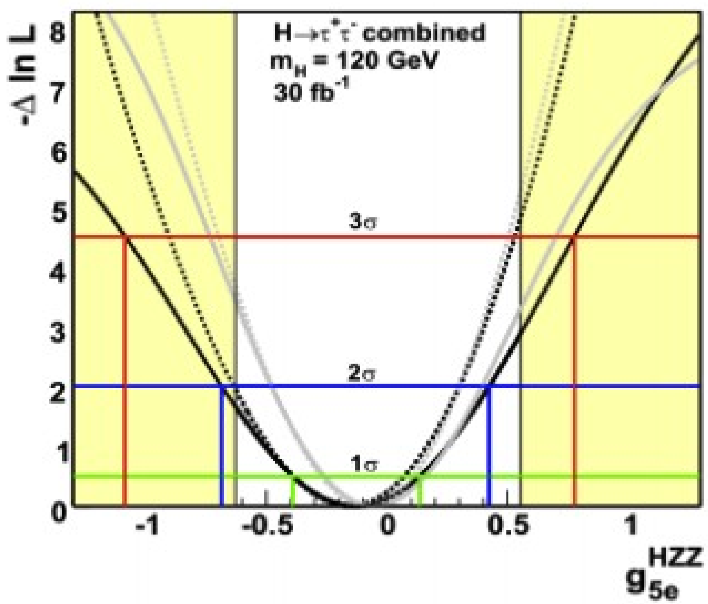


integrated luminosity, hypothesis tested		probability for $> 5\sigma$	probability for $< 5\%$	median χ^2-prob.	median dev. in σ
$H \to W^+W^- \to ll\nu\nu$					
$10\ \mathrm{fb}^{-1}$	CPE	59%	100%	1.3×10^{-7}	5.3σ
	CPO	35%	98%	6.0×10^{-6}	4.5σ
$30\ \mathrm{fb}^{-1}$	CPE	100%	100%	–	–
	CPO	100%	100%	–	–
$H \to \tau^+\tau^-$ combined					
$30\ \mathrm{fb}^{-1}$	CPE	2%	68%	1.2×10^{-2}	2.5σ
	CPO	0%	52%	4.3×10^{-2}	2.0σ



Resonance properties from VBF tags – cont.



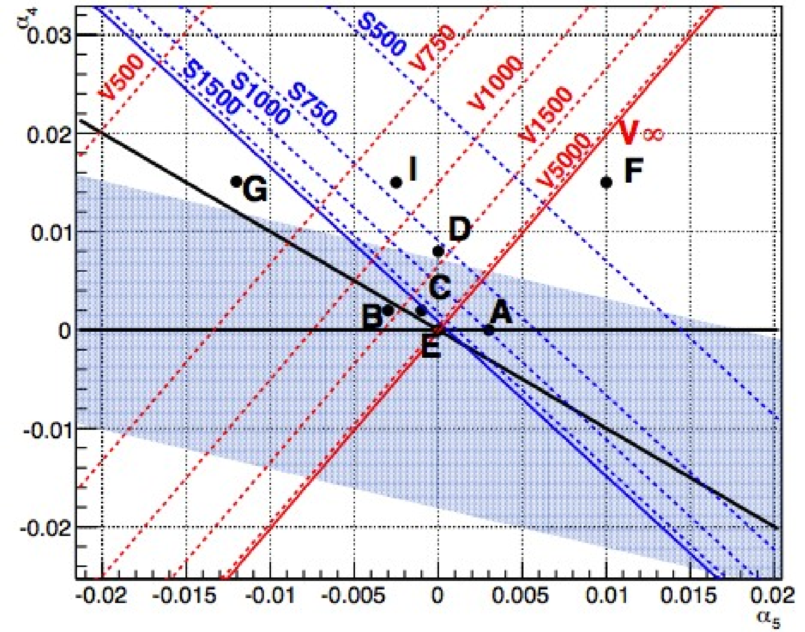


background included:

