MAÔS Reconstruction of the Standard Model Higgs Boson

JAE SIK LEE

National Center for Theoretical Sciences, Hsinchu, Taiwan

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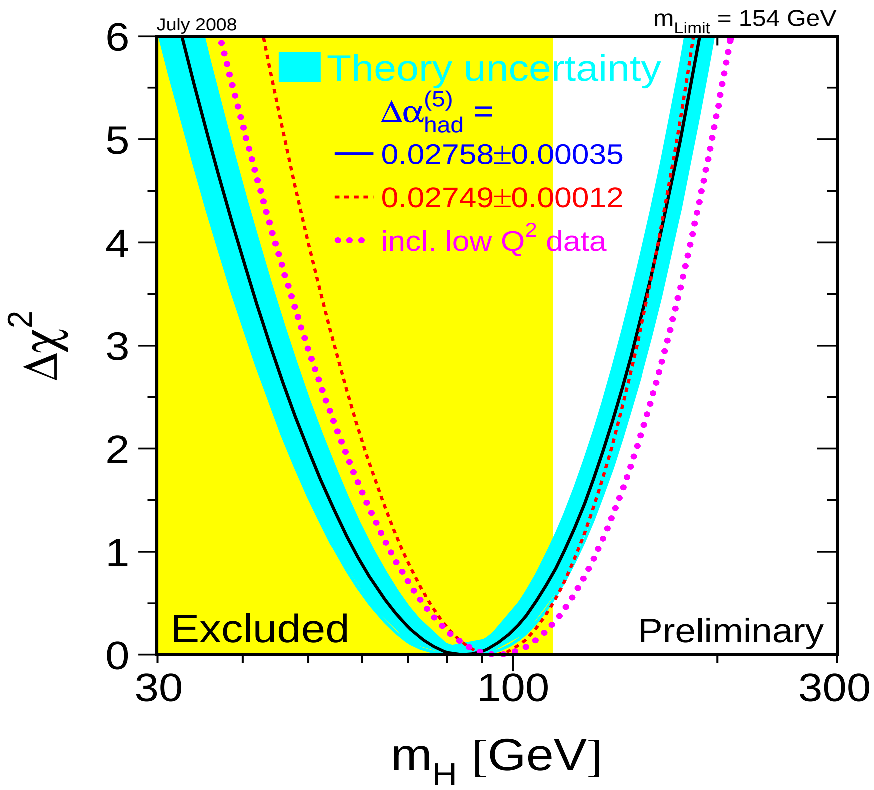
* based on arXiv:0908.0079 [hep-ph] with K. Choi, S. Choi, and C. B. Park

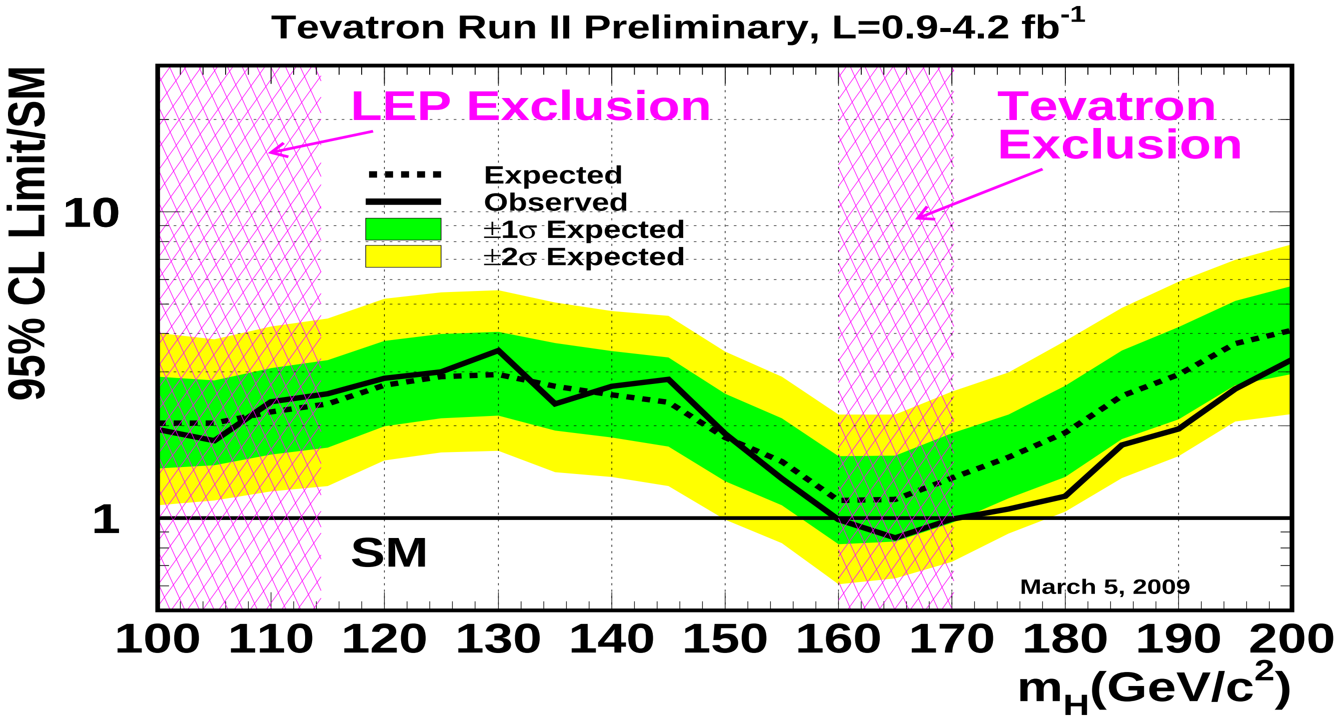
♠ *Preliminary*

- Status of the SM Higgs:
  - LEP bound: $M_H^{\rm SM} \geq 114.4$ GeV (95 % C.L.) ADLO, arXiv:hep-ex/0306033
  - Electroweak precision data: $M_H^{\rm SM} \lesssim 185$ GeV (95 % C.L.) direct-search limit included ACDDLOS, arXiv:0811.4682[hep-ex]



♠ *Preliminary*

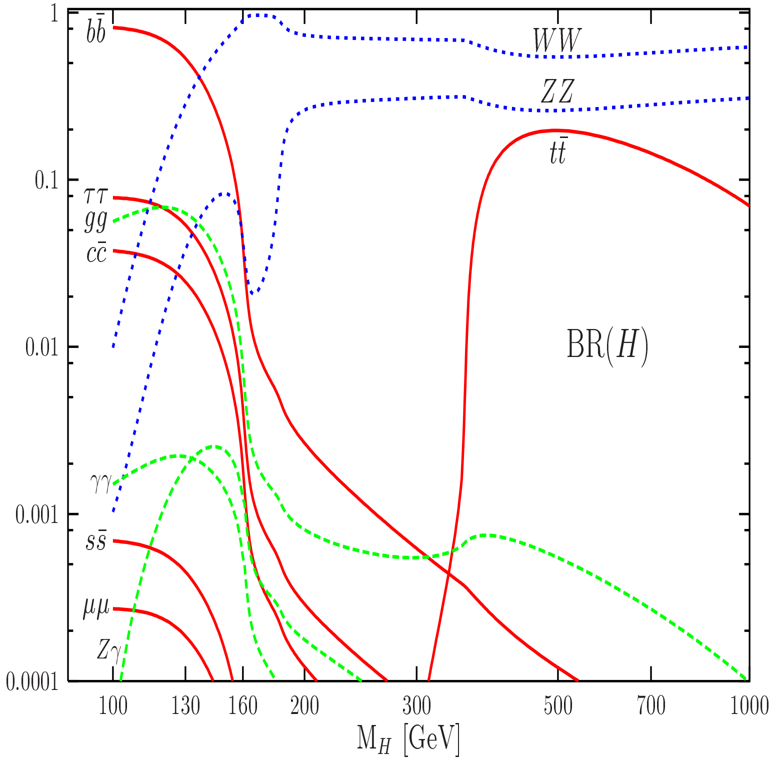
- Status of the SM Higgs: ... *continued*
  - Tevatron exclusion: 160 GeV $\lesssim M_H^{SM} \lesssim$ 170 GeV (95 % C.L.) CDF/D0, arXiv:0903.4001[hep-ex]

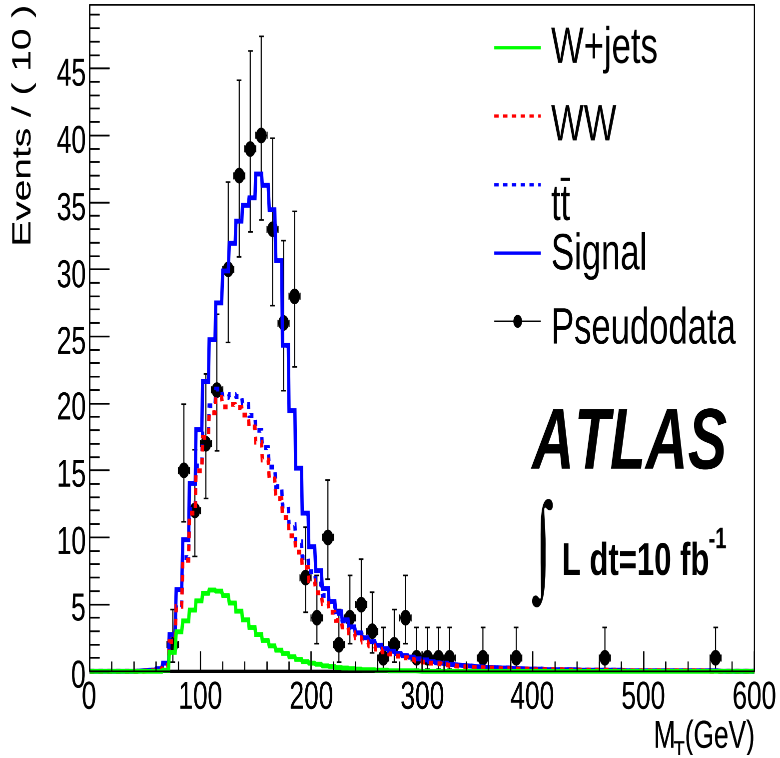


  - *We anticipate the SM Higgs boson lighter than ~ 200 GeV*

♠ *Preliminary*

- So what?: $H \to WW \to l\nu l'\nu'$ ... the best search channel at hadron colliders?