		minimum $-\Delta \ln L$	1σ interval	2σ interval	3σ interval	σ estimate
$H \to W^+W^- \to ll\nu\nu$						
$10\,\mathrm{fb}^{-1}$	non-extended	−0.09	[−0.30, 0.11]	[−0.50, 0.31]	[−0.73, 0.54]	0.20
	extended	−0.07	[−0.26, 0.12]	[−0.44, 0.31]	[−0.64, 0.51]	0.19
$30\,\mathrm{fb}^{-1}$	non-extended	−0.11	[−0.22, 0.00]	[−0.34, 0.12]	[−0.45, 0.23]	0.11
	extended	−0.10	[−0.21, 0.01]	[−0.31, 0.12]	[−0.42, 0.23]	0.11
$H \to \tau^+\tau^- \to ll + 4\nu$						
$30\,\mathrm{fb}^{-1}$	non-extended	−0.25	[−0.64, 0.12]	[−1.23, 0.53]	–	0.38
	extended	−0.25	[−0.59, 0.07]	[−0.97, 0.40]	[−1.38, 0.74]	0.33
$H \to \tau^+\tau^-$ combined						
$30\,\mathrm{fb}^{-1}$	non-extended	−0.13	[−0.40, 0.13]	[−0.69, 0.42]	[−1.08, 0.78]	0.27
	extended	−0.16	[−0.40, 0.06]	[−0.64, 0.40]	[−0.90, 0, 53]	0.23

Looking forward for high $s^{1/2}$ ...

- Search for VV scattering at high $s^{1/2}$ has to combine different channels to gain in sensitivity

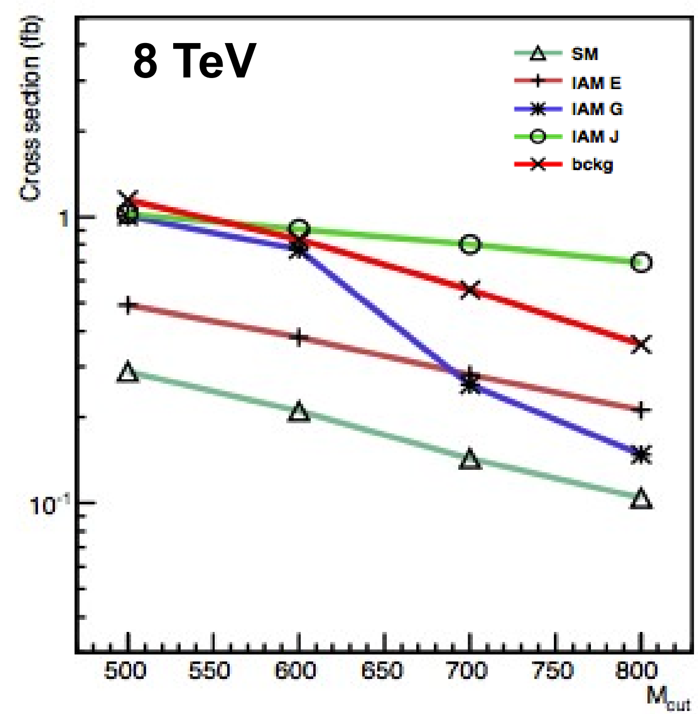


- Example from Ballestrero et al (arXiv:1203.2771)

  (in the following IAM – Inverse Amplitude Method is equivalent to the Padé protocol)