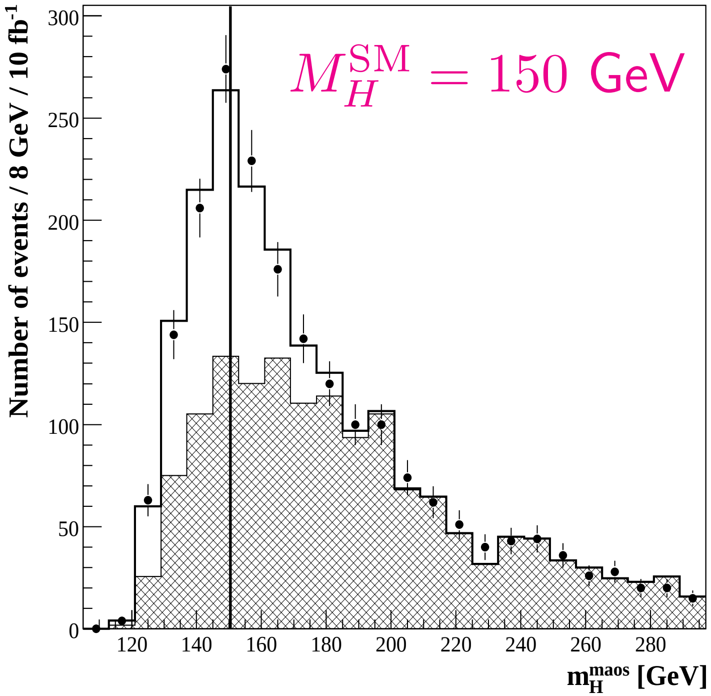




.... excess in the $M_T^{\text{approx?}}$ distribution over the accurately estimated backgrounds ... but, no mass peak

♠ *Preliminary*

- You may want to see the SM Higgs mass peak such as ....:



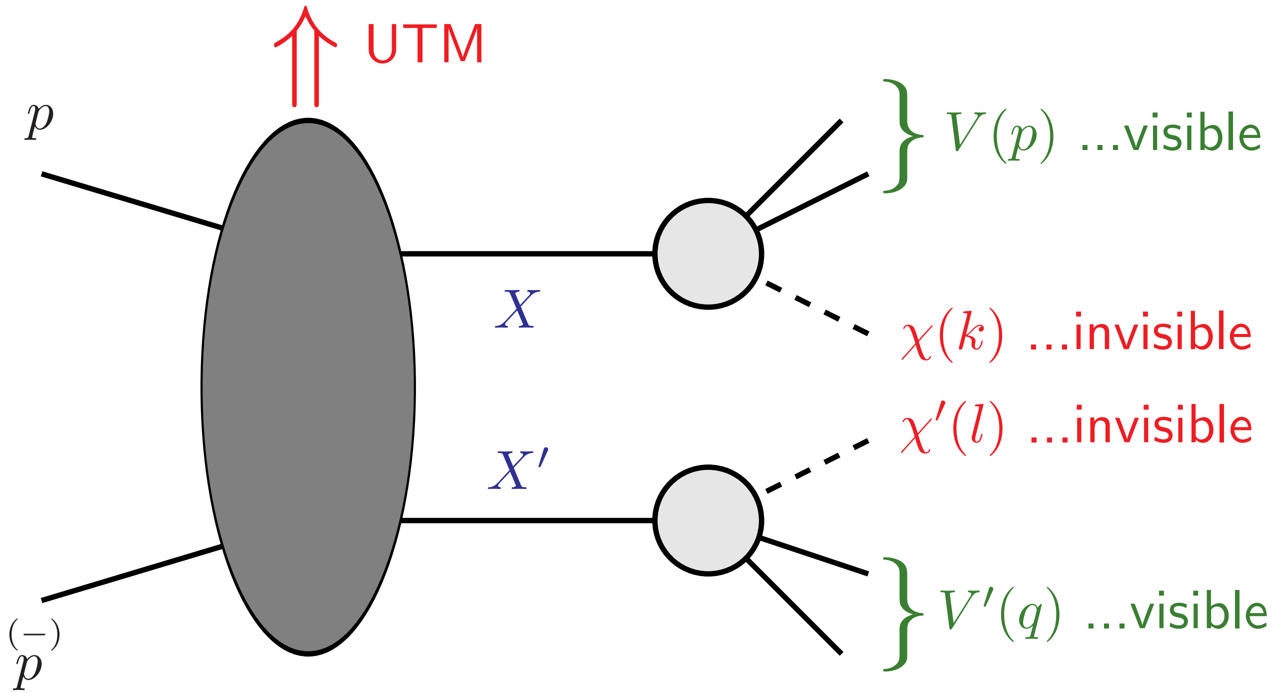
.... it is coming

♠ *Contents*

- *The process and* M_{T2}
- $\mathrm{MA\hat{O}S}$ *momenta of the missing neutrinos*
- $\mathrm{MA\hat{O}S}$ *reconstruction of the Higgs boson mass*
- *Summary and future prospects*

♠ *The process and* M_{T2} (1/7)

- LHC Signature of a New Physics Model with a Z_2 symmetry: *See YG's talk ...*



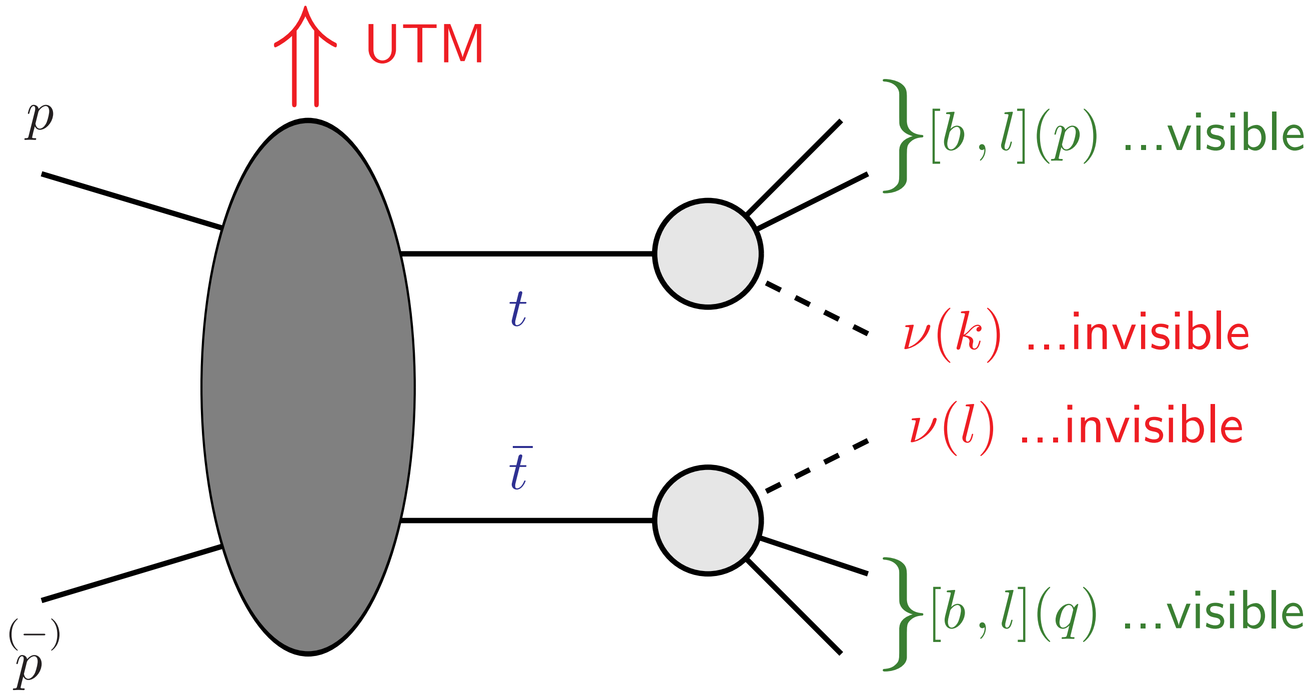
$$M_{T2}(\text{event}, m_\chi) \equiv \min_{\mathbf{k}_T + \mathbf{l}_T = \not{p}_T} \left[\max \left\{ M_T(p^2, \mathbf{p}_T, m_\chi, \mathbf{k}_T), M_T(q^2, \mathbf{q}_T, m_\chi, \mathbf{l}_T) \right\} \right]$$

a systematic scheme for determinging transverse momenta of the two invisible particles

C.G.Lester and D.J.Summers, PLB463(1999)99; A.J.Barr, C.G.Lester and P.Stephenes, JPhysG29(2003)2343

♠ *The process and* M_{T2} $(2/7)$

- Why not Standard Model with two missing neutrinos ?: *See, again, YG's talk ...*

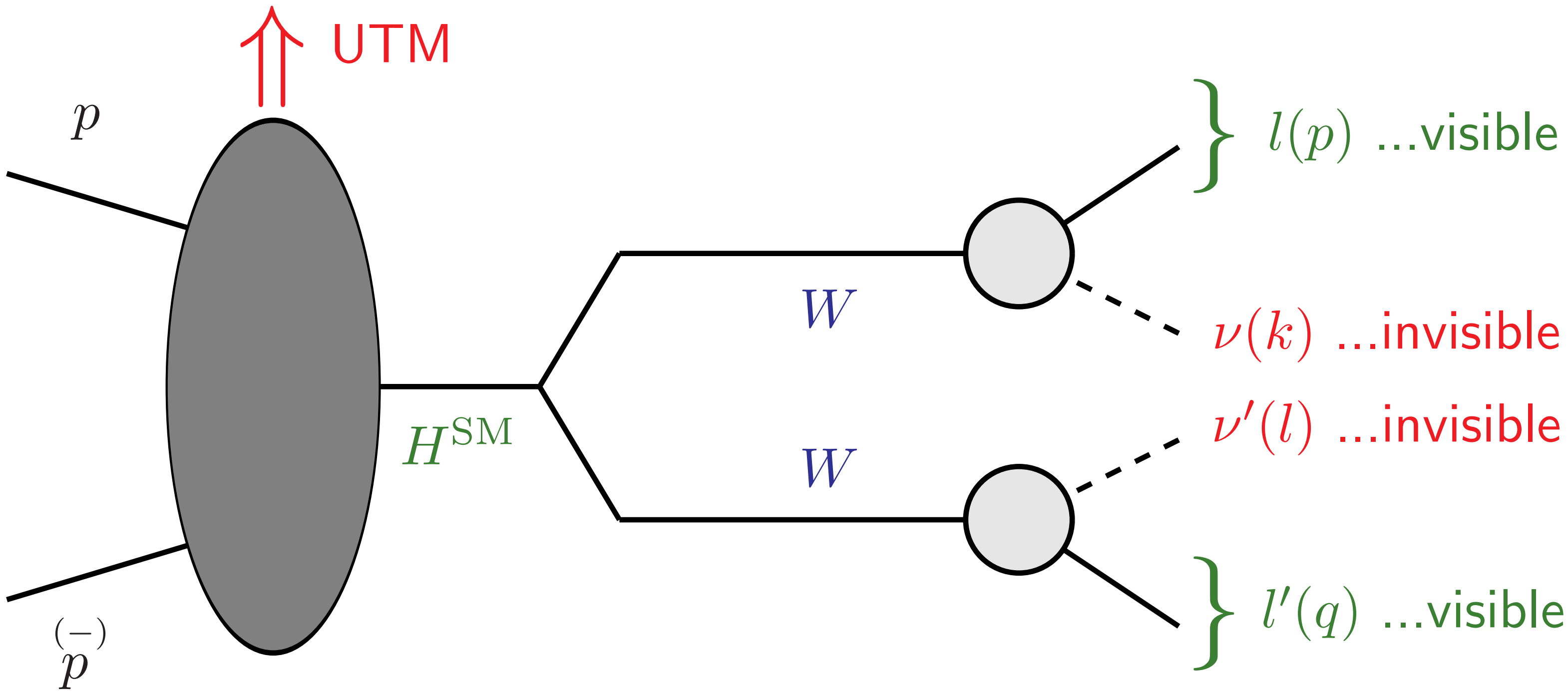


$M_{T2}(\text{event}, m_\nu = 0) \leq m_t$ in the zero-width limit

W.S.Cho, K.Choi, Y.G.Kim, C.B.Park, PRD78(2008)034019; CDF Note 9769 (2009)

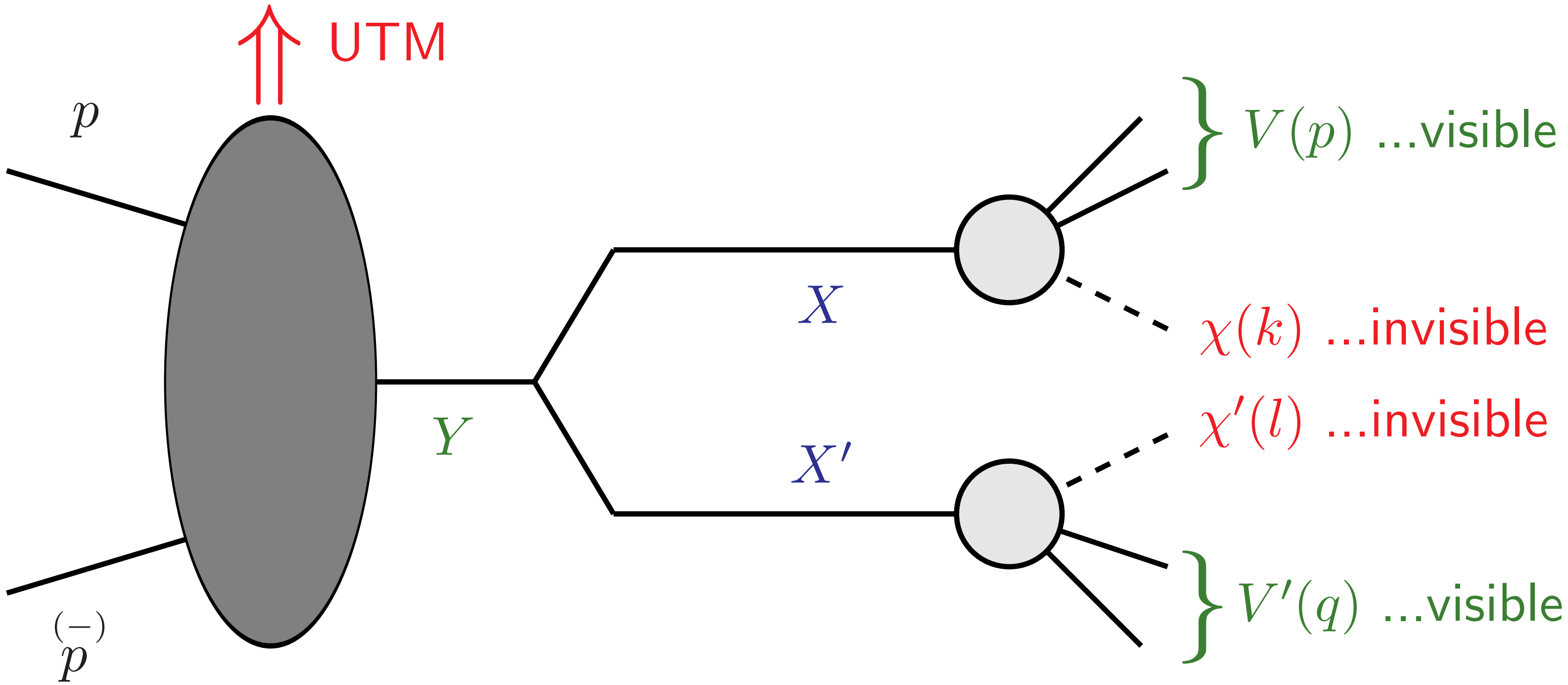
♠ *The process and* M_{T2} $(3/7)$

- The SM process we want to consider ...:

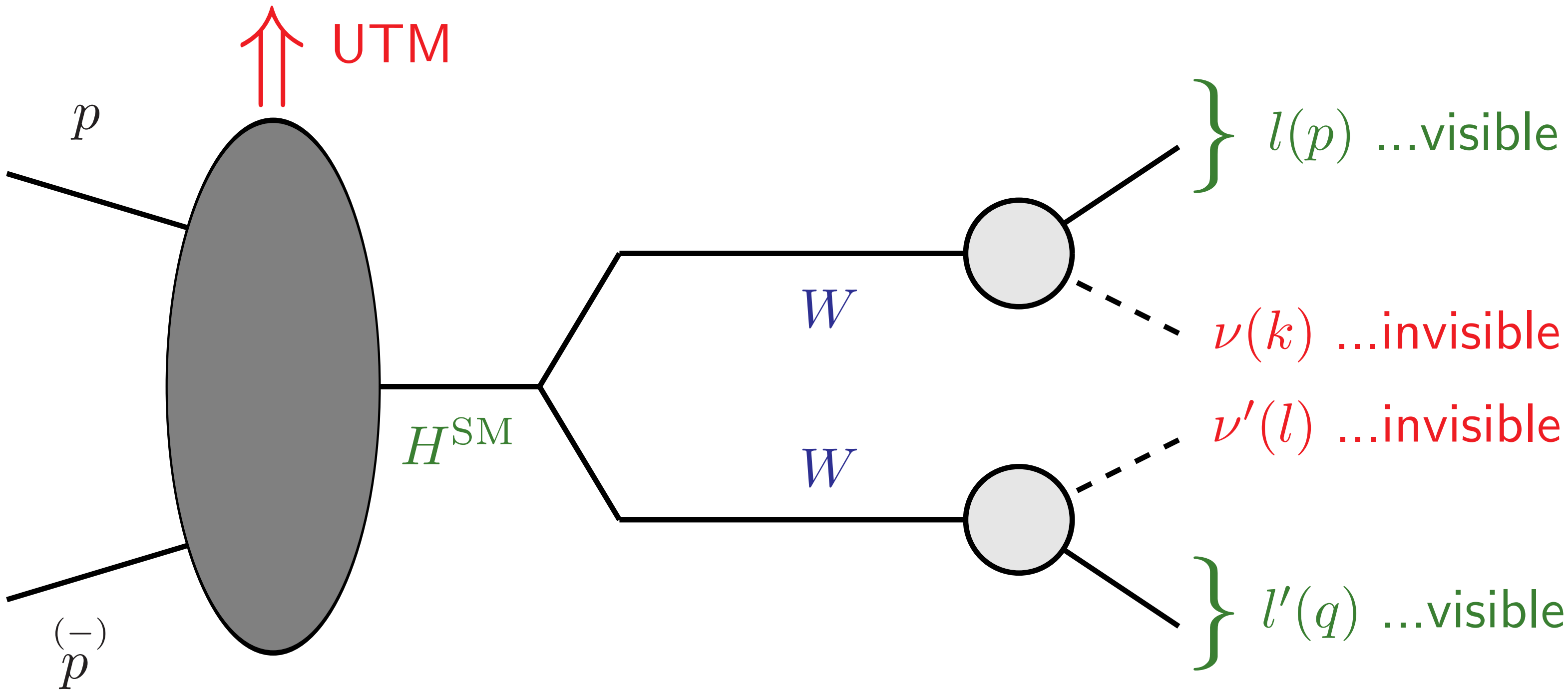


♠ *The process and* M_{T2} (4/7)

- Of course ...: *See IW's talk*, T.Han, I.W.Kim, J.Song, arXiv:0906.5009 [hep-ph]



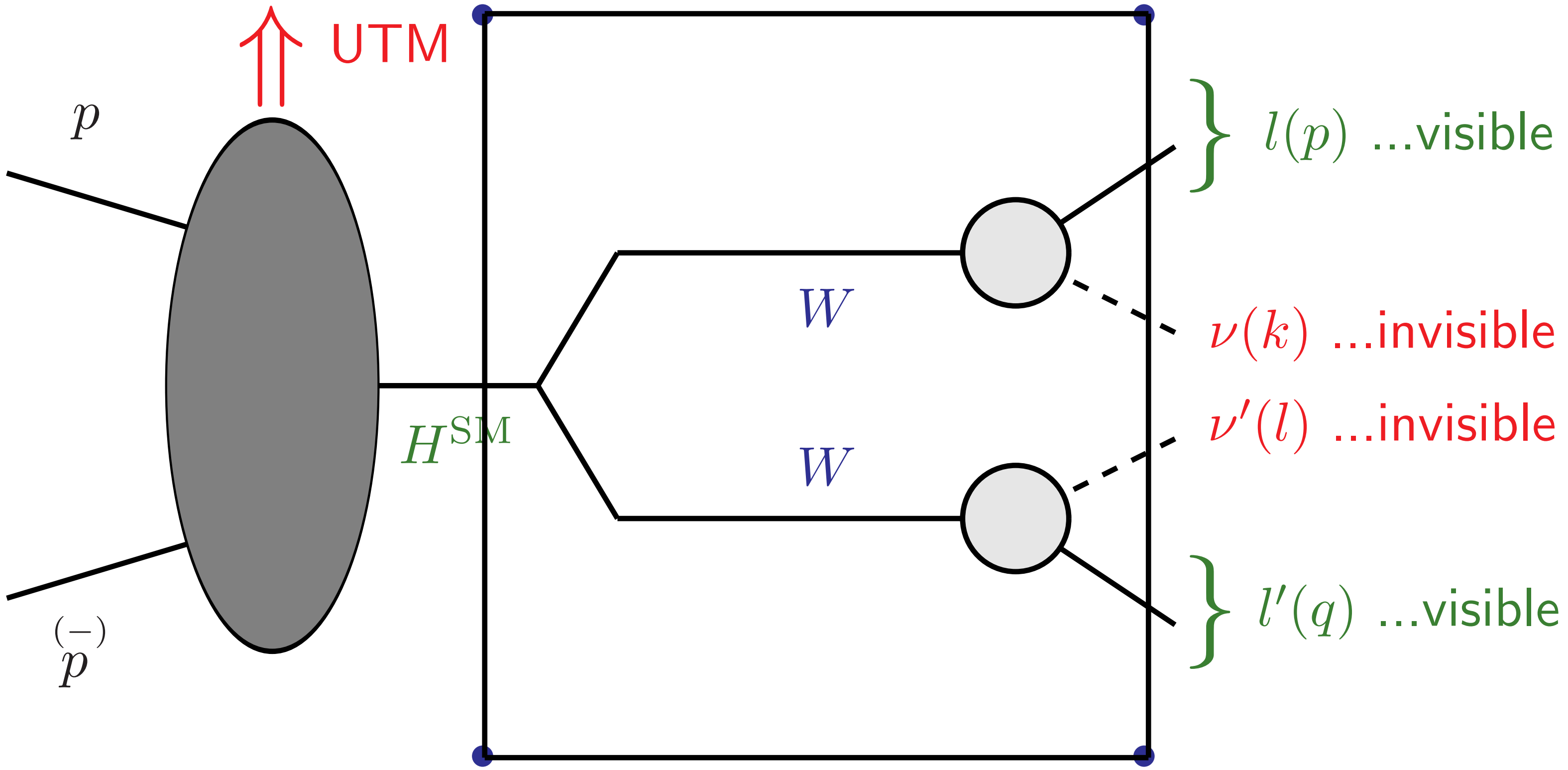
- Returning to the process:



How does it look like?