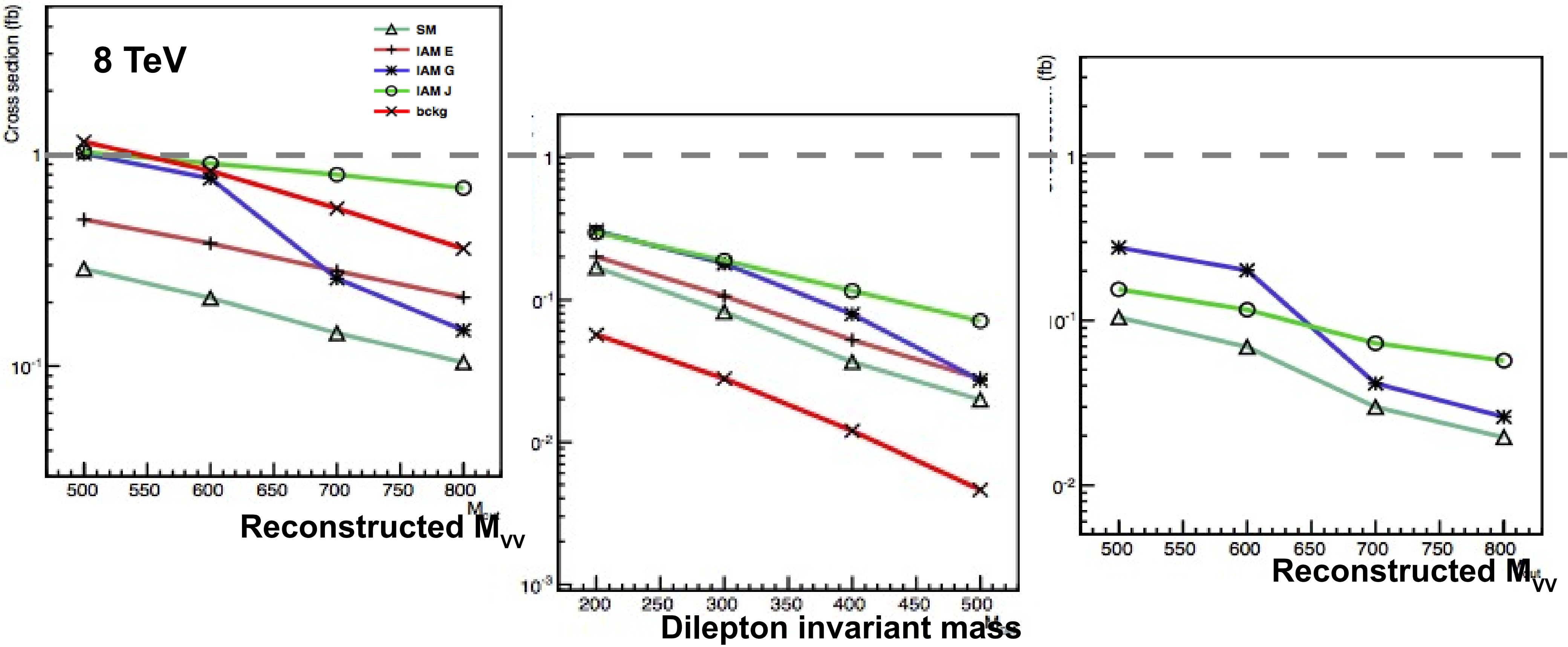
- Cuts for: lv+4j / 2l2v+2j / 3lv+2j final states

$p_T(j) > 30$ GeV	$p_T(\ell) > 70/70/20$ GeV
$p_T^{miss} > 70/20/20$ GeV	$p_T(j_c) > 70$ GeV
$\eta(j) < 6.5$	$\eta(\ell) < 2/2/3$
$\Delta\eta(j_f j_b) > 4/4/3$	$\Delta\eta(V_{rec} j) > 0.6$
$\Delta R(jj) > 0.3$	$M(\ell\ell) > 20$ GeV
$M(jj) > 60$ GeV	$M(j_f j_b) > 700/600/100$ GeV
$p_T(V_{rec}) > 70/100$ GeV	$\lvert M(V_{rec} j) - M_{TOP}\rvert > 15$ GeV
$M(j\ell) > 180$ GeV	$\lvert p_T(\ell^+) - p_T(\ell^-)\rvert > 100$ GeV



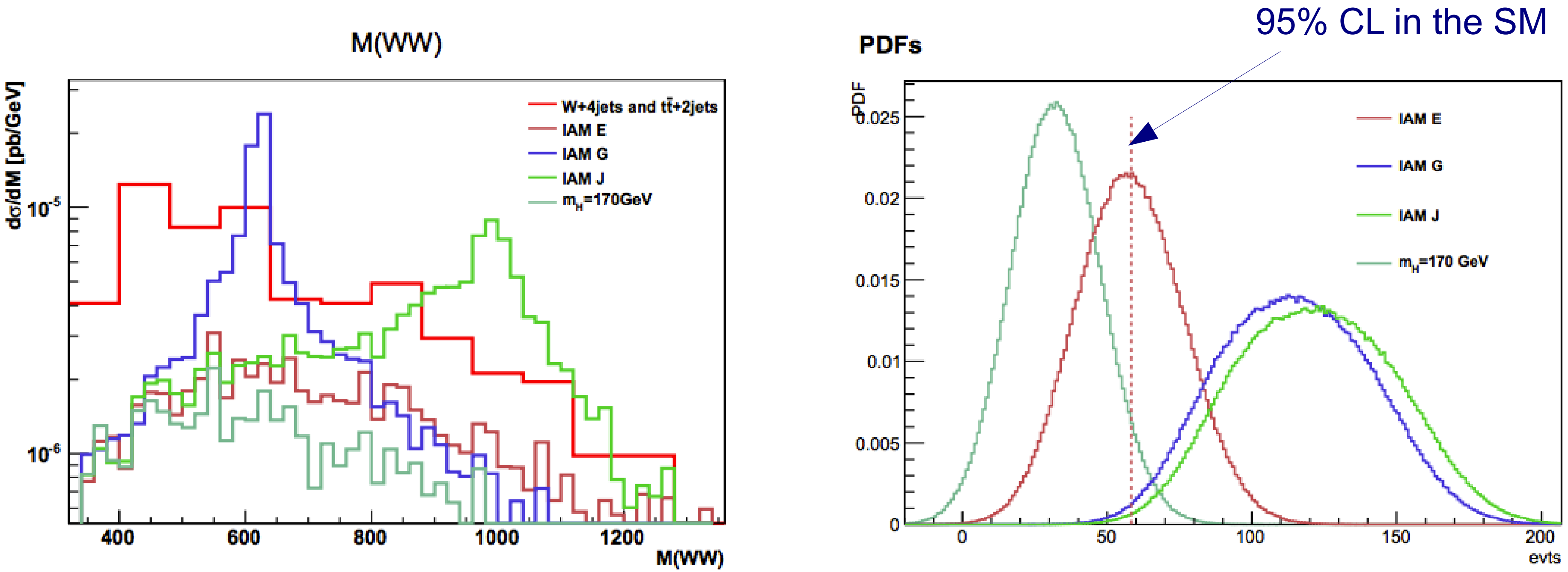
… and for high luminosity

- After the selection cuts we're expecting to select ~5 event / 10 fb^{-1}



Expected mass distributions

- The expected spectrum (right) and the probability to observe a given number of events with M_{VV}>500 GeV/c^2 for L= 50 fb^{-1}



- Within the reach of the LHC experiments after the upgrade: with this year's data we can at most exercise these searches

Probability BSM @ 95% CL

	IAM E			IAM G			IAM J		
L\E	7	8	10	7	8	10	7	8	10
25	16.06 ^{a}	19.03 ^{a}	35.37 ^{b}	71.10 ^{a}	75.48 ^{a}	93.80 ^{a}	73.32 ^{d}	81.77 ^{d}	99.32 ^{d}
50	22.70 ^{a}	27.88 ^{a}	51.56 ^{b}	89.14 ^{a}	91.68 ^{a}	99.12 ^{a}	91.55 ^{d}	95.62 ^{d}	99.99 ^{d}
100	33.51 ^{a}	41.08 ^{a}	69.28 ^{c}	97.85 ^{a}	98.54 ^{a}	99.97 ^{a}	98.89 ^{d}	99.66 ^{e}	100 ^{d}
200	48.25 ^{b}	57.08 ^{a}	83.44 ^{c}	99.87 ^{a}	99.93 ^{a}	100 ^{a}	99.97 ^{d}	100 ^{d}	100 ^{d}

Table 2. PBSM@95%CL in the $\ell\nu + 4$ jets channel with 25, 50, 100 and 200 fb^{-1} of integrated luminosity, L. For each luminosity and model we have used the mass cut which gives the best probability. They are specified by the superscript according to the following scheme: ^{a}, ^{b}, ^{c}, ^{d}, ^{e} for 500, 600, 700, 800, 900 GeV respectively

	IAM E			IAM G			IAM J		
L\E	7	8	10	7	8	10	7	8	10
25	8.47 ^{a}	10.44 ^{b}	14.23 ^{a}	24.41 ^{a}	36.49 ^{a}	51.83 ^{a}	27.17 ^{b}	42.69 ^{b}	65.68 ^{a}
50	10.02 ^{a}	13.06 ^{b}	18.94 ^{a}	35.83 ^{a}	53.23 ^{a}	70.07 ^{a}	37.90 ^{b}	61.95 ^{b}	84.73 ^{b}
100	12.63 ^{a}	17.34 ^{b}	26.37 ^{b}	52.81 ^{a}	72.07 ^{a}	84.59 ^{a}	56.76 ^{b}	81.94 ^{b}	95.97 ^{b}
200	16.49 ^{a}	24.08 ^{b}	36.35 ^{b}	71.87 ^{a}	86.74 ^{a}	93.23 ^{a}	76.92 ^{b}	94.91 ^{b}	99.50 ^{b}

Table 3. PBSM@95%CL in the $(WW)\ell\nu\ell\nu + 2j$ channel with 25, 50, 100 and 200 fb^{-1} of integrated luminosity, L. For each luminosity and model we have used the mass cut which gives the best probability. They are specified by the superscript according to the following scheme: ^{a}, ^{b} for 300, 400 GeV respectively.

Probability BSM @ 95% CL – cont.