♠ *The process and* M_{T2} (6/7)

- If you see this process from the viewpoint:

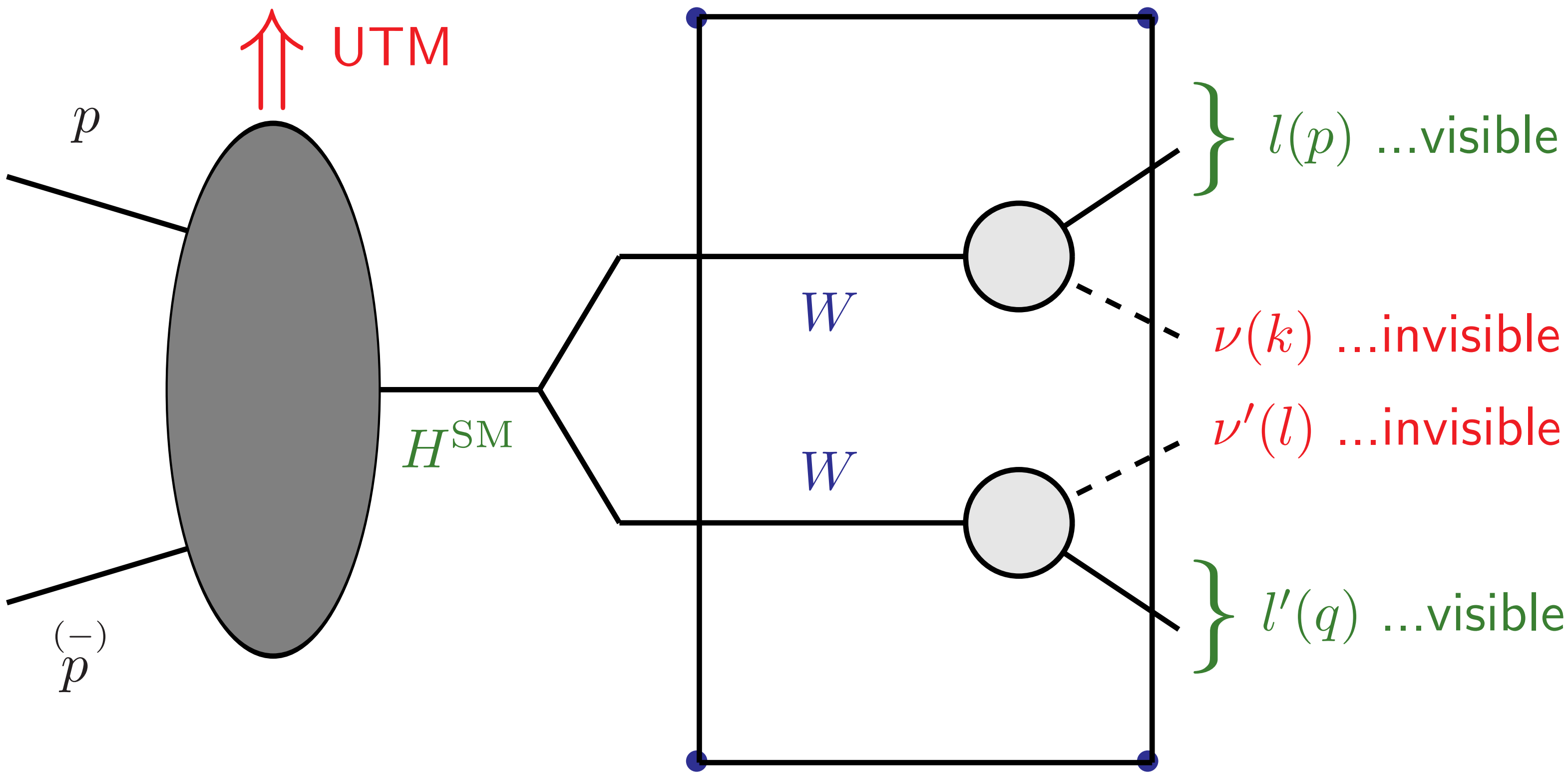


$$M_T[(p+q)^2\,,(\mathbf{p}+\mathbf{q})_T\,,(k+l)^2\,,(\mathbf{k}+\mathbf{l})_T\,] \leq M_{H^{\mathrm{SM}}}$$

A.J.Barr, B.Gripaios, C.G. Lester,JHEP0907(2009)072, arXiv:0902.4864 [hep-ph]

♠ *The process and* M_{T2} $(7/7)$

- We see this process from the WW subsystem:



$M^2_{H^{\rm SM}} = (p + k + q + l)^2$ with $\mathbf{k}$ and $\mathbf{l}$ determined by the $\mathrm{MA\hat{O}S}$

♠ MAÔS *momenta of the missing neutrinos* (1/10)

- MAÔS transverse momenta:

$$H \to W(p+k)\,W(q+l) \to l(p)\;\nu(k)\;\; l'(q)\;\nu'(l)$$

$$p^\mu = \left(\sqrt{|\mathbf{p}_T|^2 + p_L^2}\,, \mathbf{p}_T\,, p_L\right), \quad k^\mu = \left(\sqrt{|\mathbf{k}_T|^2 + k_L^2}\,, \mathbf{k}_T\,, k_L\right),$$

$$q^\mu = \left(\sqrt{|\mathbf{q}_T|^2 + q_L^2}\,, \mathbf{q}_T\,, q_L\right), \quad l^\mu = \left(\sqrt{|\mathbf{l}_T|^2 + l_L^2}\,, \mathbf{l}_T\,, l_L\right)$$

$$\left(M_T^{(1)}\right)^2 = 2\left(|\mathbf{p}_T||\mathbf{k}_T| - \mathbf{p}_T \cdot \mathbf{k}_T\right), \quad \left(M_T^{(2)}\right)^2 = 2\left(|\mathbf{q}_T||\mathbf{l}_T| - \mathbf{q}_T \cdot \mathbf{l}_T\right)$$

♠ MAÔS *momenta of the missing neutrinos* (2/10)

- <u>MAÔS transverse momenta</u>: *... continued*

  For the transverse momenta of the two neutrinos, we assign the usual M_{T2} momenta which minimize

$$\max\left\{M_T^{(1)}, M_T^{(2)}\right\}$$

  In our case, assuming vanishing UTM or $\not{\mathbf{p}}_T = -(\mathbf{p}_T + \mathbf{q}_T)$, the solution of the minimization is simply given when $M_T^{(1)} = M_T^{(2)}$ or

$$2(|\mathbf{p}_T||\mathbf{k}_T^{\rm maos}| - \mathbf{p}_T \cdot \mathbf{k}_T^{\rm maos}) = 2(|\mathbf{q}_T||\mathbf{l}_T^{\rm maos}| - \mathbf{q}_T \cdot \mathbf{l}_T^{\rm maos})$$

  which results in

$$\boxed{\mathbf{k}_T^{\rm maos} = -\mathbf{q}_T \quad \text{and} \quad \mathbf{l}_T^{\rm maos} = -\mathbf{p}_T}$$

♠ MAÔS *momenta of the missing neutrinos* (3/10)

- ... then M_{T2} is given by:

$$(M_{T2})^2 = 2(|\mathbf{p}_T||\mathbf{q}_T| + \mathbf{p}_T \cdot \mathbf{q}_T) \leq 4|\mathbf{p}_T||\mathbf{q}_T| \leq (|\mathbf{p}_T| + |\mathbf{q}_T|)^2 \leq \frac{M_H^2}{4}$$

Note $(M_T^H)^2 = 4(|\mathbf{p}_T| + |\mathbf{q}_T|)^2$

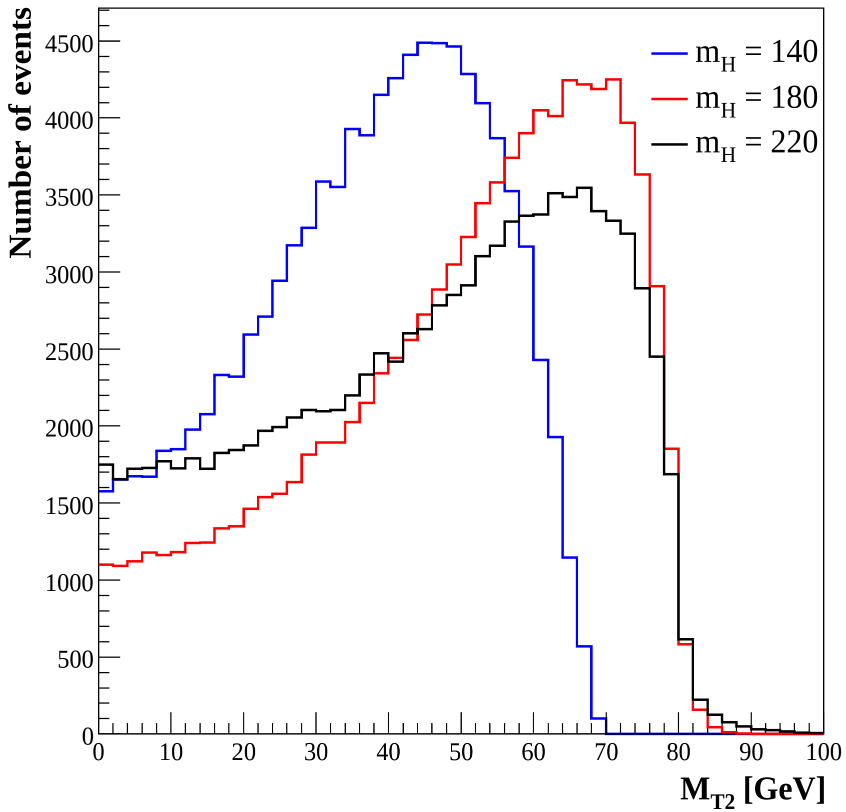
$$\boxed{M_{T2} \leq \min\left(M_W\,, \frac{M_H}{2}\right)}$$

♠ MAÔS *momenta of the missing neutrinos* (4/10)

- ... then M_{T2} is given by:

$$(M_{T2})^2 = 2(|\mathbf{p}_T||\mathbf{q}_T| + \mathbf{p}_T \cdot \mathbf{q}_T) \le 4|\mathbf{p}_T||\mathbf{q}_T| \le (|\mathbf{p}_T| + |\mathbf{q}_T|)^2 \le \frac{M_H^2}{4}$$

$$M_{T2} \le \min\left(M_W\,,\frac{M_H}{2}\right)$$



$| + |\mathbf{q}_T|)^2$

♠ MAÔS *momenta of the missing neutrinos* (5/10)

- MAÔS longitudinal momenta:

$$H \to W(p+k)\,W(q+l) \to l(p)\;\nu(k)\;\; l'(q)\;\nu'(l)$$

Using the M_{T2}-determined $\mathbf{k}_T^{\rm maos}$ and $\mathbf{l}_T^{\rm maos}$, the longitudinal momenta $k_L^{\rm maos}$ and $l_L^{\rm maos}$ can be chosen to satisfy the *on-shell* conditions $(p+k_{\rm maos})^2 = (q+l_{\rm maos})^2 = M_W^2$: W.S.Cho, K.Choi, Y.G.Kim, C.B.Park, PRD79(2009)031701,arXiv:0810.4853 [hep-ph]

$$\begin{aligned} k_L^{\rm maos}(\pm) &= \frac{1}{|\mathbf{p}_T|^2}\left[p_L\,A \pm \sqrt{|\mathbf{p}_T|^2+p_L^2}\,\sqrt{A^2-|\mathbf{p}_T|^2|\mathbf{k}_T^{\rm maos}|^2}\right], \\ l_L^{\rm maos}(\pm) &= \frac{1}{|\mathbf{q}_T|^2}\left[q_L\,B \pm \sqrt{|\mathbf{q}_T|^2+q_L^2}\,\sqrt{B^2-|\mathbf{q}_T|^2|\mathbf{l}_T^{\rm maos}|^2}\right], \end{aligned}$$

where $A \equiv M_W^2/2 + \mathbf{p}_T\cdot\mathbf{k}_T^{\rm maos}$ and $B \equiv M_W^2/2 + \mathbf{q}_T\cdot\mathbf{l}_T^{\rm maos}$

♠ MAÔS *momenta of the missing neutrinos* (6/10)

- MAÔS longitudinal momenta: *... continued*

... complication : what about off-shell W boson?