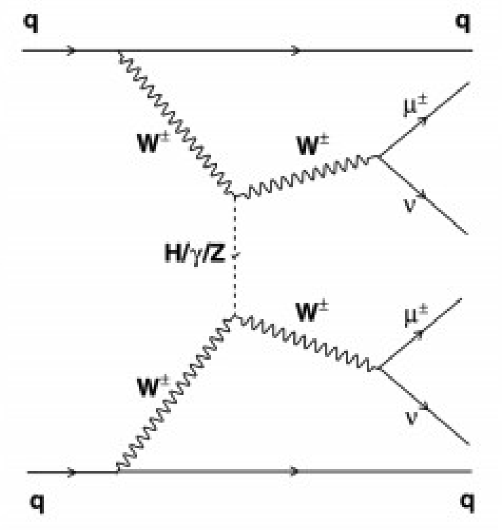
	IAM G			IAM J		
L\E	7	8	10	7	8	10
25	50.53 ^{a}	63.18 ^{a}	82.05 ^{a}	21.74 ^{d}	29.28 ^{d}	48.50 ^{e}
50	71.93 ^{a}	82.12 ^{a}	93.99 ^{a}	31.02 ^{d}	43.24 ^{e}	68.63 ^{e}
100	88.13 ^{a}	94.08 ^{a}	98.97 ^{b}	43.83 ^{e}	63.71 ^{e}	86.42 ^{e}
200	97.09 ^{b}	98.94 ^{b}	99.95 ^{b}	63.63 ^{e}	82.62 ^{e}	96.56 ^{e}

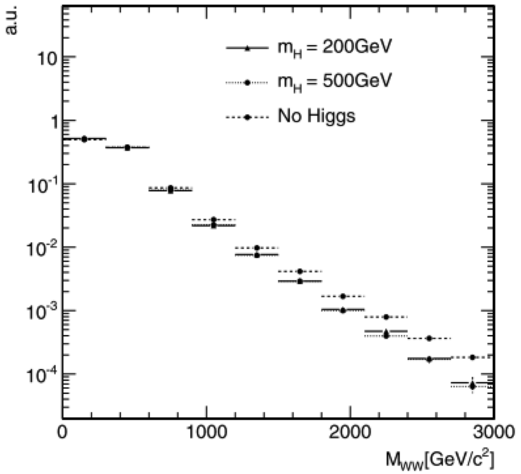
Table 4. PBSM@95%CL in the $3\ell\nu + 2$ jets channel with 25, 50, 100 and 200 fb^{-1} of integrated luminosity, L. For each luminosity and model we have used the mass cut which gives the best probability. They are specified by the superscript according to the following scheme: ^{a}, ^{b}, ^{c}, ^{d}, ^{e} for 500, 600, 700, 800, 900 GeV respectively

Same sign WW scattering

- Process has good separation for different scenarios
- Optimize selection from ratios:

$$\alpha = \frac{N_{\mathrm{NoH}} - N_{m_{\mathrm{H}}(200)}}{\sqrt{N_{m_{\mathrm{H}}(200)} + N_{\mathrm{Bkg}}}}$$