⇒ the *modified* MAÔS *scheme* using M_{T2} instead of M_W:

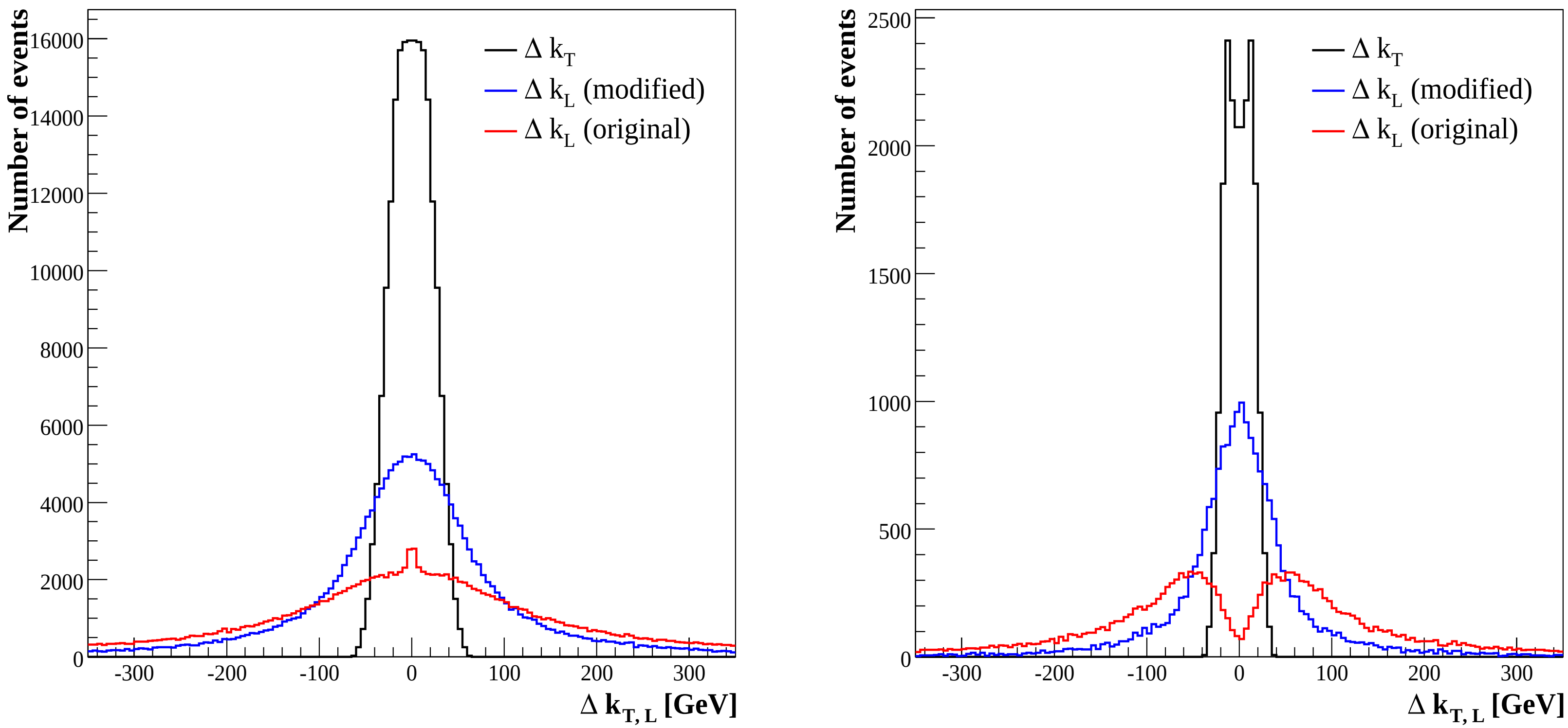
$$(p + k_{\text{maos}})^2 = (q + l_{\text{maos}})^2 = (M_{T2})^2$$

Then we arrive at, with no ambiguity,

$$\boxed{k_L^{\text{maos}} = \frac{|\mathbf{k}_T^{\text{maos}}|}{|\mathbf{p}_T|} p_L, \quad l_L^{\text{maos}} = \frac{|\mathbf{l}_T^{\text{maos}}|}{|\mathbf{q}_T|} q_L}$$

♠ MAÔS *momenta of the missing neutrinos* (7/10)

- Is the modified MAÔS scheme working well?: $M_H = 140$ GeV $< 2M_W$

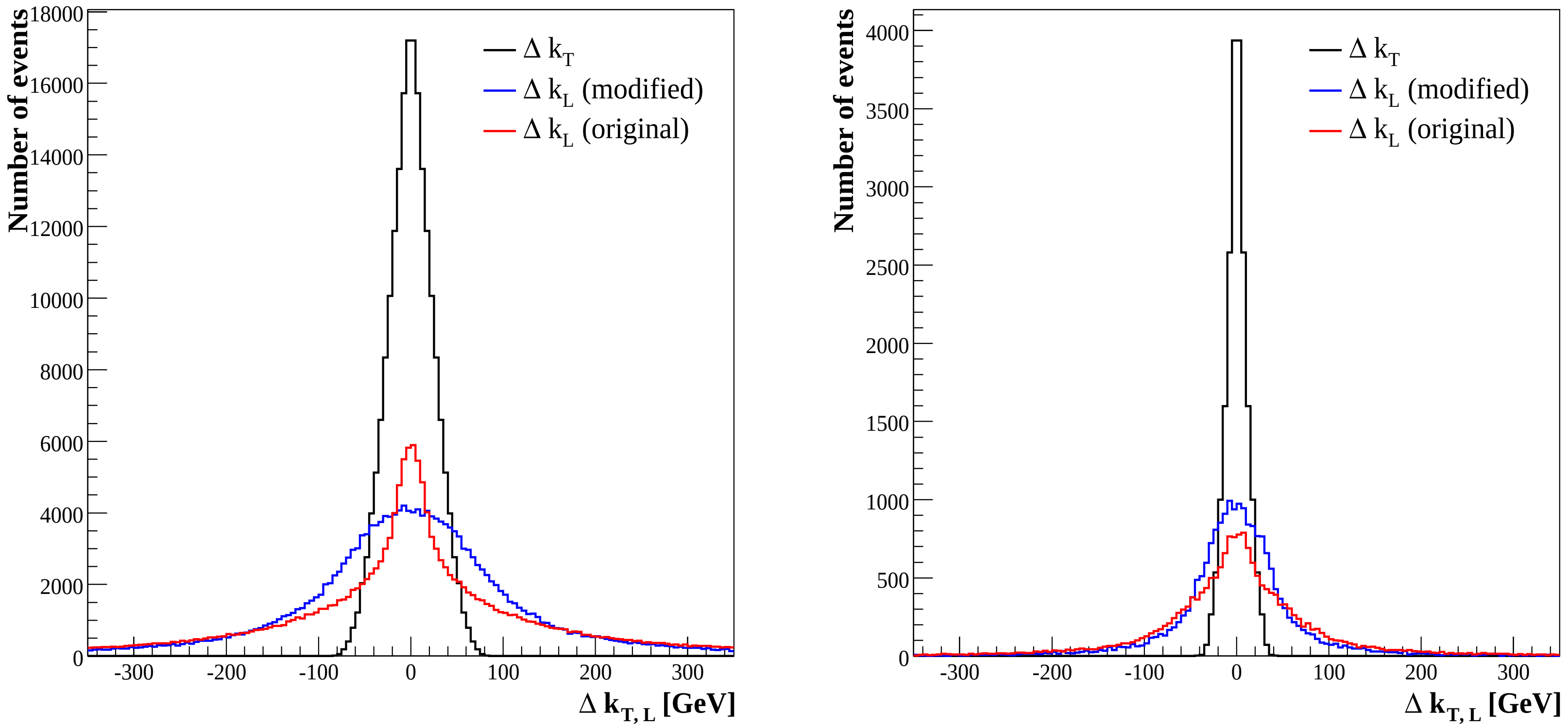


the original scheme fails (!) especially when the M_{T2} cut has been introduced

... the modified scheme works better

♠ MAÔS *momenta of the missing neutrinos* (8/10)

- Is the modified MAÔS scheme working well?: $M_H = 180$ GeV $> 2M_W$



the modified scheme is working well (!) especially together with the M_{T2} cut

♠ $\mathrm{MA\hat{O}S}$ *momenta of the missing neutrinos* (9/10)

- Is the modified $\mathrm{MA\hat{O}S}$ scheme working well?:

$\Rightarrow$ *Yes!*, it seems working well independently whether the intermediate W bosons are on-shell or not, especially when it's combined with the M_{T2} cut

$$H \to W(p+k)\,W(q+l) \to l(p)\,\nu(k)\;\; l'(q)\,\nu'(l)$$

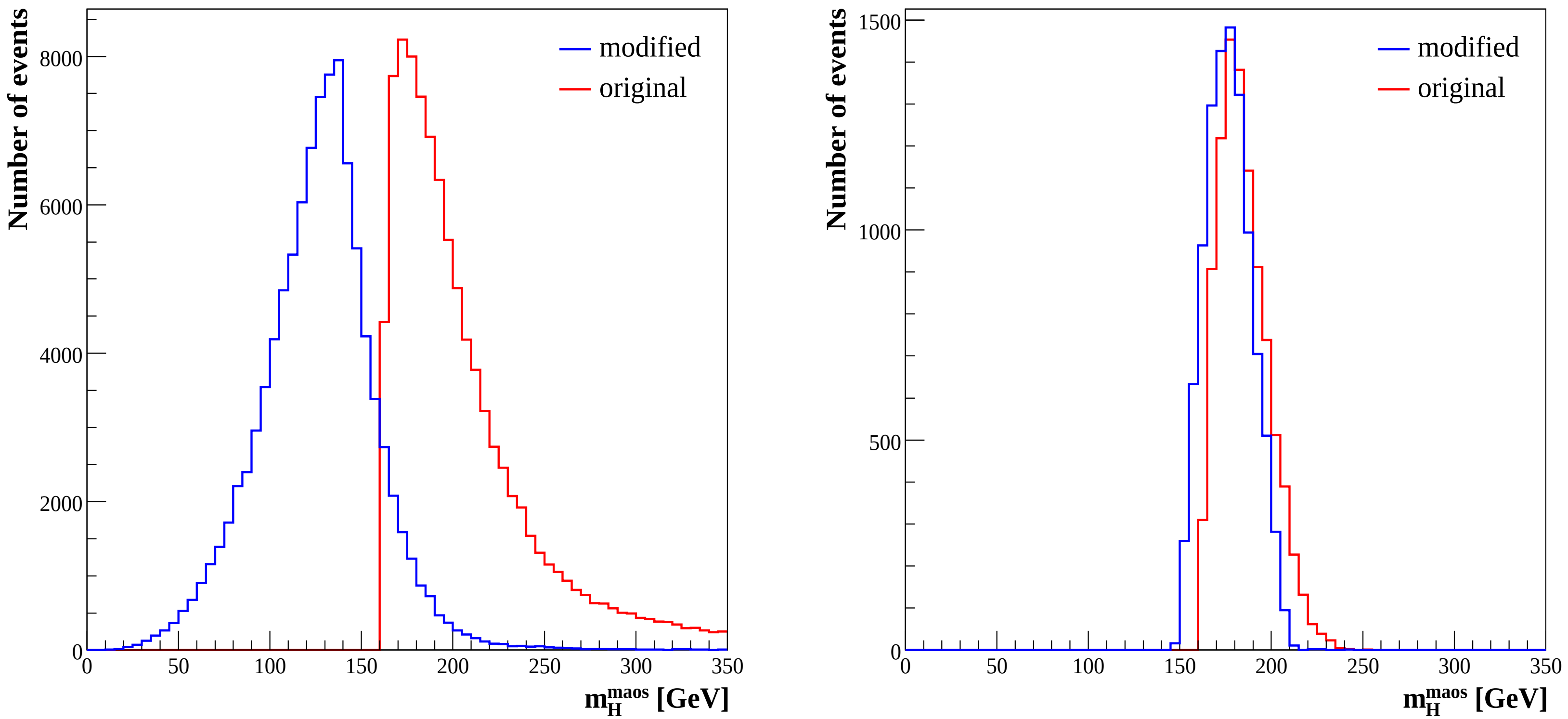
$$(M_H^2)^{\mathrm{MA\hat{O}S}} = (p + k^{\mathrm{MA\hat{O}S}} + q + l^{\mathrm{MA\hat{O}S}})^2$$

$$\mathbf{k}_T^{\mathrm{MA\hat{O}S}} = -\mathbf{q}_T \quad \text{and} \quad \mathbf{l}_T^{\mathrm{MA\hat{O}S}} = -\mathbf{p}_T$$

$$k_L^{\mathrm{MA\hat{O}S}} = \frac{|\mathbf{k}_T^{\mathrm{MA\hat{O}S}}|}{|\mathbf{p}_T|}p_L, \qquad l_L^{\mathrm{MA\hat{O}S}} = \frac{|\mathbf{l}_T^{\mathrm{MA\hat{O}S}}|}{|\mathbf{q}_T|}q_L$$

♠ MAÔS *momenta of the missing neutrinos* (10/10)

- <u>The modified MAÔS scheme does work well</u>: ... *with the upper-10% M_{T2} cut*

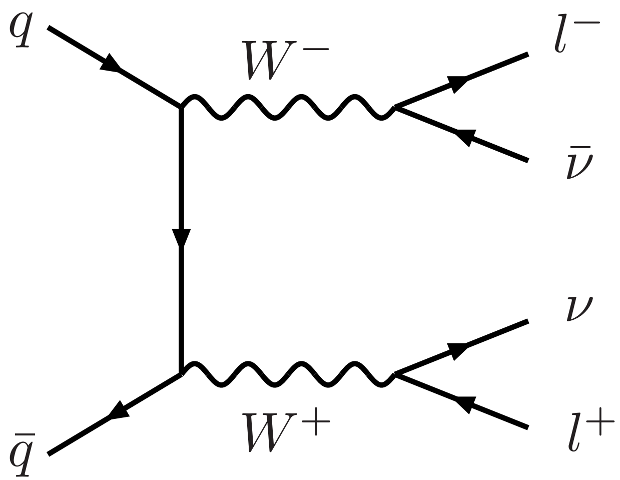


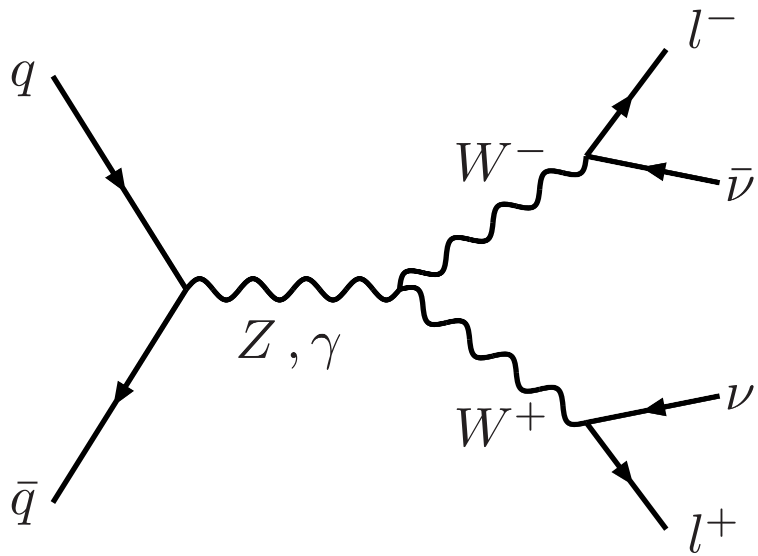
$M_H = 140$ GeV $\qquad$ $M_H = 180$ GeV

ISR yes but no hadronization, no detector smearing, no backgrounds ... yet

♠ MAÔS *reconstruction of the Higgs boson mass* (1/11)

- The main SM background: $pp \to qq/qg/gg \to WW$





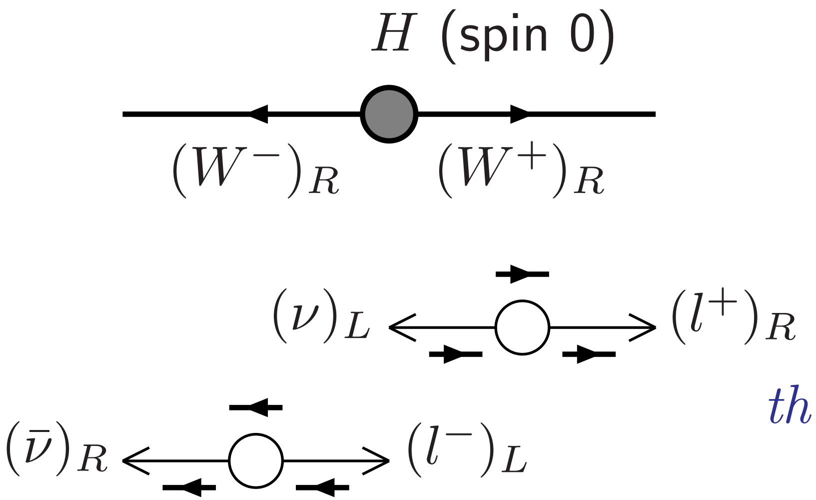
$$\sigma_{\rm bkg}^{pp\to WW} \sim 120 \text{ pb while } \sigma_{\rm signal}^{gg\to H\to WW} \sim 20 \text{ pb } (M_H = 170 \text{ GeV})$$

ATLAS TDR, arXiv:0901.0512[hep-ex]

♠ MAÔS *reconstruction of the Higgs boson mass* (2/11)

- The spin-spin correlation in the signal:

  $\Delta\Phi_{ll}$: the transverse opening angle between l^- and l^+



the two leptons tend to be aligned !

$\Rightarrow$ small $\Delta\Phi_{ll}$

♠ MAÔS *reconstruction of the Higgs boson mass* (3/11)

- Also included is the $t\bar{t}$ background: *Cut flows for* $m_H = 170\ GeV$ *with* $\Delta\Phi_{ll}^{\rm cut} = 1.6$ *and* $M_{T2}^{\rm cut} = 67\ GeV$ *at 10* fb^{-1}.

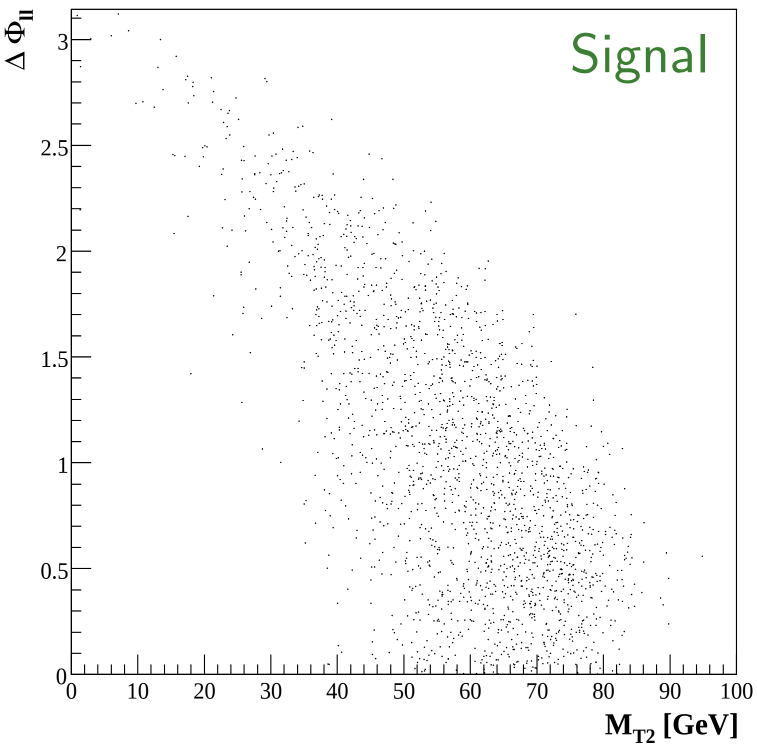
Selection	Selection cuts	$gg \to H$	WW	$t\bar{t}$
Basic Selection	Lepton selection $+m_{ll}$	$4,445$	$18,501$	$139,256$
	$\lvert \not{p}_T \rvert > 30$ GeV	$4,012$	$12,801$	$120,597$
	b-veto	$3,956$	$12,656$	$60,438$
	Jet veto	$2,039$	$8,096$	$1,287$
Tuned Selection	$\Delta\Phi_{ll} < \Delta\Phi_{ll}^{\rm cut}$	$1,621$	$2,939$	332
	$M_{T2} > M_{T2}^{\rm cut}$	619	585	107