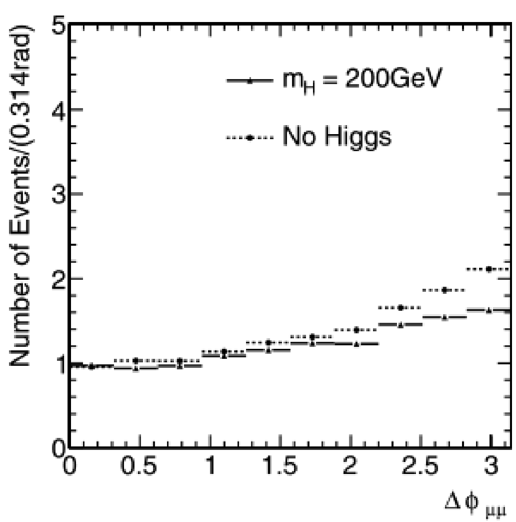


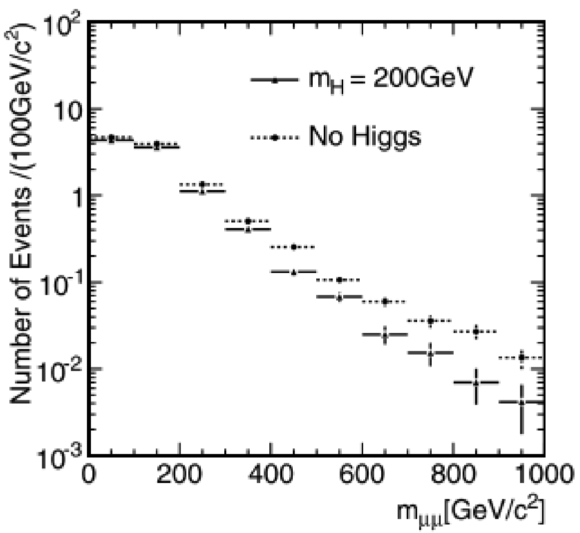


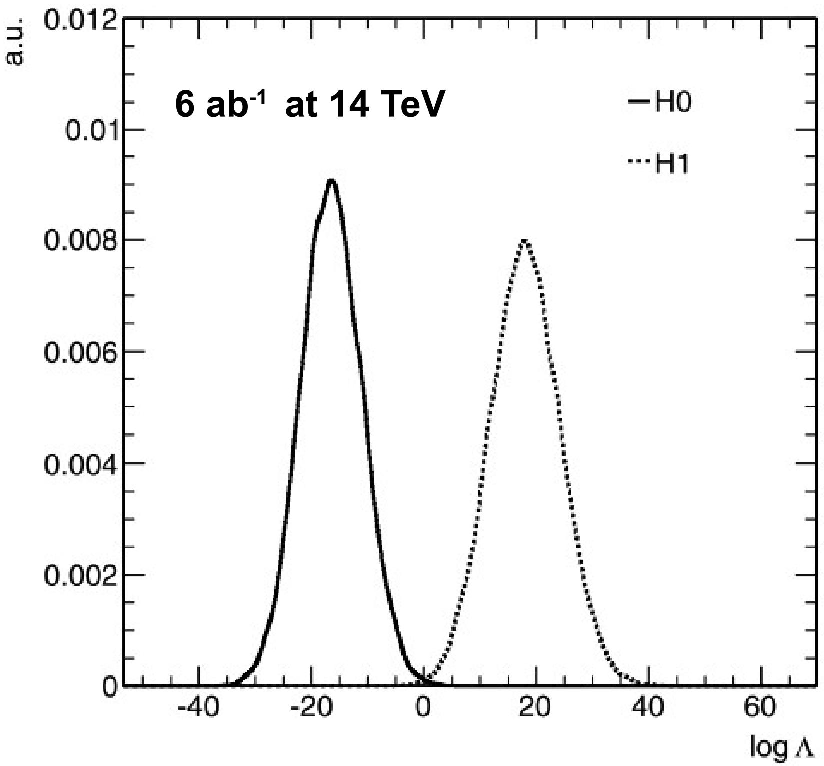
Discriminator	NoH	$m_{\mathrm{H}}(200)$	NoH/$m_{\mathrm{H}}(200)$
$m_{\mu\mu}$	2.4±0.1	1.8±0.1	1.3±0.1
$\Delta\phi_{\mu\mu}$	6.5±0.1	5.4±0.1	1.2±0.1

Expect 1 (3.5) background

events after $m_{\mu\mu}$ ($\Delta\varphi_{\mu\mu}$)







Conclusions

- **VV scattering at high $s^{1/2}$ is a territory with many unknowns**
  - Unique probe of the EWSB mechanism
  - Requires both high energy beams and high luminosity
  - many possibilities to explore
- **Can start to exercise (rule out some models) already this year**
  - EWKchL unitarized via two protocols: Padé or N/D
  - lead to **resonance or continuum predictions for the VV invariant mass spectrum**
  - combine different channels: expect sensitivity to part of phase space with ~20fb^{-1} and 8 TeV
- Not covered today (but can be looked up in Michele's presentation)
  - Usage of boosted topologies (jet substructure) to reconstruct boosted W/Z → qq

End of Lecture III on Higgs Physics

References

- Stefanidis, E., *Study of the WW scattering in the absence of light Higgs boson using the ATLAS Detector at LHC*, PhD Thesis 2007
- Rainwater, D. "*Searching for the Higgs boson*", arXiv:hep-ph/0702124
- Gao, Y et al, "Spin determination of single-produced resonances at hadron colliders", arXiv:1001.3396
- CMS Collaboration, "*Search for a narrow spin-2 resonance decaying to Z vector bosons in the semileptonic final state*", CMS PAS EXO-11-102
- **Ballestrero, A., "*Exploring alternative symmetry breaking mechanisms at the LHC with 7, 8 and 10 TeV total energy*" , ,arXiv:1203.2771**