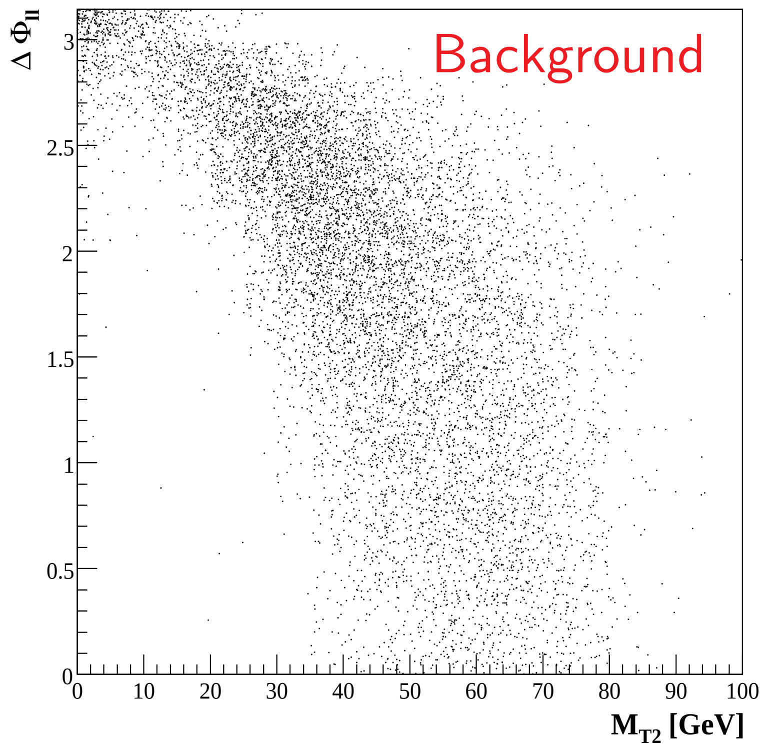
ISR, hadronization, detector smearing, ALL simulated : `PYTHIA6.4` and `PGS4`

♠ MAÔS *reconstruction of the Higgs boson mass* (4/11)

- So, we have two important cuts: $\Delta\Phi_{ll} < \Delta\Phi_{ll}^{\rm cut}$ and $M_{T2} > M_{T2}^{\rm cut}$

Actually, they are correlated: $(M_{T2})^2 = 2(|\mathbf{p}_T||\mathbf{q}_T| + \mathbf{p}_T \cdot \mathbf{q}_T)$





♠ MAÔS *reconstruction of the Higgs boson mass* (5/11)

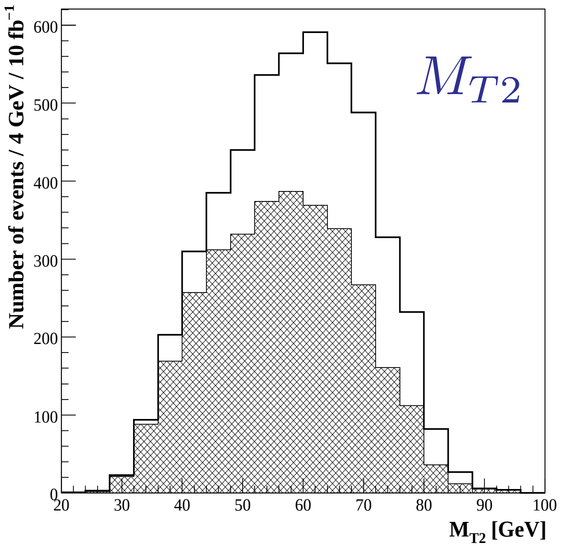
- Optimization of the cuts: $\Delta\Phi_{ll} < \Delta\Phi_{ll}^{\rm cut}$ and $M_{T2} > M_{T2}^{\rm cut}$

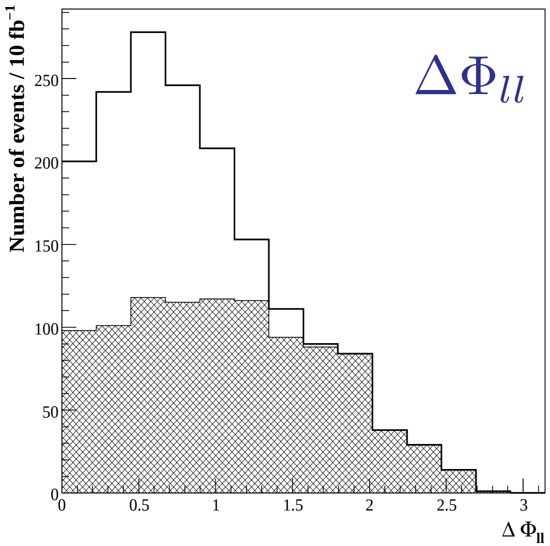
M_H (GeV)	130	140	150	160	170	180	190	200
$\Delta\Phi_{ll}^{\rm cut}$	1.85	1.70	1.65	1.50	1.60	1.70	1.90	2.05
$M_{T2}^{\rm cut}$ (GeV)	38.0	51.0	57.0	66.0	67.0	68.0	69.5	70.0

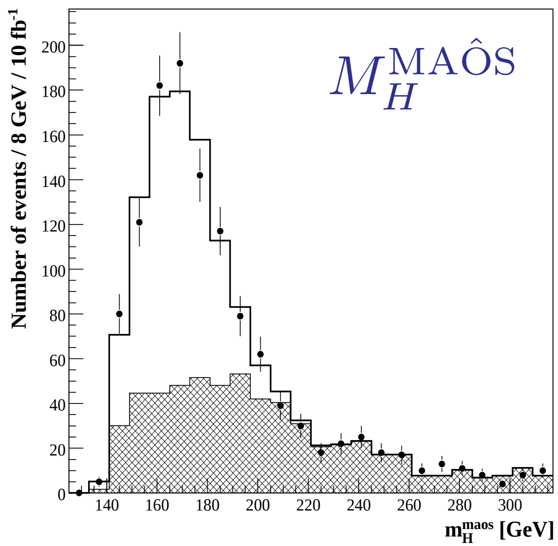
♠ MAÔS *reconstruction of the Higgs boson mass* (6/11)

- Optimization of the cuts: $\Delta\Phi_{ll} < \Delta\Phi_{ll}^{\rm cut}$ and $M_{T2} > M_{T2}^{\rm cut}$

M_H (GeV)	130	140	150	160	170	180	190	200
$\Delta\Phi_{ll}^{\rm cut}$	1.85	1.70	1.65	1.50	1.60	1.70	1.90	2.05
$M_{T2}^{\rm cut}$ (GeV)	38.0	51.0	57.0	66.0	67.0	68.0	69.5	70.0

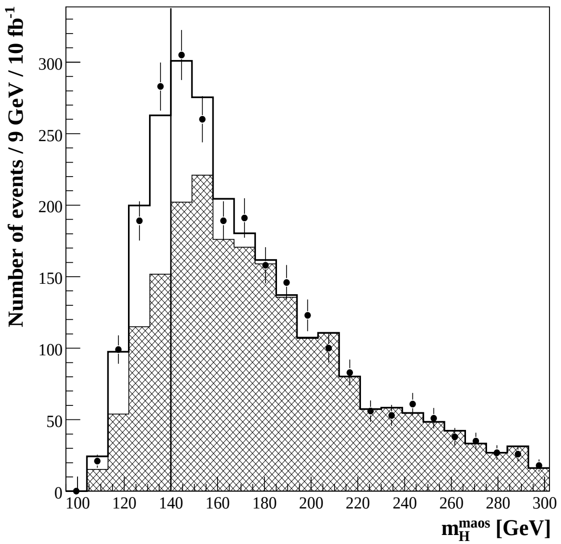




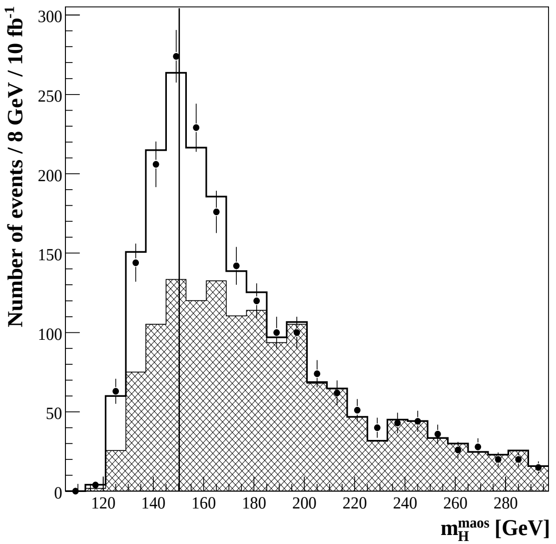


♠ MAÔS *reconstruction of the Higgs boson mass* (7/11)

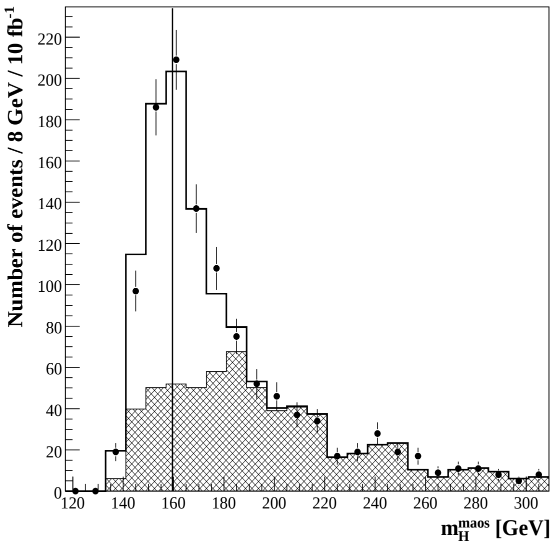
- MAÔS Higgs mass distribution:



$M_H = 140$ GeV

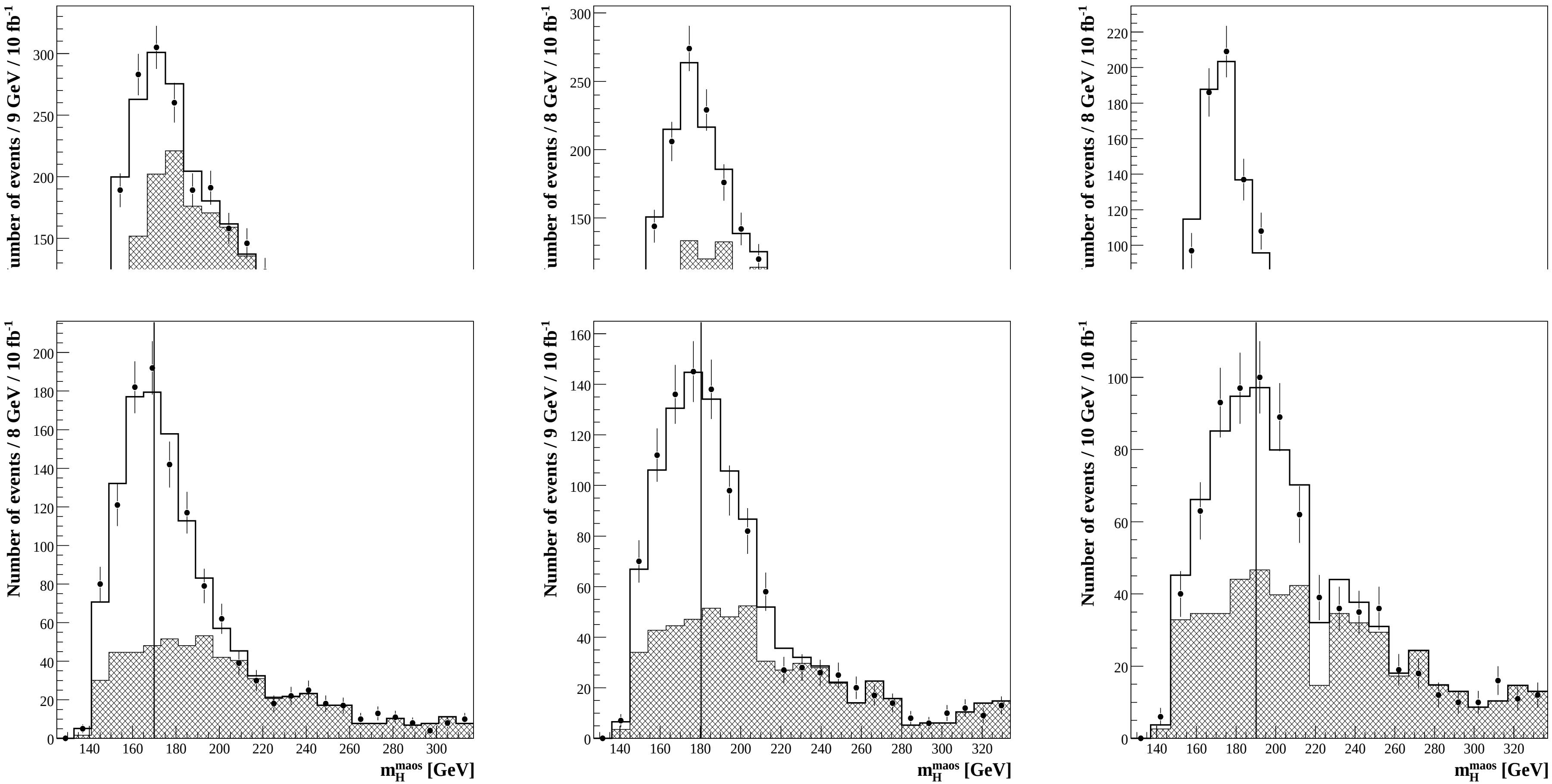


$M_H = 150$ GeV



$M_H = 160$ GeV

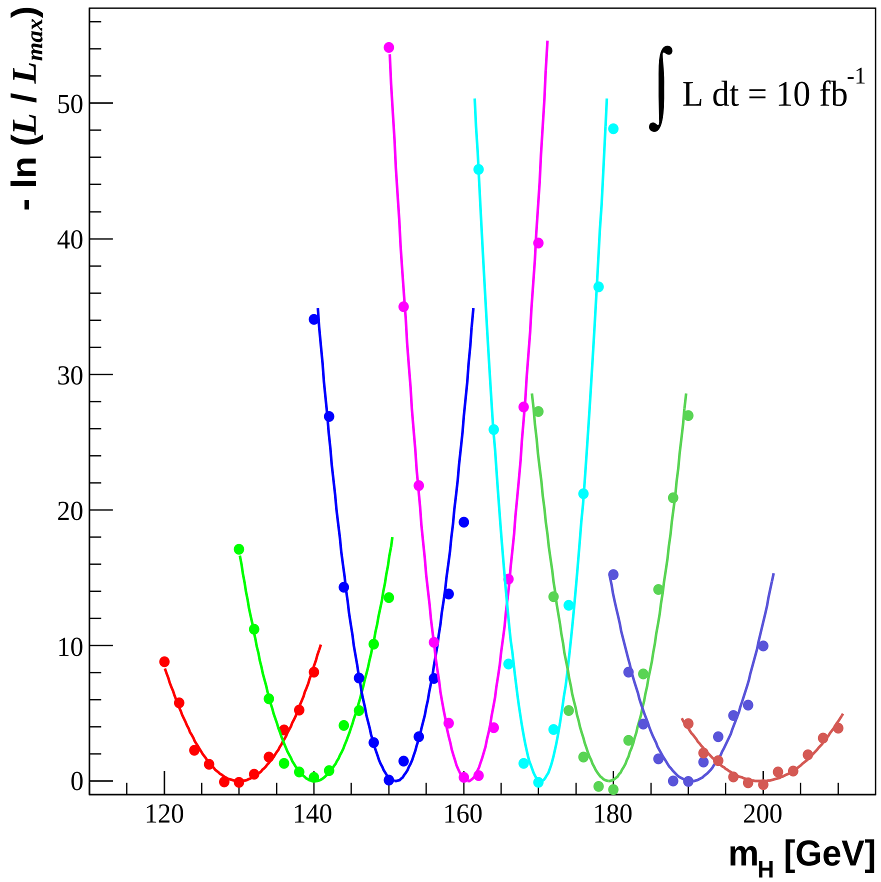
- MAÔS Higgs mass distribution:



$M_H = 170$ GeV $M_H = 180$ GeV $M_H = 190$ GeV

♠ MAÔS *reconstruction of the Higgs boson mass* (9/11)

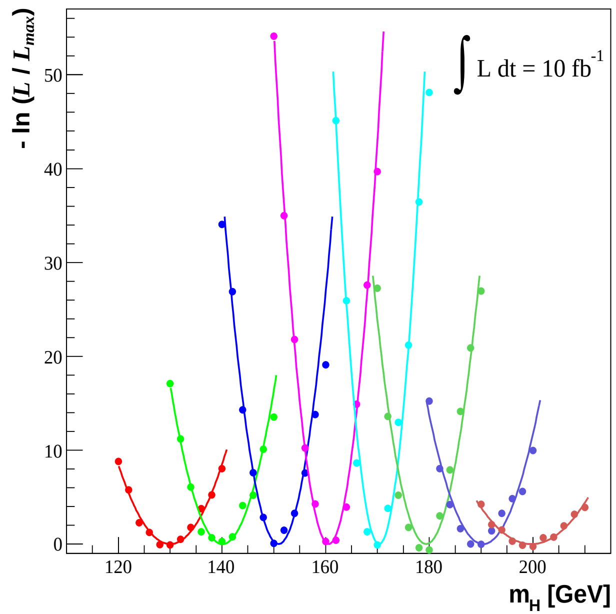
- Likelihood analysis: $\mathcal{L} \equiv \prod_i^{\mathcal{N}} \frac{e^{-m_i}\, m_i^{n_i}}{n_i!}$ with n_i/m_i the number of events in the i-th bin of the nominal $M_H^{\text{MAÔS}}$ distribution/template



♠ MAÔS *reconstruction of the Higgs boson mass* (10/11)

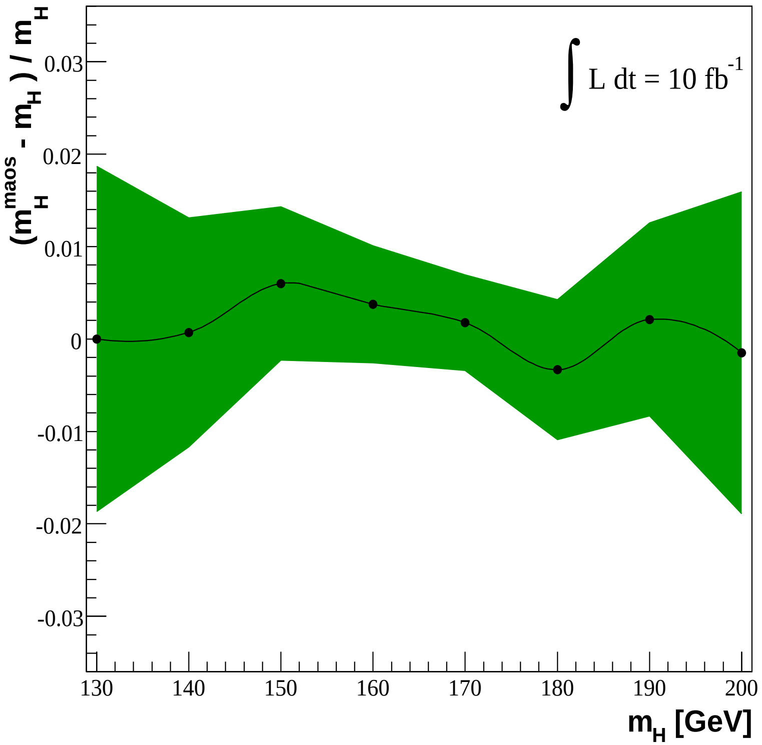
- Likelihood analysis: *... continued*

M_H (GeV)	130	140	150	160	170	180	190	200
Fitted value (GeV)	130.0	140.1	150.9	160.6	170.3	179.4	190.4	199.7
1-σ error (GeV)	2.4	1.7	1.2	1.0	0.9	1.4	2.0	3.5

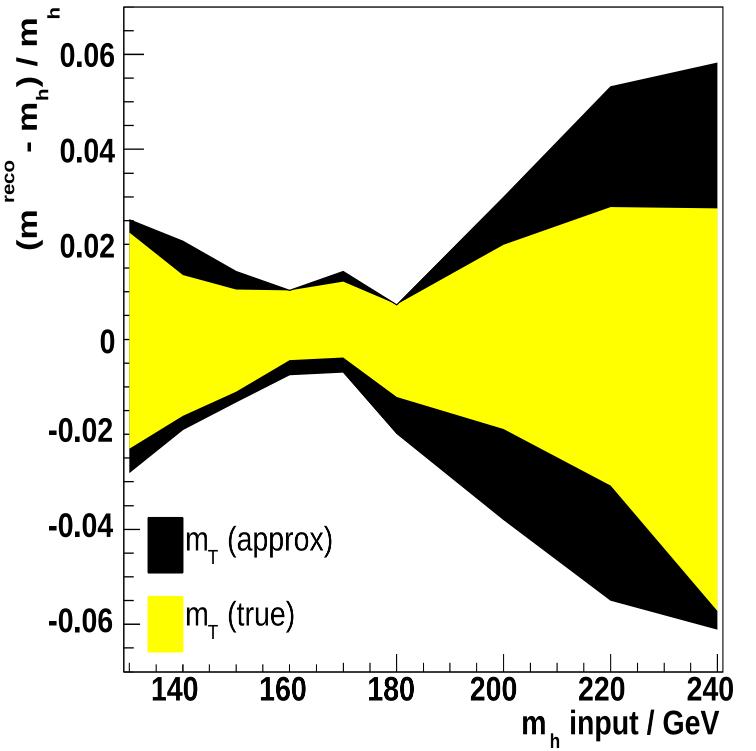


♠ MAÔS *reconstruction of the Higgs boson mass* (11/11)

- Comparison: *... looks better?*



Ours



BGL,arXiv:0902.4864

♠ *Summary and future prospects*

- The modified $\mathrm{MA\hat{O}S}$ is powerful in the reconstruction of the SM Higgs boson decaying into leptonically decaying W bosons with two missing neutrinos

- You may have more ideas on how to apply the $\mathrm{MA\hat{O}S}$ to other SM/NP processes